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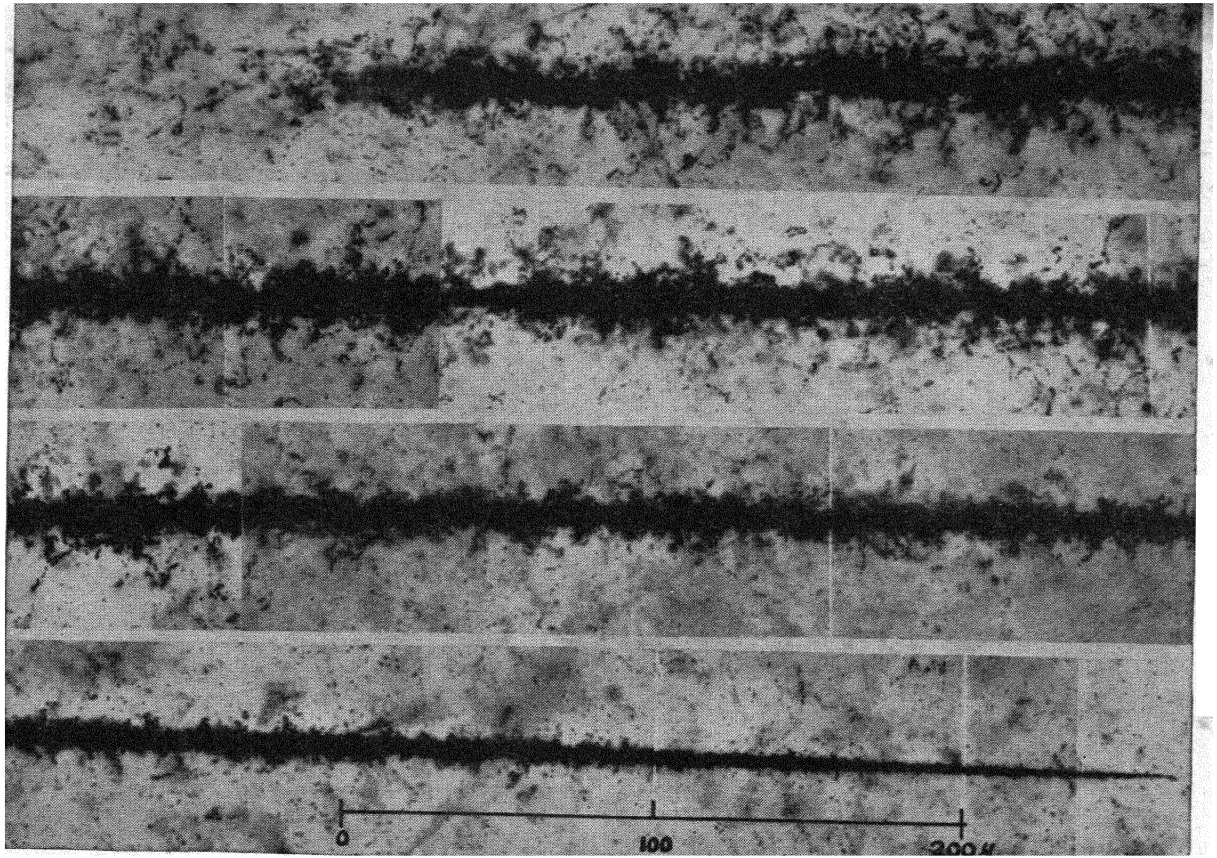
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Author ANDREWS, Howard L.

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RADIATION BIOPHYSICS



A heavily ionizing event recorded at an extreme altitude in a nuclear emulsion. The biological consequences of these "thindowns" are unknown, but they may be regularly encountered in space travel. Courtesy of H. Yagoda.

RADIATION BIOPHYSICS

Howard L. Andrews

Radiation Safety Officer
National Institutes of Health

Prentice-Hall, Inc.

Englewood Cliffs, New Jersey

1961

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PREFACE

The discovery and exploitation of the self-sustaining nuclear chain reaction has had an explosive impact upon all facets of human existence. On the one hand nuclear detonations of fantastic power can be readily produced, so that all living things are potentially exposed to radiation from such detonations. On the other hand nuclear power is becoming increasingly available both in fixed installations and for vehicle propulsion. Hundreds of varieties of radioactive nuclides have been added to those few formerly available in minute amounts from natural sources.

These new radiation sources carry both a promise and a threat. The promise includes improvements in medical diagnosis and treatment, and the unknown future benefits to be derived from improved research methods. The threat includes the possibility of causing, through careless use today, injury to presently unborn thousands, through an accumulation of an undesirable genetic burden. Obviously, both the potentialities and the hazards of these new substances must be thoroughly understood by all who use them.

In the early days detailed knowledge of the physical and biological properties of penetrating radiation resided largely with those

who were collaterally increasing that knowledge. Today such an enormous body of literature is available that it is sometimes difficult to separate the pertinent from the relatively less important.

The present book is aimed at presenting a working knowledge of radiation fundamentals to those just making its acquaintance. No apology is made for what may seem to be an overemphasis on physical principles. Without an understanding of these principles one can hardly expect to explain chemical and biological actions, or to use effectively and safely any of the wide variety of radiation sources presently available. Large numbers of disconnected bits of biological information exist, but there seems little to gain by a routine description of many of them. A detailed treatment must await the discovery of some unifying principles not now available. It is this philosophy which has led to what may seem like a casual treatment of the phenomenological aspect of radiation injury.

This book, like almost any other, comes from the work of so many investigators and teachers that complete acknowledgment is impossible. I am particularly indebted to Drs. W. W. Smith and F. Smith for much invaluable advice and counsel. To Jean and Alice Andrews, who participated in all of the tedious phases of manuscript preparation, my gratitude for a job well done.

H. L. A.

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RADIATION BIOPHYSICS

1

BASIC PRINCIPLES

1.01 ELEMENTARY PARTICLES

The production of X-rays in 1895 and the discovery of radioactivity in 1896 inaugurated an era of most intensive research into the nature of matter and energy, and the interactions between them. Experiment and theory agreed that matter is made up of various combinations of a relatively few types of elementary particles. As research in nuclear physics intensified, and more refined equipment became available, more and more particles were discovered, and at present the list of identified types is a formidable one. The roles played by some of these particles are quite clear but the function of others is obscure.

Some of the elementary particles interact very weakly with the matter through which they pass, or appear as free particles only rarely. These play no direct, major role in the reactions of radiation with chemical systems or living tissue. For present purposes we can

confine our attention to those particles listed in the upper section of Table 1-1.

Table 1-1. PROPERTIES OF ELEMENTARY PARTICLES

Name	Symbol	MASS amu	MASS m_e	Charge	Comments
Electron	e^-	0.000519	1	−1	Stable
Positron	e^+	0.000549	1	+1	Lifetime 10^{-6} sec
Proton	p	1.007593	1,836	+1	Nucleus of hydrogen
Neutron	n	1.008982	1,838	0	Lifetime 13 min
Neutrino	ν	Less than $0.01m_e$		0	Accompanies β decay
L meson	π,μ	$(206\text{–}273)m_e$		+1, −1, 0	Lifetime 10^{-6} sec
K meson	$\tau,\theta,\chi,\varkappa$	$(960\text{–}965)m_e$		+1, −1, 0	or less
Hyperon	Λ,Σ,Ξ	$(2{,}180\text{–}2{,}580)m_e$		+1, −1, 0	

Particle masses are given in Table 1-1 in terms of *atomic mass units* (amu) and as multiples of the electron mass, m_e. By definition one amu is equal to $\frac{1}{16}$ the mass of one atom of the most common form or *isotope* of oxygen. In the physical system of atomic weights this oxygen isotope is assigned the value 16.0000 to form the basis for the system. Since one gram-atom of any element contains 6.02×10^{23} atoms,* a single atom of the common isotope of oxygen will have a mass of $16/6.02 \times 10^{23} = 2.66 \times 10^{-23}$ gm. Hence 1 amu $= 1.66 \times 10^{-24}$ gram. The amu is very nearly, but not quite equal to the chemical atomic weight unit, which is obtained by assigning 16.0000 to naturally occurring oxygen instead of to the common isotope.

The values of electric charge listed in Table 1-1 are obtained by assigning to the electron the value of −1. The magnitude of this charge is the smallest amount of free electric charge known to exist. In general, electrical quantities are expressed in one of three systems of units derived from the basic definitions of mass, length, and time. We shall occasionally make use of these three systems, but for most calculations shall find the electron unit to be preferred. The systems are interrelated as shown below.

$$\text{one electron charge} \begin{cases} 1.6 \times 10^{-20} \text{ electromagnetic units (emu)} \dagger \\ 1.6 \times 10^{-19} \text{ practical units (coulombs)} \\ 4.8 \times 10^{-10} \text{ electrostatic units (esu)} \end{cases} \quad \text{(1-1)}$$

* Avogadro's number. More accurate values of this and other constants will be found in the Appendix.

† The notation and abbreviations used in this book are in accord with the Style Manual, 2nd ed., American Institute of Physics, New York, 1959.

In the domain of these elementary particles size cannot be uniquely defined. Fortunately, exact sizes are of little consequence for present purposes—it is sufficient to think of the elementary particles as spheres with radii of the order of 10^{-13} cm.

1.02 ELECTROMAGNETIC RADIATION

Long before substantial progress was made in identifying the elementary particles, physicists had recognized that energy could be transmitted through space by *electromagnetic radiation*. The nature of visible light, one of the many manifestations of electromagnetic radiation, had been intensively investigated. It was known that electromagnetic radiation was propagated like a wave motion, and methods were devised for measuring wavelengths with extraordinary accuracy.

Theoretical studies by Maxwell showed that electromagnetic radiation consisted of interdependent electric and magnetic fields vibrating at a frequency ν which is related to the wavelength λ and the velocity of propagation c by the basic wave equation

$$\lambda\nu = c \tag{1-2}$$

In free space the velocity of propagation of any electromagnetic wave is nearly 3×10^{10} cm/sec. In a ponderable medium the velocity may be considerably less than c, $\cong (2 \times 10^{10}$ cm/sec), and this results in a phenomenon known as Cerenkov radiation, to be discussed later.

At the turn of the century it was becoming evident that wave properties would not serve to explain energy interchanges between radiation and matter. In 1901 Max Planck made the then startling assumption that in energy exchanges radiation does not behave like a continuously distributed wave, but rather like an energy package of discrete size, the size being given by

$$E = h\nu \tag{1-3}$$

where E = energy in ergs
h = Planck's constant, 6.62×10^{-27} erg sec
ν = number of vibrations per second.

Each energy package is known as a *photon*, or *quantum*.

The dual nature of electromagnetic radiation has been demonstrated repeatedly. Since we will be concerned primarily with energy

exchanges there will be little occasion to consider the wave properties, and quantum concepts will be used almost exclusively.

Known electromagnetic radiations cover an enormous wavelength range, Fig. 1-1, and have strikingly different properties. Although

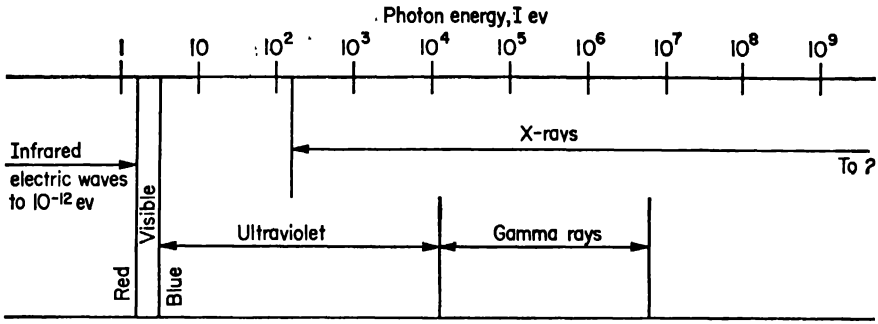


Fig. 1-1. The electromagnetic spectrum plotted on a logarithmic energy scale.

methods of generation differ, all the various electromagnetic radiations are basically similar, differing only in wavelength and hence in photon energy. In particular, as we shall see later, X-rays and gamma rays are produced by quite different processes, but once emitted are indistinguishable if the photon energies are equal.

Because of the enormous range of the electromagnetic spectrum, a variety of units has been found useful in measuring wavelength. In the radio region the meter or centimeter is the usual unit. The centimeter is an inconveniently large unit in the domain of X-rays and gamma rays, where the *Angstrom,* A, is customarily used

$$1 \text{ A} = 10^{-8} \text{ cm} = 10^{-10} \text{ m}$$

Some older wavelength data are given in x units where

$$1 \text{ xu} = 10^{-11} \text{ cm} = 10^{-3} \text{ A}$$

1.03 THE ELECTRON VOLT

Consider an evacuated tube, Fig. 1-2, containing a fine wire filament F, and a cold metal anode A. If the filament is heated by passing an electric current through it, free electrons will be emitted by the hot wire into the surrounding space. If the anode is positively charged to potential difference V above the filament, each emitted

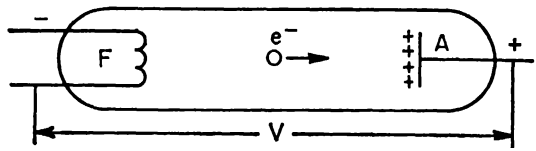


Fig. 1-2. Kinetic energy acquired by an electron as work is done on it by an electrical potential.

electron will experience an attractive force and will move toward the anode. Just before striking the anode each electron will have a kinetic energy equal to the work done by the potential V on the electric charge e, carried by the electron.

The principle of conversion of work by an electric potential into kinetic energy is simple but the application is complicated by the various systems of electrical units. To avoid restriction to the electronic charge e, consider the general case of any electric charge Q moving through a potential difference V. The various systems of units are arranged to satisfy the following relations:

$$\begin{aligned} V\text{ (esu)} &\times Q\text{ (esu)} &&= W\text{ (ergs)} \\ V\text{ (emu)} &\times Q\text{ (emu)} &&= W\text{ (ergs)} \\ V\text{ (volts)} &\times Q\text{ (coulombs)} &&= W\text{ (ergs} \times 10^7\text{) or joules.} \end{aligned}$$

Now let V, Fig. 1-2, equal one volt and consider an electron which, from Eq. (1-1) has a charge of 1.6×10^{-19} coulomb. Then

$$W\text{ (electron volts)} = 1 \times 1.6 \times 10^{-19}\text{ joule} = 1.6 \times 10^{-12}\text{ erg} \quad \textbf{(1-4)}$$

The *electron volt,* ev, defined by Eq. (1-4) is the basic unit of energy used in most radiation studies. Natural extensions are:

10^3 ev = 1 Kilo electron volt, Kev
10^6 ev = 1 Mega electron volt, Mev = 1.6×10^{-6} erg
10^9 ev = 1 Billion electron volt, Bev

Careless application of these terms may lead to confusion between units of electrical potential and units of energy. When, for example, 250 kilovolts (250 kv) is applied to an X-ray tube, each electron striking the target has an energy of 250 Kev. The numerical agreement comes about because the accelerated particles have a single charge. The same potential would impart twice the energy to doubly charged particles, and so on.

Equation (1-3) may now be put in a form more useful for numerical calculations. This is best done in terms of λ since this is a quan-

tity capable of experimental determination. From Eqs. (1-2) and (1-3)

$$E \text{ (ergs)} = \frac{hc}{\lambda} \tag{1-5}$$

$$E \text{ (ev)} = \frac{6.62 \times 10^{-27} \times 3 \times 10^{10}}{1.6 \times 10^{-12} \lambda} = \frac{1.24 \times 10^{-4}}{\lambda}$$

If λ is expressed in Angstroms instead of centimeters and E is in Kev

$$E \text{ (Kev)} = \frac{12.4}{\lambda_A} \tag{1-5A}$$

Illustrative Example

Radioactive cobalt, Co^{60} emits a gamma ray whose wavelength is measured as 0.01060 A. Calculate the energy of this gamma-ray photon.

$$E = \frac{12.4}{0.01060} = 1170 \text{ Kev} = 1.17 \text{ Mev}$$

1.04 THE BOHR ATOM

In 1910, Rutherford reported the results of a series of experiments which demonstrated that matter consists essentially of empty space with particles separated by distances which are large compared to their own size. The Rutherford model was extended and put on a quantitative basis by Niels Bohr, who in 1913 announced the theory of atomic structure now bearing his name. The Bohr theory was based on a simple physical picture of atomic structure and gave surprisingly accurate predictions of the spectral lines emitted by atomic hydrogen.

According to the Bohr theory an atom of hydrogen appears as in Fig. 1-3. The *nucleus* of the atom is a single proton which is very massive when compared to the electron revolving around it. An electrostatic force of attraction exists between the two unlike charges, and indeed such a force is required to maintain the electron in uniform circular motion. The attractive force follows an *inverse square law*

$$F = \frac{e \times e}{r^2} \tag{1-6}$$

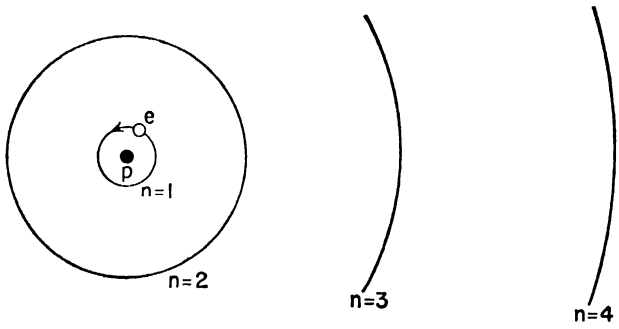


Fig. 1-3. The Bohr model of hydrogen in its ground state. The proton and electron are enlarged 10^6 times in relation to the radii of the orbits.

where F is the force in dynes, e the electric charge in esu, and r the orbital radius in cm. Conditions imposed by the theory restrict the electron to a series of *allowable* orbits whose radii can be calculated from well-known physical constants. These radii are of the order of 10^{-8} cm so the Bohr model is in accord with the empty-space requirements of the Rutherford experiments.

Each allowable orbit has an associated energy content and it is actually more precise to think of a series of allowable *energy levels* rather than a series of orbits. Normally the electron remains in the state of lowest possible energy, or *ground state,* corresponding to the innermost orbit. This orbit or energy level is designated by a *principal quantum number* $n = 1$.

In an electric discharge, or at high temperatures where energetic collisions can occur, the electron may receive sufficient energy to raise it to a higher energy level $n = 2, 3 \ldots$ and then the atom is said to be in an *excited state.* Note that energy must be put *into* the electron to raise it from the ground state against the electrostatic force of attraction. After perhaps 10^{-12} sec the electron will return spontaneously to the ground state and will get rid of the excess energy by the emission of a photon of electromagnetic radiation. The return to the ground state may take place in a single step or as a series of transitions through intermediate allowed states, each accompanied by the emission of a photon.

Each photon emission obeys the relation

$$h\nu = E' - E \tag{1-7}$$

where E' is the energy of the state preceding radiation and E is the

energy of the state following. In the case of hydrogen the emitted frequencies lie in the visible and ultraviolet regions of the electromagnetic spectrum, Fig. 1-4.

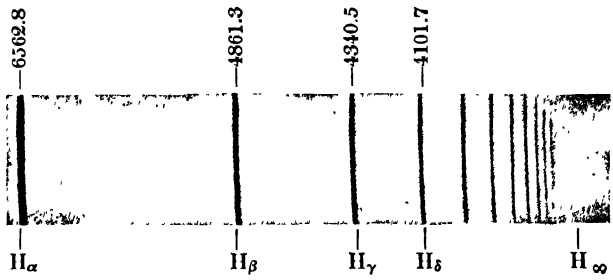


Fig. 1-4. Emission spectrum of atomic hydrogen in the visible and near ultraviolet. Wavelengths in Angstroms. From Herzberg, *Atomic Spectra and Atomic Structure*. Prentice-Hall, Englewood Cliffs, N. J., 1937.

Values of E corresponding to values of the principal quantum number 1, 2, 3 . . . can be readily calculated from known physical constants and so predicted values of $h\nu$ can be compared with those actually observed in the emission spectrum of atomic hydrogen. The close correspondence shows that at worst the Bohr model is a good approximation to the true situation. Later theories have reduced the physical reality of the orbits, but the concept of energy levels is retained, as is the relation between radiated energy and energy-level transitions.

1.05 THE FOUR QUANTUM NUMBERS

Although the original Bohr theory gave wavelength predictions in remarkable agreement with observation, there were discrepancies well outside the experimental errors, and many physicists attempted to modify the theory to obtain closer agreement. As a result of this work it appears that four quantum numbers rather than one are needed to specify the energy state of an electron.

The principal quantum number n, which can take on integral values 1, 2, 3, . . . has been used in referring to circular orbits. The laws of mechanics governing planetary motion permit elliptical as well as circular orbits, but quantum restrictions allow only certain

values of eccentricity. Allowable eccentricities are determined by an *azimuthal quantum number l,* which can take on any integral value from 0 to $n-1$, inclusive. For $n = 1$, l can only take on the value 0 and hence only circular orbits are allowed in the ground state. Although the concept of eccentric orbits is a useful one, it is more accurate to say that the azimuthal quantum number specifies or *quantizes* the *angular momentum* of the electron around the nucleus.

A third quantum number arises from the magnetic properties of the atom. Any moving charge, such as an electron moving in an orbit, is equivalent to an electric current and as such should behave like a magnet. In particular the atom would be expected to orient itself when subjected to an external magnetic field. Quantum considerations permit only certain discrete orientations governed by a *magnetic quantum number m,* which can take on any integral value, including zero, from $-l$ to $+l$. Thus if $l = 1$, m can have three possible values: $-1, 0, +1$.

The electron also appears to spin about its own axis and this gives rise to a fourth quantum number s. The *spin quantum number* can have either of two values $-\frac{1}{2}$ or $\frac{1}{2}$ corresponding to two spin directions referred to the orbital motion. Values of s are not interrelated with values of n, l, or m.

1.06 ELECTRON SHELLS

The importance of the four quantum numbers becomes evident when they are applied to elements heavier than hydrogen. In the heavier elements the nucleus consists of an integral number of protons Z and an integral number of neutrons N. Z is known as the *atomic number* and N is the *neutron number.* The neutron number is of importance in later discussions, but for the moment we are concerned only with values of Z. Since an element with atomic number Z has a nucleus containing Z protons, each neutral atom must have Z electrons bound to this nucleus. These electrons are not arranged at random, but are specified by quantum numbers in accordance with the *Pauli Exclusion Principle.*

In brief the Pauli Exclusion Principle states that in any atomic structure no two electrons can exist in exactly the same energy state; that is to say with exactly the same set of quantum numbers n, l, m, and s. This principle puts an upper limit to the number of electrons

that can have a given value of n. For example, if $n = 1$, l can only take on the value 0, and m must also be zero. There can therefore be only two electrons for $n = 1$, corresponding to the two possible values of s.

Electrons having the same principal quantum number form a group or *shell*. Thus the two electrons with $n = 1$ are in the K shell, those with $n = 2$ form the L shell, and so on. For values of $n > 1$ detailed counting is required to determine the maximum number of occupants in a given shell.

Illustrative Example

Determine the maximum number of electrons in the L shell, $n = 2$.

For n 2	$l =$	0 or 1		
For $l = 0$	$m =$	0	s	$-\frac{1}{2}$ or $+\frac{1}{2}$ — 2 electrons
$l = 1$	$m =$	-1	s	$-\frac{1}{2}$ or $+\frac{1}{2}$ — 2 electrons
	$m =$	0	s	$-\frac{1}{2}$ or $+\frac{1}{2}$ — 2 electrons
	$m =$	$+1$	s	$-\frac{1}{2}$ or $+\frac{1}{2}$ — 2 electrons
				Total L shell occupants: 8 electrons

An examination of the periodic table of the elements shows that a completely filled shell is associated with chemical stability. Thus He, $Z = 2$ has a filled K shell and is an inert gas. Similarly Ne, $Z = 10$ is also chemically inert because of filled K and L shells. Some complexities arise at high atomic numbers, but in spite of this many chemical properties of the elements are explainable in terms of the shell structures.

1.07 ISOTOPES

Any atomic configuration capable of more than a transitory existence (lifetime greater than 10^{-10} sec) is called a *nuclide*. A nuclide can be completely specified by atomic number Z, neutron number N, and its energy content. For most purposes the specification of energy content is unnecessary and Z and N provide sufficient identification of the species. More commonly, identification is made by specifying Z and *mass number* A, where $A = Z + N$. A is therefore the total number of particles, or *nucleons* in the nucleus. The usual notation is ${}_Z(\text{chemical symbol})^A$, specific examples being

$${}_2\text{He}^4, \qquad {}_{26}\text{Fe}^{56}, \qquad {}_{92}\text{U}^{238}$$

The chemical behavior of any nuclide is determined primarily by the orbital electron structure and this, in turn, is determined by the atomic number Z. Following pioneer work by Thomson and Aston, precision *mass spectrographs* have been developed for accurately measuring nuclear masses. All mass spectrographs are based on the fact that moving charged particles can be deflected by electric and magnetic fields. Precise values of nuclear masses are of great importance, and the techniques and equipment of mass spectroscopy have been highly developed.

Even early nuclear-mass measurements served to show that some chemical elements as found in nature consisted of several nuclear masses, differing by approximately one or more atomic-mass units. These nuclides with equal atomic number but different masses were called *isotopes* even before their exact nature was understood. With the discovery of the neutron in 1935 it became clear that isotopes are nuclides with equal atomic numbers but different neutron numbers. Since a neutron does not have an electric charge it does not require an orbital electron for neutralization, but it does add about one amu to the nuclear mass. Figure 1-5 is a schematic representa-

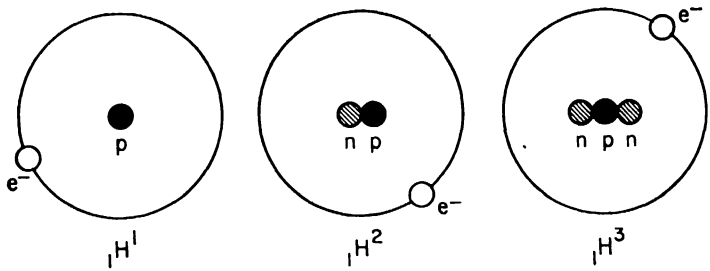


Fig. 1-5. The three isotopes of hydrogen

tion of the three known isotopes of hydrogen. *Deuterium,* $_1H^2$ is a naturally existing form discovered by Urey and his collaborators in 1935. *Tritium,* $_1H^3$ is a manmade radioactive isotope produced in nuclear reactors. The nuclei of these isotopes are known as the *deuteron,* d, and *triton,* t, respectively.

1.08 NATURAL ISOTOPIC ABUNDANCE

Some elements exist in nature as a single nuclide, whereas other elements have six or more isotopes. With a few notable exceptions

the isotopic composition, or *natural abundance,* is independent of the source of the material. Even elements of extra-terrestrial origin, as in meteors, have natural abundances similar to the same elements found on earth. Table 1-2 lists the isotopes and natural abundances of some of the more common elements.

Table 1-2. NATURAL ABUNDANCE OF ISOTOPES

Element	Z	Isotope	Natural Abundance (Per cent) *	Atomic Mass †
Hydrogen	1	H^1	99.9844	1.008142
		H^2	0.0156	2.014711
		H^3	—	3.016980
Helium	2	He^3	1.3×10^{-4}	3.017000
		He^4	100	4.003873
Carbon	6	C^{12}	98.892	12.003844
		C^{13}	1.108	13.00750
		C^{14}	—	14.00768
Nitrogen	7	N^{14}	99.636	14.00755
		N^{15}	0.364	15.00190
Oxygen	8	O^{16}	99.759	16.000000
		O^{17}	0.037	17.00453
		O^{18}	0.201	18.00488
Sodium	11	Na^{23}	100	22.99645
Phosphorus	15	P^{31}	100	30.98441
Sulphur	16	S^{32}	95.06	31.98227
		S^{33}	0.74	32.98194
		S^{34}	4.18	33.97876
		S^{36}	0.02	35.97893
Chlorine	18	Cl^{35}	75.4	34.98006
		Cl^{37}	24.6	36.97767
Potassium	19	K^{39}	93.08	38.97606
		K^{40}	0.01	39.97654
		K^{41}	6.91	40.97490
Iron	26	Fe^{54}	5.90	53.95704
		Fe^{56}	91.52	55.95272
		Fe^{57}	2.24	56.95359
		Fe^{58}	0.34	57.9520
Iodine	53	I^{127}	100	126.94528
Gold	79	Au^{197}	100	197.039

* Adapted from *National Bureau of Standards Circular 499.*

† Adapted from Lapp, R. E., and H. L. Andrews, *Nuclear Radiation Physics,* 2nd ed., Prentice-Hall, Englewood Cliffs, N. J., 1954.

Lead is one of the few elements whose isotopic composition depends upon the source of the sample. Lead is found as a natural element with isotopes of mass number 206, 207, and 208. Lead is,

however, also formed as the stable end product of the decay of some radioactive elements. For example, U^{238} undergoes a series of radioactive decays to end as stable Pb^{206}, the Actinium series ends in Pb^{207}, and the Thorium series in Pb^{208}. Hence a sample of lead may contain some radiogenic lead and show an abnormal isotopic composition.

The isotopic composition depends upon the relative contributions from the three radioactive series and the age of the mineral. Because of the age dependence, measurements of isotopic composition can be used to determine the time of formation of the sample. Very careful measurements on lead samples give an age of 3.3×10^9 years for the earth's crust. More details of age determination by isotopic composition are given in Chapter 5.

1.09 RELATIVITY THEORY

At the beginning of the twentieth century physicists were attempting to explain the results of a long series of experiments conducted by the American physicists Michelson and Morley. In brief the Michelson and Morley experiment consisted of measuring the velocity of light in a series of different directions. From these measurements they hoped to determine the velocity of the earth, to which the instruments were attached, relative to the *luminiferous ether.* This ether was an assumed but undetected medium in which light waves were presumably propagated. The analogous experiment with sound waves in air is readily carried out, and does indeed yield the velocity of the source of the waves relative to the transmitting medium.

After a long series of measurements made under a wide variety of experimental conditions Michelson and Morley concluded that the measured velocity of light was independent of the direction of propagation. Several explanations of this result were offered but no satisfactory description was obtained until Einstein announced his special theory of relativity in 1905. The Einstein theory explained the results of the Michelson and Morley experiment and also predicted several then unsuspected relationships capable of experimental verification. The impact of the Einstein relativity theory upon physical theory was profound, but here we can only list some of the more important results.

One of the predictions of the theory is that c, the velocity of

light, is an upper limit for any motion capable of carrying energy. Classical mechanics required that the velocity of a body moving under a constant force increase without limit. According to the relativity theory this cannot be. Instead there is an increase in mass according to the relation

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}} = \frac{m_0}{\sqrt{1 - \beta^2}}$$

where m = mass at velocity v **(1-8)**

m_0 = mass at zero velocity = rest mass.

A constant force applied to a body will then result in velocities which approach, but never reach the velocity of light. The mass, however, may increase without limit in accordance with Eq. (1-8). Figure 1-6

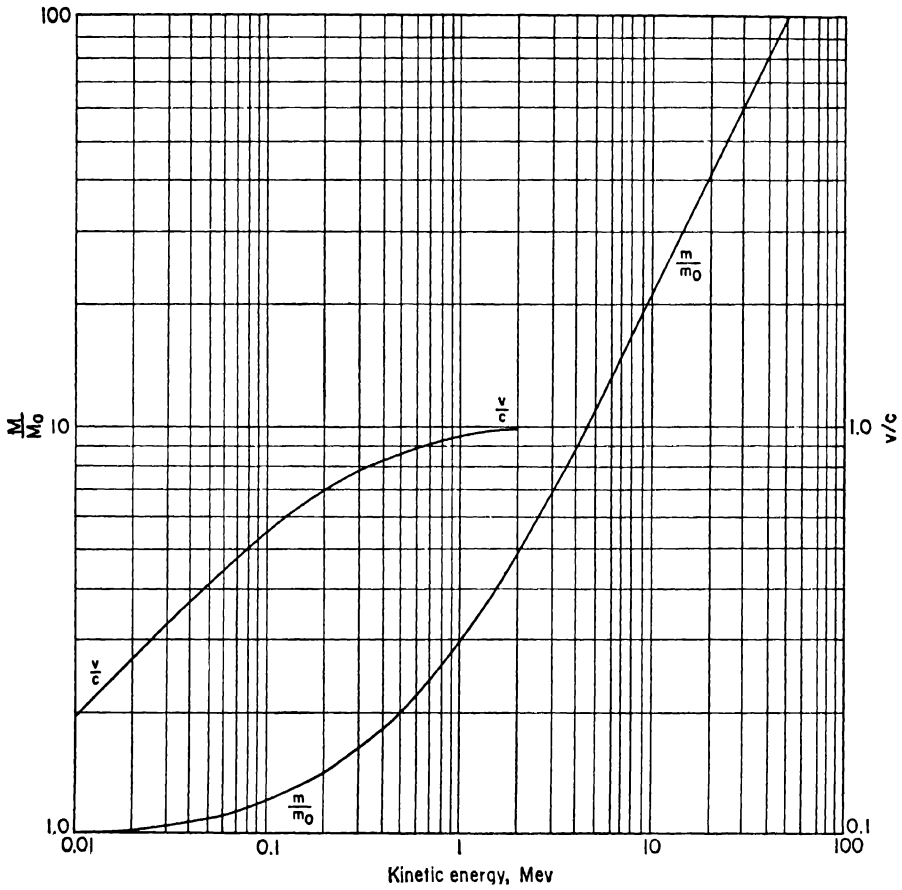


Fig. 1-6. Electron mass and velocity as a function of kinetic energy.

shows how the mass and velocity of an electron vary with kinetic energy.

Another result of the theory is the equivalence of mass and energy. According to this theory, there is an amount of energy

$$E = m_0c^2 \qquad \text{Ergs} = \text{grams (cm/sec)}^2 \tag{1-9}$$

inherent in mass itself, and if mass is lost by any means an equivalent amount of energy will be gained. This requires that the classical expression for kinetic energy $E_K = \frac{1}{2}mv^2$ be replaced by

$$E_K = m_0c^2\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right) \tag{1-10}$$

For low velocities Eq. (1-10) is essentially equivalent to the classical expression, but at high velocities there is a substantial difference between the two.

The theory of relativity was so revolutionary that some doubted its validity for many years. In every case where it has been subjected to experimental scrutiny the agreement has been remarkable and today the theory is completely accepted.

1.10 MASS AND ENERGY

Table 1-2 lists values of atomic masses as determined by precision mass spectroscopy. It should be noted that the values listed are *atomic* masses, that is, the nuclear mass plus the mass of Z electrons. Nuclear masses are of course obtained by subtracting the total mass of the orbital electrons. An examination of Table 1-2 will show substantial discrepancies between the measured mass values and the sum of the masses of the constituent particles.

Illustrative Example

Consider the case of $_2He^4$.

Measured atomic mass	4.003873 amu
Mass of two orbital electrons	0.001098
Measured mass of $_2He^4$ nucleus	4.002775
Mass of constituent protons 2×1.007593	= 2.015186 amu
Mass of constituent neutrons 2×1.008982	= 2.017964
Total mass of constituents	4.033150

Loss in mass $4.033150 - 4.002775 = 0.030375$ amu

The loss in mass calculated as in the illustrative example is known as the *mass decrement*, δ. Mass decrement arises from the existence of an attractive *nuclear force*, which holds the nuclear particles or *nucleons* together. The origin and nature of this nuclear force cannot be discussed here. Suffice it to say that the nuclear force is always attractive, is independent of electric charge, and has an extremely short range ($\sim 10^{-13}$ cm).

Now consider a process whereby free protons and neutrons are assembled into a nuclear structure. During the assembly work will be done *by* the nuclear force and the completed system will have less energy than the total energy of the separate particles. This energy will be lost by electromagnetic radiation at the time of assembly. Energy radiated and mass decrement are related by the Einstein equation, Eq. (1-9). A simple conversion of units leads to the more useful relation

$$1 \text{ amu} \equiv 931 \text{ Mev} \tag{1-11}$$

In the illustrative example the mass decrement of ${}_2\text{He}^4$ was calculated to be 0.030375 amu. By Eq. (1-11) this requires the release of $0.030375 \times 931 = 28.28$ Mev during the synthesis. It must be emphasized that this is energy lost by the resulting structure, which is now stable with respect to its original state and hence will not return spontaneously to it. Because of this the energy lost is known as the *binding energy*, E_b.

It is sometimes useful to think of the binding energy as uniformly distributed over all the nucleons. The *binding energy per nucleon*, e_b, is then

$$e_b = \frac{E_b}{A} \tag{1-12}$$

In the case of ${}_2\text{He}^4$, $e_b = 7.07$ Mev. The value of either E_b or e_b tells nothing about the feasibility of a given transformation. It does, however, show the energy relationships if the process is carried out. Binding energy is a complex function of the number of protons and neutrons in the nucleus. As shown in Fig. 1-7, the general trend is an increase in e_b with mass number up to the middle of the periodic table. After passing through a broad maximum e_b decreases slowly with increasing A.

Since binding energy represents energy lost by the structure, elements located at the maximum are most energy-poor. Energy will

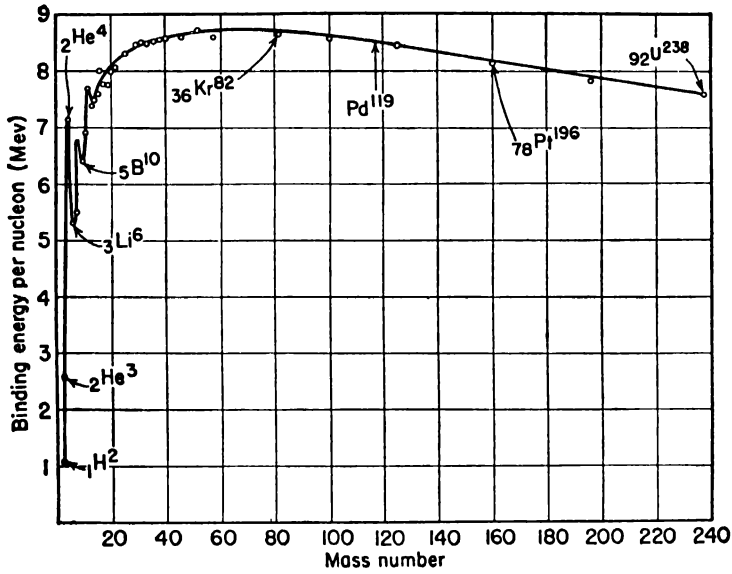


Fig. 1-7. Binding energy per nucleon as a function of mass number.

be released if a very heavy nucleus with small e_b can be split into roughly equal parts by the process of *fission*. The two fragments or *fission products* will have A values close to the maximum value of e_b and consequently will have a total energy content lower than that of the original structure. Conversely, if two or more nuclides with low values of A can be combined by some *fusion* process a structure having a large value of e_b will result and again energy will be released.

The magnitude of the energy available from nuclear rearrangement is large compared to that involved in orbital electron transitions. Thus we have seen that each nucleon in He^4 has a binding energy of over 7 Mev, whereas Fig. 1-4 shows that only a few ev are involved in the orbital energy levels of hydrogen. The K electrons of heavy nuclei are more tightly bound than the electron of hydrogen, but the energies are still small compared to those associated with nuclear transformations.

PROBLEMS

1-1. Calculate the mass of an electron in grams.

Ans. 9.11×10^{-28} gram.

1-2. What is the difference in mass between the neutron and the proton, expressed in grams? What is the energy equivalence of this mass, in ergs and in Mev?

1.3. An X-ray tube emits photons having a wavelength of 0.07 A. Calculate the photon energy in Kev and the frequency of vibration ν.
Ans. 177 Kev, 4.3×10^{19} per sec.

1-4. A betatron produces X-rays with a maximum energy of 22.3 Mev. What is the wavelength and frequency of this radiation?

1-5. The radius of the innermost Bohr orbit in hydrogen is 0.529 A. Calculate the force of attraction between the proton and the electron.
Ans. 8.26×10^{-3} dyne.

1-6. Calculate the allowed number of electrons in the M shell, $n = 3$.

1-7. Calculate the binding energy of the deuteron. Express the answer in ergs and in Mev. *Ans.* 3.55×10^{-6} erg, 2.22 Mev.

1-8. Calculate the total binding energy and the binding energy per nucleon for Fe^{56}.

1-9. What are the energetics of the synthesis of O^{16} from 4 atoms of He^4? *Ans.* 14.4 Mev radiated.

1-10. List the nuclei He^4, Na^{23}, K^{39}, and I^{127} in order of stability against the emission of a nucleon.

1-11. What velocity is required to double the rest mass of the electron? *Ans.* 2.60×10^{10} cm/sec.

1-12. Calculate the velocity at which the mass of the electron becomes equal to the rest mass of the proton. What is the kinetic energy of an electron having this velocity, in ergs and in Mev?

1-13. Calculate the energy inherent in the electron. Express the answer in ergs and in Mev. *Ans.* 8.20×10^{-7} erg: 0.511 Mev.

1-14. The orbital electron in hydrogen, normally in the ground state, can be ejected from the atom by an expenditure of 13.6 ev. Calculate the mass lost in forming an atom of hydrogen from a free proton and an electron.

1-15. An electrical discharge will strip both electrons from He^4 to form double-charged He^{++}. Calculate the energy of these helium ions in ergs after they have been accelerated by a potential difference of 3.5 Mv. *Ans.* 1.12×10^{-5} erg.

1-16. When a slow-moving positron encounters an electron, charge

is neutralized and mass disappears to form two photons of electromagnetic radiation. Calculate the total energy content of these photons in ergs and in Mev.

1-17. Starting with Eq. (1-9) show that 1 amu $\equiv$ 931 Mev.

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2

THE PRODUCTION OF X-RAYS

2.01 ROENTGEN'S DISCOVERY

During the early 1890's many physicists had been studying electrical conduction in gases at low pressures. The high voltages necessary to produce the gaseous discharge were obtained from crude spark coils or from electrostatic generators known as "influence machines." By applying these voltages to electrodes in partially evacuated glass tubes, Crookes, Lenard, and Hittorf, among others, had discovered many of the basic phenomena associated with gaseous conduction.

Wilhelm Conrad Roentgen was also working with gas discharge tubes and in December, 1895 he announced the discovery of a new type of radiation,* which he called X-rays because their nature was then almost completely unknown. This report aroused great scientific interest, and many laboratories were able to repeat and extend Roent-

* Communication to the Physikalisch Medicinschen Gesellschaft of Wurzburg, Dec. 28, 1895. Translated by A. Stanton, *Science* III, 227, 726, 1896.

gen's experiments promptly. Studies of these new radiations proceeded so intensively that the first case of human injury from X-rays appears to have been recorded early in 1896.†

It is impossible to evaluate accurately the importance of Roentgen's discovery to science and indeed to all mankind. Prior to this work many scientists believed that there was little left for physics to accomplish, save the more accurate determination of numerical constants. Today, with radiation both a powerful servant and a potential destroyer of man, it is foolhardy to predict where future developments will lead.

2.02 GAS-FILLED X-RAY TUBES

Early research soon led to the type of discharge tube shown in Fig. 2-1 as most suitable for the production of X-rays. The electrical

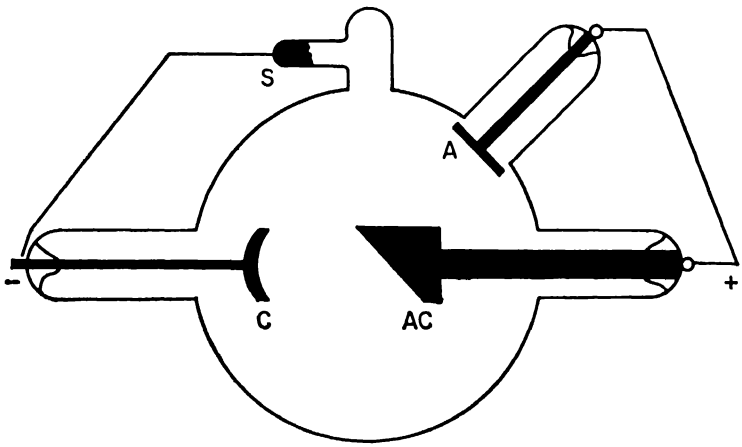


Fig. 2-1. Early type of gas-discharge X-ray tube. Positively charged gas ions bombard cathode *C* and liberate electrons. When these electrons strike anti-cathode *AC*, X-rays are produced.

discharge between the electrodes depended upon the presence of residual gas left in the tube by incomplete pumping. As the tube was used some of the residual gas became adsorbed on the glass walls and the pressure decreased. At the lower pressure more voltage was

† Brown, P. *American Martyrs to Science Through the Roentgen Rays.* Charles C. Thomas, Springfield, Ill., 1936.

required to start the discharge and because of this difficulty the tube was said to be *hard*. To maintain the tube at proper working pressure a gas-evolving material was heated, by either an electric current or a small flame, and the evolved gas *softened* the tube by increasing the pressure. Today, X-rays are not produced in gas-filled tubes, but we still refer to *hard* X-rays, meaning those produced by high voltage and having good penetrating power, as contrasted to the *soft* radiations produced at lower voltages.

Quality or the penetrating ability of X-radiation is determined by the voltage applied to the tube. The *quantity* of radiation produced at any given voltage is directly proportional to the number of electrons striking the target, which is to say, the current through the tube. In the old gas tubes, current and voltage were related through the gas pressure and only by changing this pressure could the current-voltage ratio be altered. Frequent checks were required to assure that the tube was in proper operating condition.

Tube operation was customarily checked by examining the bones in the left hand, held close to the tube, with a fluorescent screen held in the right hand. This practice was responsible for the large number of malignancies, which originated almost universally in the left hands of early radiologists.

2.03 THE COOLIDGE TUBE

In 1913 W. D. Coolidge announced the development of a hot cathode X-ray tube in which current and voltage were independently variable, and which did not depend for its operation on an erratic gas discharge. By this time effective vacuum pumps had been developed and in the new tubes great care was taken to obtain the highest possible vacuum. Modern tubes are pumped for many hours and during this time the entire tube is enclosed in a furnace for "baking out" at temperatures just below the softening point of the glass. Before the tube is sealed off from the pumps it is operated at abnormally high power so that all interior metal parts reach a red heat. These procedures drive off most of the occluded and adsorbed gas, so that in the sealed-off tube residual gas plays no role.

Current-voltage independence is achieved by obtaining the electrons from a hot filament instead of from cathode bombardment by gas ions. When a filament is heated in a high vacuum the most

energetic electrons leave the wire to form an electron cloud, or *space charge,* around the filament. If a second electrode has a sufficiently high positive potential all of the electrons emitted by the filament will flow to the *target,* or *anode.* This *saturation current* varies rapidly with filament temperature according to

$$I = AT^2e^{-b/T} \tag{2-1}$$

where I = saturation current
T = absolute temperature
A and b = constants.

The strong dependence of emission upon temperature arises from the exponential term.

Although there are many types of X-ray tube designs for specific applications, nearly all modern tubes use a hot filament as the source of electrons. Radiation quality is varied by making appropriate adjustments to the high voltage, which accelerates the electrons toward the target. Radiation quantity is independently varied by changing filament temperature. By setting the filament in an appropriately shaped focussing cup the electron stream can be brought to a *focal spot* of the desired dimensions at the target surface. It is most common to use either a spot or a line focus.

Tubes for voltages up to about 250 kv are made with *reflection targets,* Fig. 2-2(A). Above 250 kv, *transmission targets* are customarily used, Fig. 2-2 (B). At the higher voltages it has been found

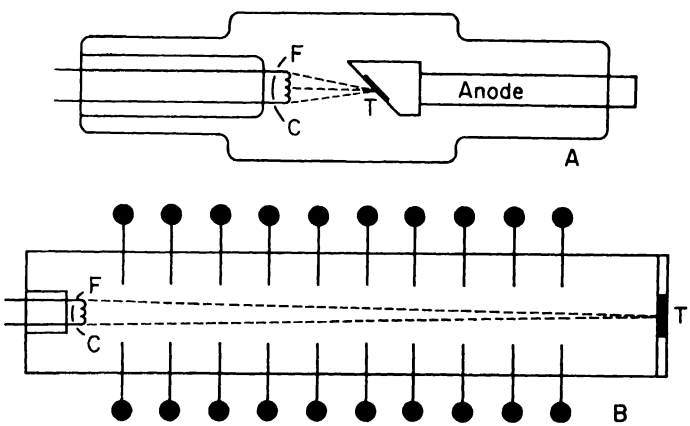


Fig. 2-2. Modern types of X-ray tubes. (A) Reflection target for moderate voltages. (B) Multi-section tube with 10 accelerating electrodes and a transmission target. In each tube the filament is set in a focussing cup.

desirable to sectionalize the tube so that the total accelerating voltage is applied in a series of steps. Sectionalizing maintains a more uniform voltage gradient along the tube, and reduces tube failures caused by high voltage flash-overs.

2.04 WAVELENGTH MEASUREMENTS

In the years immediately following Roentgen's discovery much effort was devoted to determining the nature of the new radiation. It was suspected that X-rays were electromagnetic waves, but wave motions universally exhibit *interference* and *diffraction*, and early attempts to demonstrate these phenomena with X-rays failed. We now know that the failure resulted from the very short wavelengths involved.

In 1912 Von Laue succeeded in demonstrating X-ray diffraction, using a crystal as the diffracting material. In a simple cubic crystal such as NaCl or KCl the atoms are arranged in a regular alternating manner with an inter-atomic spacing or *grating constant*, d. These recurring atoms serve as scattering or diffracting centers for an X-ray beam with a grating constant calculable from crystallographic data.

Illustrative Example

Calculate the grating constant for a sodium chloride crystal, density 2.163 gm/cm^3, M.W. 58.45.

Molecules in 1 gram NaCl	$6.02 \times 10^{23}/58.45 = 1.03 \times 10^{22}$
Atoms per gram	$2 \times 1.03 \times 10^{22} = 2.06 \times 10^{22}$
In a cube of 1 gram, atoms per edge	$= \sqrt[3]{2.06 \times 10^{22}} = 2.74 \times 10^{7}$
Volume of 1 gram	$= 1/2.163 = 0.4623$ cm^3
Length of cube edge	$= \sqrt[3]{0.4623} = 0.7732$ cm
Interatomic spacing	$= 0.7732/2.74 \times 10^{7} = 2.820 \times 10^{-8}$ cm

The experimental arrangement is shown in Fig. 2-3. Lead slits S_1 and S_2 produce a *collimated* or essentially parallel beam of X-rays, which strike the face of the diffracting crystal. The crystal is mounted on an X-ray spectrometer in such a way that the angle of reflection into some sort of radiation detector is always kept equal to the angle of incidence θ. The ray diffracted at B and entering the detector

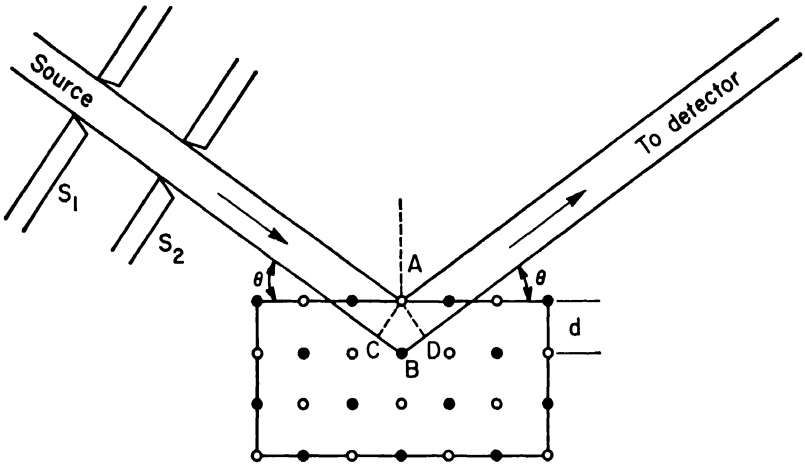


Fig. 2-3. Diffraction of X-rays by a crystal.

must travel a distance $CBD = 2d \sin \theta$ farther than a similar ray diffracted at atom A. When the difference in path is equal to an integral number of wavelengths, $n\lambda$, the diffracted waves will add constructively and radiation will reach the detector in phase, and the detector will respond. The condition for constructive interference is

$$n\lambda = 2d \sin \theta \tag{2-2}$$

With d known, λ can be determined from measurements of θ.

Equation (2-2) shows that d must be of the same order as λ if reasonable values of θ are to be obtained, and this explains the failures of the early workers to demonstrate X-ray diffraction. The coarse diffraction gratings originally used resulted in undetectably small values of θ. With diffracting crystals the angles become large enough for accurate measurement. In practice, calcite crystals, $CaCO_3$, are used for precision measurements since these crystals can be grown with fewer imperfections than most other crystals.

Studies with the X-ray spectrograph show a *continuous spectrum* having a sharp lower wavelength limit and a maximum energy emission at a considerably longer wavelength. When the voltage on the tube is sufficiently high the continuous spectrum has superposed on it narrow bands of relatively intense emission, the *characteristic spectrum*. Both of these spectra can be explained in terms of known mechanisms.

2.05 BREMSSTRAHLUNG PRODUCTION

Classical theory predicts that electromagnetic energy will be radiated whenever an electric charge is accelerated. Radiation produced in this way is known as *bremsstrahlung* from the German for "braking radiation," and this forms the continuous emission spectrum.

X-ray targets are customarily made of metals of high atomic number. A fast-moving electron in an X-ray tube, entering the target, will experience violent, random accelerations as it interacts with the electric fields of the target atoms. We would expect all values of acceleration from zero up to some maximum value, and this should result in radiated photons having energies from zero to some maximum value $h\nu_0$.

The maximum photon energy is readily calculated. With a potential difference V across the X-ray tube the external power source will do an amount of work Ve on each electron striking the target. If V and e are both expressed in emu or esu the work done will be in ergs. If the electron now loses its entire kinetic energy in a single deceleration process, conservation of energy requires that

$$Ve = h\nu_0 \tag{2-3}$$

Equation (2-3) provides one of the best means for obtaining h since all the other quantities can be measured with considerable precision.

Relatively few photons will have an energy $h\nu_0$ for it is more probable that an incident electron will lose its energy in a series of encounters rather than in a single one. Kramers * has deduced an expression giving the intensity of bremsstrahlung production as a function of wavelength.

$$I_\lambda = \frac{KiZ}{\lambda^2}\left(\frac{1}{\lambda_0} - \frac{1}{\lambda}\right) d\lambda \tag{2-4}$$

where I_λ = emitted intensity in wavelength interval λ to $\lambda + d\lambda$
K = constant
i = tube current
Z = atomic number of target
λ_0 = limiting wavelength as calculated from Eq. (2-3).

* Kramers, H. A. "On the Theory of X-Ray Absorption and the Continuous X-Ray Spectrum." *Phil. Mag.* **46**, 836–871, 1923.

According to Eq. (2-1), the energy radiated in a given wavelength interval will be directly proportional to the tube current and the atomic number of the target. For a given current and target material the emission should pass through a maximum at $\lambda_M = 3\lambda_0/2$. The broken line in Fig. 2-4(A), calculated from Eq. (2-4), is in good agreement with the observed intensities, except at the longer wavelengths. The discrepancies here are due to strong absorption of the low energy photons.

2.06 EFFICIENCY OF X-RAY PRODUCTION

Many of the decelerations experienced by the incident electrons are too small to produce X-ray photons and consequently much energy appears as heat in the anode structure. Efficiency of X-ray production may be defined as

$$\text{Eff.} = \frac{\text{Total radiated X-ray energy}}{\text{Total energy delivered to anode}}$$

Kramers' analysis leads to an expression for efficiency

$$\text{Eff.} = VZ \times 10^{-9} \tag{2-5}$$

where V = applied potential in volts
Z = atomic number of target.

Equation (2-5) cannot be exactly correct since it leads to efficiencies greater than 100 per cent at very high voltages. For voltages up to a few Mv, however, Eq. (2-5) gives about the correct dependence on V and Z. With a tube current of I amperes the power input to the target will be VI and from Eq. (2-5),

$$\text{Radiated power} = V^2IZ \times 10^{-9} \text{ watt.}$$

X-ray tubes can be ruined quickly if the heat generated at the anode is not removed. Tungsten is widely used as a target material because of its high atomic number and high melting point. Tungsten is a poor conductor of heat, however, and tungsten targets are usually imbedded in copper blocks to improve the transfer of heat to cooling water or oil. Air cooling is satisfactory for moderate power, and some tubes have anode cooling fins to increase the rate of heat dissipation.

Rotating anode tubes are also used to increase heat dissipation without attaining dangerously high anode temperatures. In this type of tube, commonly used in radiography, the anode consists of a disc of large diameter driven by an induction motor. The anode is brought up to speed before high voltage is applied to the tube, and the resulting bombardment and heating is spread over a large area along the periphery of the disc.

2.07 CHARACTERISTIC X-RAY SPECTRA

When an X-ray tube voltage is sufficiently high the continuous spectrum will have superposed narrow lines of relatively intense emission, the *characteristic* spectrum. The wavelengths of these characteristic emission lines are determined only by the atomic number of the target. The continuous spectrum, on the other hand, is independent of target composition, except as it affects the efficiency of bremsstrahlung production.

Typical X-ray emission spectra are shown in Fig. 2-4. In Fig. 2-4(B) the short-wave length limit from the molybdenum target ($Z = 42$) is the same as that obtained from a tungsten target ($Z = 74$) at the same voltage. The molybdenum spectrum has a reduced intensity in accord with Eq. (2-5). In the molybdenum spectrum a group or *series* of characteristic lines appear which have no counterpart in the tungsten spectra.

The lines shown in Fig. 2-4(B) constitute the *K series* of molybdenum. In addition, molybdenum has a low-intensity *L* series at about 5.4 A, and in some elements low-intensity, long-wavelength *M* and *N* series are known. In each series the high-intensity line of longest wavelength is given the subscript α as K_α with other subscripts following in order as L_α, L_β, L_γ. Moseley established in 1914 the relationship between the photon energy of a given line and the atomic number of the target. This relation, known as Moseley's law, is

$$\nu^{1/2} = K(Z - \sigma) \tag{2-6}$$

where K and σ are constants whose values depend upon the line being considered. Moseley's law was an empirical fact in 1914, but can now be understood in terms of the Bohr theory and the Pauli Principle.

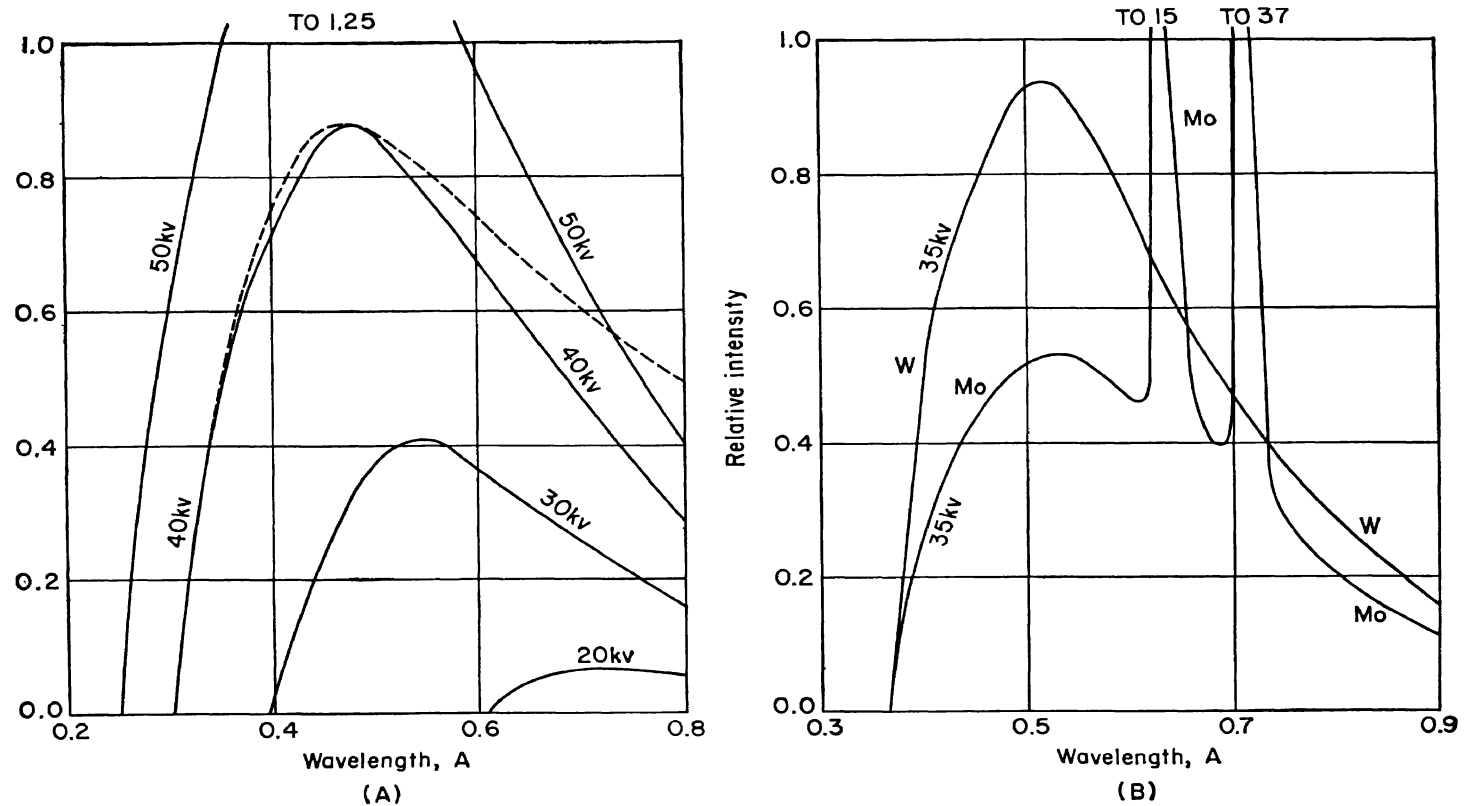


Fig. 2-4. X-ray emission intensities as a function of wavelength. (A) Tungsten target, variable kv. The dotted line is calculated from Kramers' equation. (B) Constant kv, tungsten and molybdenum targets.

2.08 PRODUCTION OF CHARACTERISTIC SPECTRA

Figure 2-5 shows schematically the energy levels and electronic structure for copper ($Z = 29$) which is frequently used as a target in

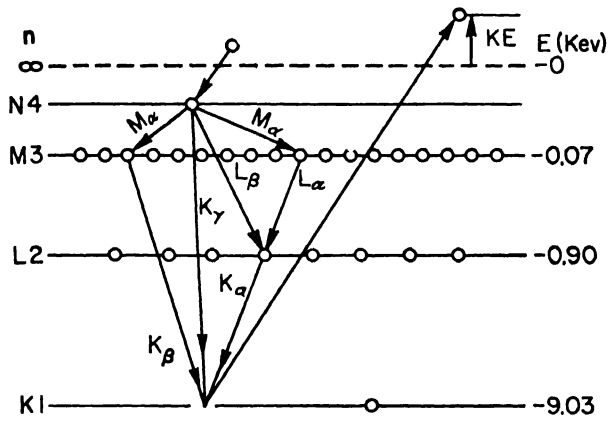


Fig. 2-5. Characteristic X-ray emission from a copper atom.

X-ray diffraction tubes. In accordance with previous discussion there will be 2 K, 8 L, 18 M, and 1 N electron in each copper atom. No attempt is made in Fig. 2-5 to show the small energy differences for the different values of l, m, and s.

In Fig. 2-5 a bombarding electron has interacted with one of the K electrons, which has received enough energy to be ejected from the atom. Any excess energy remaining after the K electron is ejected goes into kinetic energy of the now free electron. The removal of the K electron leaves the target atom with a vacancy in the K shell which will be filled promptly.

An L, M or N electron has an energy greater than that required for K shell occupancy, so any of these outer electrons can spontaneously drop into the K vacancy. An L electron will most probably fill the K vacancy and when it does the energy excess will be radiated as a K_α photon. The less probable transfer from the M shell results in the emission of a K_β photon, and so on. Following a K_α emission there will be an L shell vacancy, which can be filled from above with an M or N electron. Finally the N vacancy will be filled with a free

electron, the atom will again be electrically neutral, and the radiation process will be ended.

A K shell vacancy can only be created if the bombarding electron has sufficient energy to remove an electron from the ground state and free it from the atom. An electron incapable of creating a K shell vacancy may still have energy enough to remove an L electron. In this case all K lines would be missing from the spectrum but L and M lines would be present. Thus in Fig. 2-1(B) the K series lines are missing from the tungsten spectrum since an energy of 72 Kev is required to remove a K electron from tungsten.

The mathematical treatment developed by Bohr for the hydrogen atom can be extended to more complex nuclides. In the hydrogen atom the single electron moves in the electric field of the single proton composing the nucleus. In a nuclide of atomic number Z the two K electrons will move in the more intense electric field due to the Z protons in the nucleus. Electrons in outer shells will not experience the full nuclear field due to the positive charge Ze since part of this field will be *screened* by the negative charges of the inner electrons. This effect is taken into account by introducing a *screening constant* σ into the equation for the radiated frequencies. This is

$$\nu = \frac{2\pi^2 m_0 e^4}{h^3}(Z - \sigma)^2\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) \qquad (2\text{-}7)$$

where m_0, h, and Z have their usual meanings

e = charge on electron in esu

n_i = number of initial shell

n_f = number of final shell.

The screening constant σ is a complicated function of the initial and final state involved in each transition. A σ value for a given transition is reasonably constant for all elements since σ is only slightly affected by electrons in outer shells. For example, since the K_α line arises from the drop of an L electron to the K shell, σ for this transition is little affected by the presence or absence of M or higher shell electrons.

2.09 ANGULAR DISTRIBUTION OF RADIATION

Radiation emitted by an X-ray tube may have a spectral distribution quite different from that actually generated at the target.

Absorption in the target and windows provided for the beam exit may alter both the spectral and the spatial distribution of the *useful beam* which emerges. The unavoidable structural components through which the beam passes to go from the high vacuum in the tube to normal atmospheric pressure provide an *inherent filtration* and hardening of the useful beam. As we shall see later, any absorber will in general be more effective at lower photon energies and hence absorption will tend to raise the average or effective photon energy.

Theory can predict the spatial distribution of radiation from an X-ray target so thin that the incident electrons experience only one encounter in passing through. Such a target has an impractically low efficiency for bremsstrahlung production since only a small fraction of the electron energy is delivered to the target. In the practical case targets must be thick enough to stop the most energetic electrons and for these thick targets theory is incomplete.

Scherzer * has derived an expression for the angular distribution of X-rays from a thin target.

$$I_\theta = K_v \sin^2\theta\left[\frac{2(1-\beta)^{3/2}}{(1-\beta\cos\theta)^4} + \frac{(1-\sqrt{1-\theta^2})(1-2\sqrt{1-\beta^2})}{(1-\beta\cos\theta)^3}\right]d\theta \quad (2\text{-}8)$$

where I_θ = X-ray intensity radiated at an angle between θ and $\theta + d\theta$ with the incident electron beam

β = v/c for the incident electron

K_v = factor which depends upon the applied voltage but not upon θ.

$$K_1 = \frac{\alpha^2 Z^4 e^2 h^2 c}{m_0^2 c^4\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right)\left(e^{-\frac{2\pi\alpha Z}{\beta}} - 1\right)} \quad (2\text{-}9)$$

where m_0, c, Z, e, and h have their usual meanings

α = "fine structure constant" = 7.3×10^{-3}

e = (in denominator) = base of natural logarithms.

Figure 2-6 shows a plot of Eq. (2-8) for two values of tube voltage. As the accelerating voltage is increased, the isotropic emission characteristic of low energies shifts to an unsymmetrical distribution with increased intensity in the forward direction. Measurements made with thick targets, Fig. 2-7, agree reasonably well with the predictions of thin-target theory except for $\theta = 0$.

* Scherzer, O. *Ann. de Physik.* 13, 133, 1932.

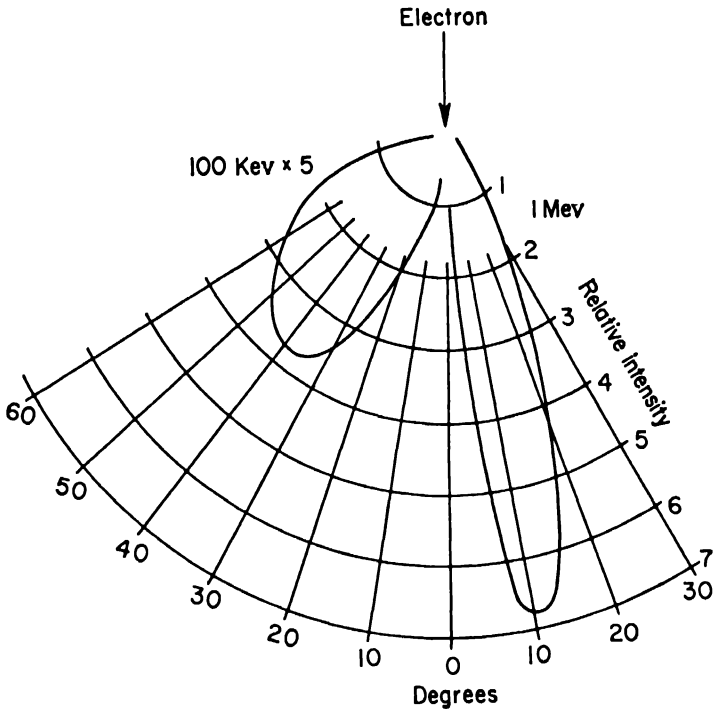


Fig. 2-6. Angular distribution of X-radiation from a thin target.

It is usually desirable to cover a radiation field of some size with an essentially constant intensity and this becomes more difficult at the higher voltages where emission is strongly peaked in the forward direction. X-radiation appears as a diverging beam, and large, uniform fields can be obtained at large distances from the target. This distance is known as FSD (focal skin distance) or TSD (target skin distance). Since the radiant energy passing through a unit area decreases as the square of the FSD, exposure times may become long, if uniform fields are obtained by increasing distance.

Field-flattening filters may also be used to improve radiation distribution. These filters are specially shaped to reduce the on-axis hot spot without seriously affecting the intensity at the edges of the desired field. Figure 2-8 shows the effect of field flattening in a 2.5 Mev beam.

Either increased FSD or field flattening reduce the available dose-rate and hence much, or all, of the increase in efficiency of production resulting from high accelerating voltages may be lost in

obtaining a uniform field. The exact situation depends upon the size of field desired, since small fields can utilize the high on-axis intensities without loss from field-flattening.

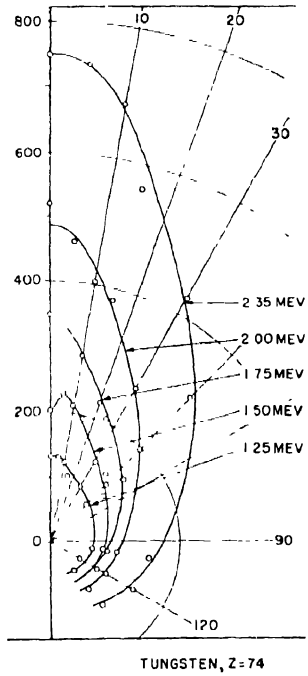


Fig. 2-7. Angular distribution of X-radiation at various voltages From Buechner, Van de Graaff, Burrill, and Sperduto, *Phys. Rev.* **74**, 1348, 1948.

2.10 TRANSFORMER VOLTAGE SUPPLIES

From the earliest days medical and industrial uses have demanded higher and higher voltages for the production of more and more penetrating radiation. Some truly mammoth induction coils and electrostatic machines were built, but action was erratic and it became evident that other power sources were needed.

High-voltage transformers provide the simplest replacement. A step-up transformer with many turns of wire on the secondary coil furnishes the high voltage needed for the production of hard X-rays. A step-down transformer with a few secondary turns gives the 2–10 volts needed to supply the filament of the Coolidge tube. A special

voltage-regulating transformer is frequently put in the filament circuit to reduce the effects of line voltage fluctuations.

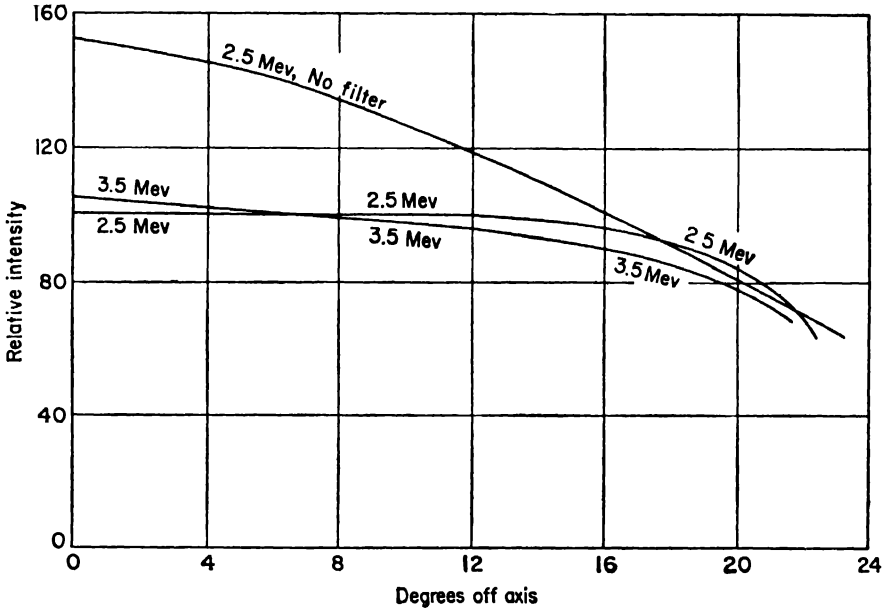


Fig. 2-8. Effect of special filter designed to produce a flat radiation field.

In its simplest form the high-voltage winding is connected directly to the X-ray tube in a *self-rectifying* circuit, Fig. 2-9. Self-rectified

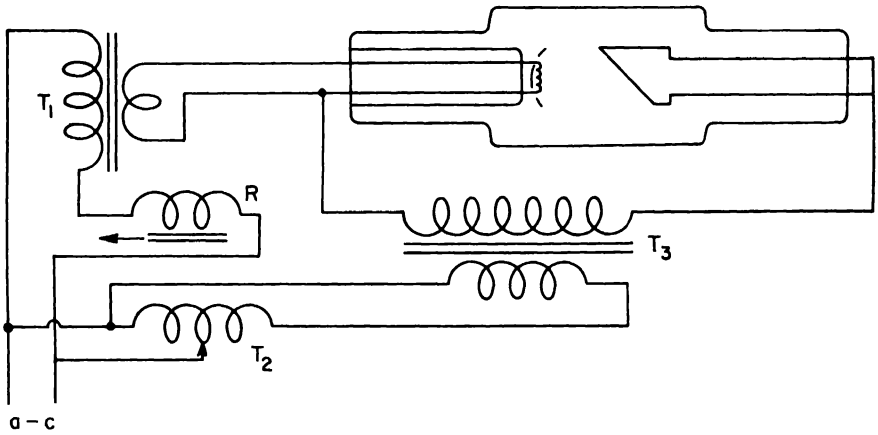


Fig. 2-9. X-ray tube in a self-rectified circuit with variable-reactor filament control and autotransformer.

circuits are hard on the X-ray tube and full output capabilities cannot be realized.

In practically all transformer power units the high voltage is controlled by an autotransformer, T_2, Fig. 2-9. By changing the tap on this single winding transformer the voltage applied to the primary of the step-up transformer T_3 is changed with a resulting change in the X-ray quality.

Filament control is usually obtained with a variable *reactor,* which consists of a single winding with a movable magnetic core.

2.11 TRANSFORMER-RECTIFIER UNITS

When a rectifier tube or diode is added to a self-rectified circuit the X-ray tube is relieved of the electrical stresses associated with cutting off the inverse half-cycle, and reverse electron emission is prevented. Figure 2-10 shows a single rectifier tube in a *half-wave*

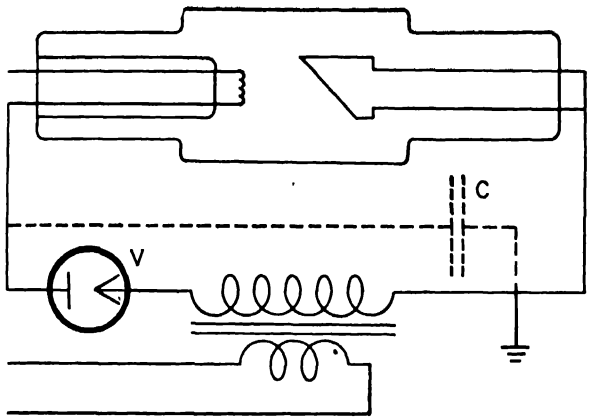


Fig. 2-10. Half-wave rectifier circuit.

circuit which passes alternate half-cycles to the X-ray tube. The rectifier has a hot filament and a cold anode and consequently acts as a *valve,* passing current in only one direction.

The half-wave circuit is shown with the *anode grounded* so that the tube may be operated close to a patient or to other objects at or near ground potential. With this arrangement the filament will be

at a high potential to ground, and the filament transformer must be insulated to withstand the full transformer voltage.

Full-wave rectification can be obtained by using two rectifier tubes, Fig. 2-11(A), or four rectifiers in a *bridge circuit,* Fig. 2-11(B).

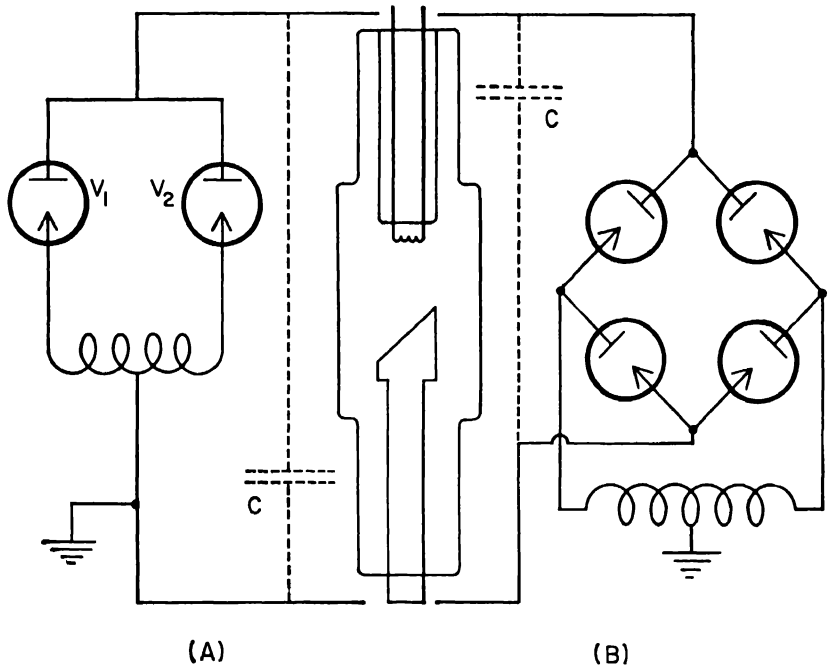


Fig. 2-11. Full-wave rectifier circuits.

Each of these circuits passes both halves of the alternating cycle, but with proper polarity, to the X-ray tube. The two-tube *split secondary* circuit can be operated with the anode grounded, as shown. In the bridge circuit both filament and anode are at high potential with respect to ground, but for many applications this is no disadvantage. In the bridge circuit the full voltage of the transformer is applied to the X-ray tube, whereas in the two-tube circuit the tube receives only one-half of the transformer voltage.

Transformer-rectifier units are commonly used at voltages up to 250 kv and higher voltage units have been constructed. Potentials greater than 500 kv can probably be best obtained by other means. All simple rectifier circuits have the disadvantage that the voltage drops to zero twice each cycle.

2.12 CONSTANT POTENTIAL CIRCUITS

When a fluctuating voltage is applied to a tube it is customary to specify the peak value of the wave in kilovolts peak, or kvp. During the low-voltage portions of the cycle only soft X-rays will be generated; these may be useless if penetrating radiation is desired. A greater output of hard X-rays will be obtained if the tube voltage can be kept at a constant high value.

If a condenser C, dotted lines in Figs. 2-10 and 2-11, is added, the circuit is said to be *constant potential,* CP. The condenser will store energy during the high-voltage portions of the cycle and release energy during the low-voltage portions. This storing action reduces the voltage fluctuations to a *ripple*, which will be only a small percentage of the supply voltage amplitude. The voltage will then be specified as kv CP.

The exact calculation of the amount of ripple obtained with a given circuit is complex, but a simple approximation will suffice for most purposes. Let a capacitor of capacitance C be connected to an X-ray tube operating at V volts and I amperes, average values. Then the quantity of electricity stored in the condenser will be

$$Q = CV \tag{2-10}$$

coulombs if C is expressed in farads. During the low-voltage portion of the cycle the quantity of charge given up by the capacitor will be

$$q = It \tag{2-11}$$

where t is the time of current discharge, in seconds.

Practically all power in the United States is supplied at 60 cycles, so for a half-wave circuit $t = 1/120$ second, approximately. The drop in voltage due to the discharge current will be

$$v = \frac{q}{C} = \frac{It}{C} \tag{2-12}$$

and the fractional drop in voltage, or ripple, will be

$$\text{Ripple} = \frac{v}{V} = \frac{It}{CV} \tag{2-13}$$

Illustrative Example

What is the percentage ripple in a half-wave 60 cycle circuit

operating at 120 kv and 3 milliamperes with an 0.05 microfarad condenser?

$$\text{Ripple} = \frac{It}{CV} = \frac{3 \times 10^{-3} \times 1/120}{0.05 \times 10^{-6} \times 1.2 \times 10^{5}}$$

$$= 4.15 \times 10^{-3} = 0.415\%$$

Thus the circuit is essentially constant potential.

In a full-wave rectified circuit the discharge time t will be considerably shorter than the time of one-half a cycle, and a given condenser will be more effective in reducing ripple.

2.13 VOLTAGE DOUBLERS

Transformers capable of supplying voltages of 250 kv or more are expensive and bulky. To reduce cost, several circuits have been devised for doubling the transformer voltage before it is applied to the X-ray tube. The Villard circuit and the Greinacher circuit are the most commonly used *doublers.*

Voltage multiplication can be carried beyond doubling in the Cockcroft-Walton circuit. A transformer of moderate voltage supplies a network of condensers and rectifiers. By a repetitive condenser charging, and charge sharing, the condensers are effectively put in series so that about one million volts can be attained. This circuit can operate at either polarity and is used mostly in positive ion accelerators.

2.14 RESONANCE TRANSFORMERS

In 1939 the General Electric Company announced an X-ray tube operating at 1 Mv and supplied by a *resonant* transformer. In this circuit the normal 60-cycle supply frequency is tripled by a special transformer connection, and 180 cycles is applied to the few turns constituting the primary of the resonant transformer. The number of secondary turns is so adjusted that this winding is tuned to the 180-cycle supply. Under resonance conditions heavy circulating currents flow and the secondary voltage becomes very high.

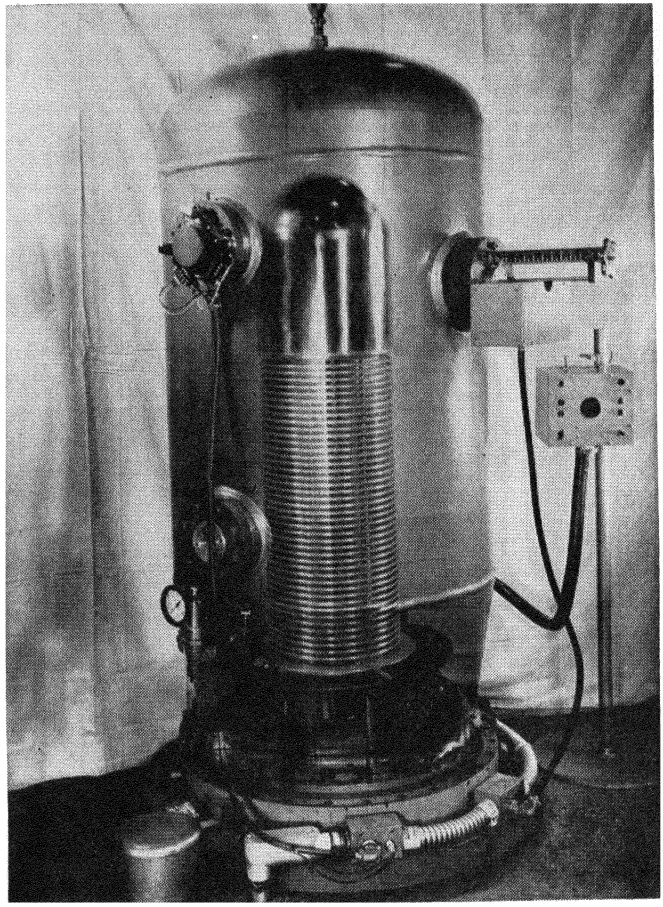


Fig. 2-12. Phantom view of 2 Mev Van de Graaff generator inside pressure tank. Courtesy of High Voltage Engineering Corp.

The customary iron core is omitted from the transformer and the multi-section X-ray tube is placed along the transformer axis. The entire unit is enclosed in a steel tank for operation at a gas pressure of some 150 pounds per square inch. Gas under pressure has superior insulating qualities and the high voltages can be maintained without excessive distances to grounded objects. There are no rectifiers in the secondary circuit, so the resonant transformer is a self-rectifying arrangement.

*

2.15 VAN DE GRAAFF ELECTROSTATIC GENERATORS

Many of the early X-ray workers were convinced, erroneously, that less injury was sustained by the X-ray worker if his tube was excited with a frictional electricity generator or "influence machine." Huge rotating plate electrostatic generators were built, but operation was erratic and they were supplanted by transformers.

In 1928 Van de Graaff announced a real advance in the design of electrostatic generators. The principle is illustrated in Fig. 2-13. A belt of some insulating material is driven at high speed by a motor. When a charging voltage, perhaps 20–40 kv, is applied across the belt from the needle points to inductor plates, a corona discharge will take place at the points and electric charge will be sprayed onto the belt. The belt carries the charge inside the top terminal, which has a smooth outer surface to reduce spark discharges. No electric field can be maintained inside a conductor such as the terminal, and so a comb set close to the belt will pick off the ascending charge and carry it to the terminal.

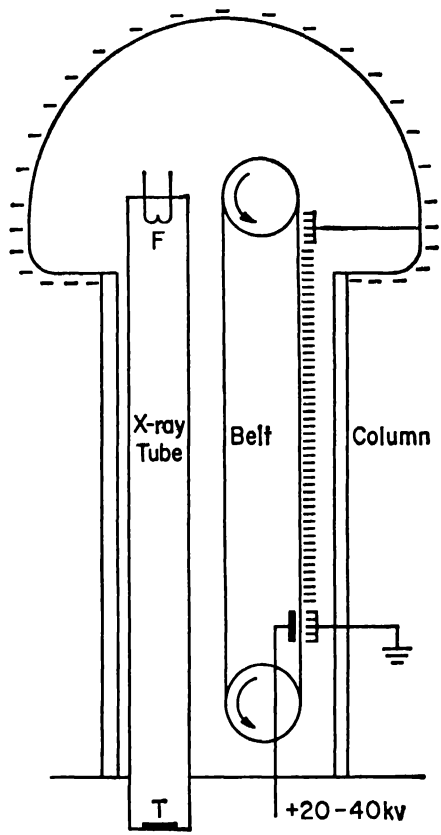


Fig. 2-13. Schematic of Van de Graaff generator. For high voltages both the column and the tube are sectionalized to obtain uniform potential gradients.

High voltages can readily be built up by this scheme, the limit being set by the radius of the top terminal and the insulation of the column supporting it. With the generator inside a steel tank and operating at 200–300 pounds per square inch, voltages

of 8.5 Mv have been reached. This probably represents about the maximum voltage to be expected from the Van de Graaff design. It is customary to put the X-ray tube inside the column. Since the Van de Graaff is a true direct-current generator, the unit is a constant potential source.

2.16 BETATRON

All the voltage sources so far described are essentially "brute-strength" arrangements in which the high potential is generated in a single step or in a relatively small number of steps. In such machines some parts must be insulated to withstand the full generator voltage; insulation becomes increasingly difficult as one goes above 1 mv.

In 1931 Lawrence and Livingston described a revolutionary method for accelerating charged particles by the repeated application of a relatively low voltage. The *cyclotron* is a resonance machine not suited for electron acceleration. Since the electron mass changes rapidly with energy, cyclotron resonance conditions cannot be maintained over a wide energy range. Several types of resonance accelerators were developed subsequent to the cyclotron, and in 1941 Kerst described the *betatron*, a machine capable of accelerating electrons to very high energies. The betatron can be considered as a special type of transformer.

Suppose the secondary winding of the transformer T_3 in Fig. 2-9 removed, and replaced by the evacuated "doughnut" of Fig. 2-14. Further suppose a pulse of electrons, accelerated to perhaps 50 kv, injected into the doughnut at the exact instant that the current flowing in the primary coil passes through zero and starts to increase.

As the injected electrons start circling through the doughnut they link an increasing magnetic flux produced by the increasing primary current. Each electron will, by Faraday's law of magnetic induction, acquire kinetic energy at a rate $c\Delta\phi/\Delta t$, where $\Delta\phi$ is the increase in magnetic flux during a small interval of time Δt. With the proper arrangement of magnetic fields the electrons will move inside the doughnut with increasing energy in an orbit of constant radius.

When peak primary current and magnetic flux are attained the electrons will have acquired maximum energy. A pulse of current

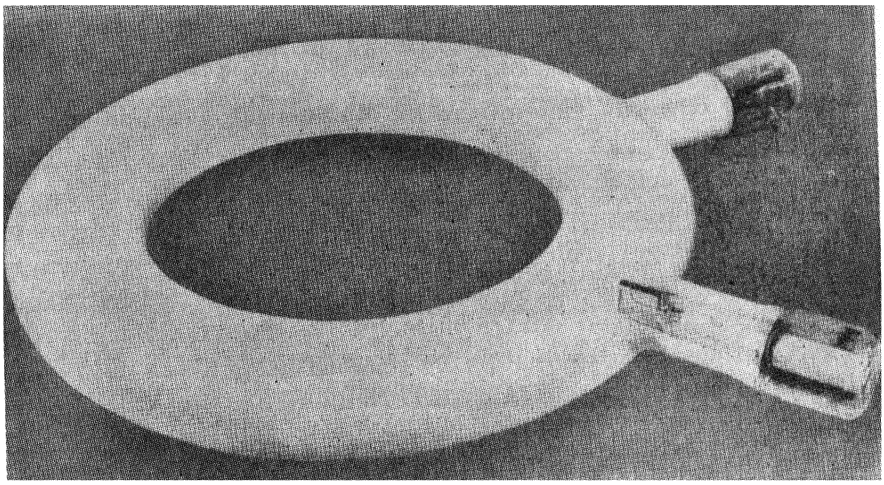


Fig. 2-14. Phantom view of betatron doughnut. Courtesy of Machlett Laboratories.

is then sent through an auxiliary coil, altering the radius on which the electrons are orbiting. They will spiral out to strike a target and produce a pulse of X-rays. The entire process will be repeated on the next magnetization cycle. Betatrons are usually designed to operate at voltages of 10 Mv or more and since here the efficiency of X-ray production is high, target cooling is not required.

In pulsed devices such as the betatron the fractional time of radiation emission is known as the *duty cycle*. Thus if a betatron emits f pulses per second, each having a duration of t seconds

$$\text{Duty cycle} = ft \tag{2-14}$$

A betatron may have a duty cycle of about 10^{-4} which means that the radiation intensity in the pulses is 10^4 times as great as the average value. Because of the high output in the pulses care must be taken in making measurements of betatron radiation to insure proper instrument operation.

With a slight change in doughnut design and in pulsing arrangement the electron beam can be brought outside the doughnut for deep electron therapy, food processing, or sterilization.

In the betatron, high-energy electrons are obtained without the presence of extremely high voltages. Problems connected with high-voltage insulation are avoided but are replaced by those associated with accurate timing of the various phases of pulsed operation.

2.17 ELECTRON SYNCHROTRON

Extreme electron energies can be obtained by a second type of magnetic-induction accelerator called an *electron synchrotron.* As in the betatron, electrons are accelerated along a circular path inside an evacuated doughnut. In the synchrotron doughnut a short section is internally plated with copper or silver to form a conducting portion or *resonant cavity.* When such a cavity is excited by a high-frequency oscillator an electric field will sweep axially along the cavity at a speed nearly equal to the velocity of light.

In the synchrotron, electrons are given an energy of several Mev by the betatron principle. Betatron action is then switched off and the resonant cavity excited by a series of short pulses. At each circuit around the doughnut the electrons will be accelerated by the electric field sweeping along the cavity. High electron energy is obtained by the repetitive application of a relatively low voltage. When full energy is attained the electrons are made to strike a target by pulsing a magnet, as in the betatron. Energies of up to 350 Mev have been attained with the electron synchrotron.

2.18 LINEAR ACCELERATOR

A series of resonant cavities can be arranged in a linear fashion so that an electron, accelerated in one cavity, reaches a succeeding cavity just in time to receive further acceleration from a voltage pulse impressed on the cavity. Energies up to 500 Mev have been attained and there seems no reason to believe that this is the limit. Although energy increments of more than 1 Mev per foot of cavity length have been attained, linear accelerators become long at extreme energies.

PROBLEMS

2-1. Radioactive Cobalt −60 emits gamma radiation with an effective energy of 1.2 Mev. What voltage must be applied to an X-ray tube to produce radiation having a maximum emission at the Cobalt −60 energy? *Ans.* 1.8 Mev.

2-2. Derive the expression for I_M in terms of λ_0.

2-3. Calculate the energy emitted per second as X-rays from a tungsten target tube operating at 250 kv and 15 millamperes.

Ans. 69.5 watts.

2-4. Compare the X-ray output of the tube in Problem 2-3 with that from a tungsten target tube in a Van de Graaff generator operating at 2 Mv and 250 μamp. Make the same comparison for a tungsten target in a betatron operating at 10 Mv and 10 μamp.

2-5. At what rate must heat be removed from the three targets in Probs. 2-3 and 2-4? *Ans.* 3,680 watts, 426 watts, 26 watts.

2-6. Assume an isotropic distribution of radiation from the 250 kv target of Prob. 2-5 and calculate the energy flux across 1 cm^2 at a distance of 1 meter from the target.

2-7. The K_α line of tungsten gives a maximum intensity in an ionization chamber when diffracted from a rock-salt crystal at an angle of 2°7′. What is the wavelength and quantum energy of the tungsten K_α line? *Ans.* 0.208 A, 59.5 Kev.

2-8. Sketch the spectral distribution to be expected from a tube with an iron target excited with 30 kv electrons. Compare this with the spectrum from a gold target bombarded with 30 kv electrons.

2-9. The K_α line of platinum has a wavelength of 0.1822 A and for copper the K_α line is 1.537 A. Calculate the value of K and σ in Eq. (2-6). *Ans.* $K = 5.41 \times 10^7/\text{sec}^{1/2}$, $\sigma = 3.16$.

2-10. The element astatine ($Z = 85$) was predicted for many years before it was experimentally demonstrated. An important part of the identification involved the appearance of the K_α emission line at the expected wavelength. What would this expected wavelength be?

2-11. A betatron operating at 22 Mv emits 180 radiation pulses per second, each of 10 μsec duration. The average radiation output is 75 roentgens per minute at 1 m from the target. What is the peak radiation output at the same distance? What is the duty cycle?

Ans. 41,700 roentgens/min, 1.8×10^{-4}.

2-12. An X-ray tube operating at 50 kv and 50 ma is supplied from a 220 v, 60 cycle line. What size condenser must be used in a half-wave rectifier circuit to reduce the ripple to 500 volts? Will the ripple be more or less if the tube current is reduced to 30 ma?

2-13. An electron being accelerated in a betatron travels in an orbit of 20 cm radius and gains 100 ev each complete revolution. How far does an electron travel in attaining an energy of 20 Mev?

Ans. 2.51×10^7 cm or 157 miles.

2-14. Estimate the time required for the electron in Problem 3-5 to attain full energy.

2-15. The top terminal of a Van de Graaff generator has a capacitance of 50 μμfd and is charged to 2.5 Mv. Calculate the average current flow in an X-ray tube assuming that the entire terminal charge is dissipated in a pulse of 100 μsec duration. *Ans.* 1.25 amperes.

2-16. A tungsten X-ray target can dissipate heat at a rate of 3 kilowatts. Calculate the total X-ray output from this target if the electron accelerating voltage is 70 kv, 400 kv, 6.0 Mv.

2-17. When operating steadily with a beam current of 200 μamp, the generator in Problem 2-15 produces an output of 120 roentgens per minute one meter from the target. Calculate the average output at the same distance during the 100 μsec pulse, assuming an average potential of 1.25 Mv during the pulse.

Ans. 1.87×10^5 roentgens/minute.

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3

RADIOACTIVITY

3.01 NATURAL AND ARTIFICIAL RADIOACTIVE NUCLIDES

Within the year following Roentgen's discovery of X-rays, Henri Becquerel observed that uranium salts spontaneously emitted penetrating radiations. Some of these radiations were capable of blackening photographic emulsions even after passing through substantial thicknesses of opaque materials and thus seemed to have properties similar to those of X-rays. A long series of investigations pioneered by Pierre and Marie Curie showed that the element uranium was only one feebly emitting member of a long series of related radioactive nuclides. Subsequent research has revealed four radioactive series and also a few isolated radioactive nuclides which show no series relationships.

As high-energy accelerators were developed, man-made radioactive nuclides were produced by bombarding stable nuclei with

beams of protons or other heavy charged particles. The neutron was found to be particularly effective in producing radioactive nuclides and the nuclear reactors developed in connection with the atomic weapons program provided very large neutron fluxes. As a result we now have over 500 radioactive nuclides never before available in usable quantity.

The process of nuclear fission, on which the nuclear reactor operates, produces radioactive *fission products* which may undergo several successive decays before the nucleus attains stability. In addition to being radioactive these fission products have provided usable quantities of many rare elements previously known only as scientific curiosities.

3.02 STABLE AND UNSTABLE NUCLEI

It might appear that there is a clear-cut distinction between a nucleus which is stable and one which is radioactive, emitting energy in one form or another. In general, there is, but it well may be that there is really a smooth transition between the two classes. Nuclides which undergo radioactive decay at a very slow rate are extremely difficult to detect, and improved techniques may demonstrate radioactivity in species now thought to be stable.

When the known stable nuclides are displayed on a neutron number-atomic number plot, Fig. 3-1, a smooth *line of stability* is obtained. There are some variations from the smooth curve but these are relatively small. Nuclides falling on a vertical line have equal Z and are *isotopes*. Those on a horizontal line have equal N and are *isotones*. Nuclides of equal A, *isobars*, lie on the 45-degree lines as shown.

For each value of Z there appears to be a corresponding small range of N values for stability. If the Z-N relationship is upset by any means an unstable nuclide will result. Suppose, for example, that an artificial nuclide was created by introducing an excess neutron into a stable configuration. The resulting structure would lie above the stability line and would be expected to return to it by radioactive decay. It could do so by either a decrease in N or an increase in Z.

Conversely, if an extra proton can be driven into a nucleus the

resulting structure will be below the stability line and can return by either a decrease in Z or an increase in N.

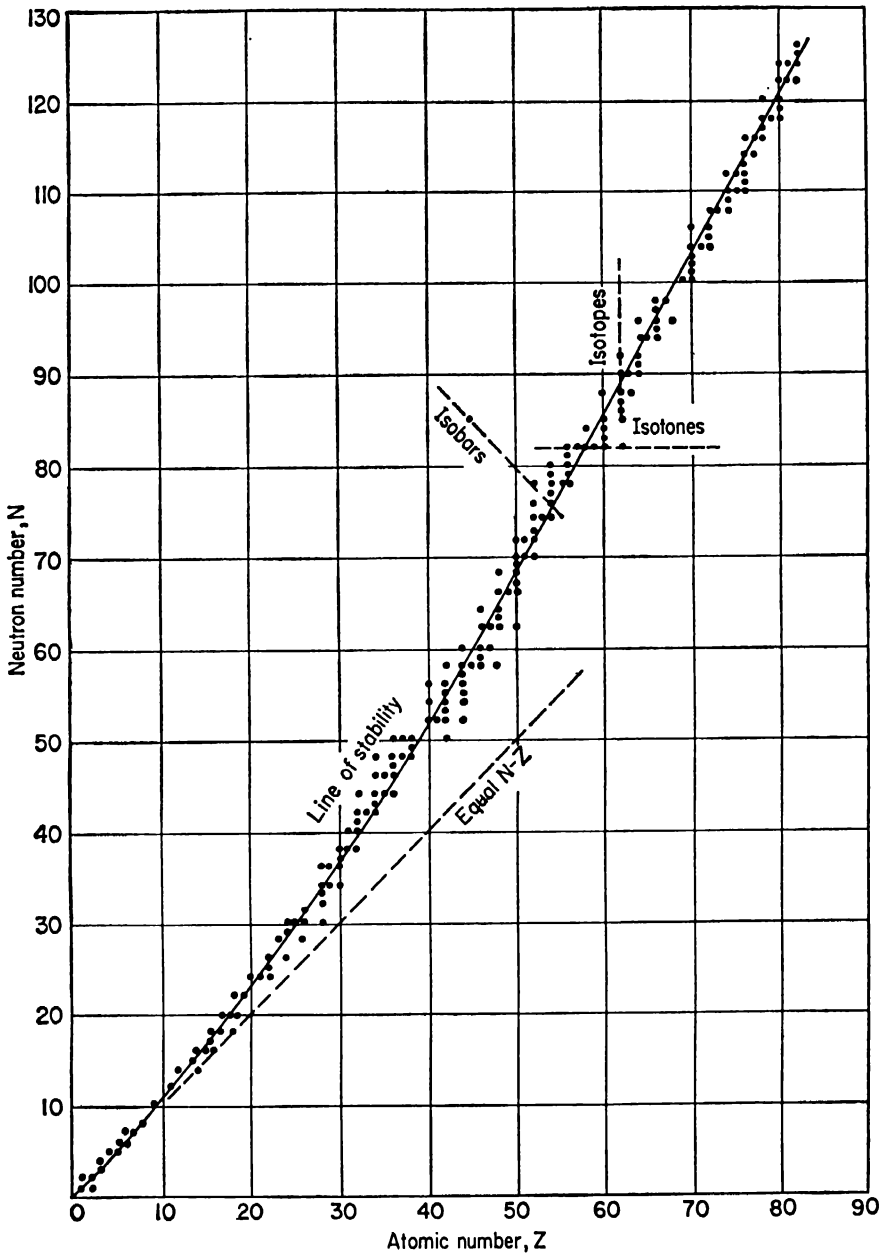


Fig. 3-1. N–Z plot of stable nuclides.

3.03 THE POTENTIAL BARRIER

Hydrogen, deuterium, and helium ions have been used most extensively as bombarding particles for producing nuclear reactions. The neutral gas atoms can be readily ionized by an electron beam into H^+, D^+, and He^+ respectively; these ions can then be given a high kinetic energy by any one of several types of accelerators. A high kinetic energy is necessary because a positive ion will experience a retarding force as it approaches a target nucleus. The force field (or more accurately, the potential-energy field) around a nucleus is shown schematically in Fig. 3-2. Beyond about 10^{-12} cm from the

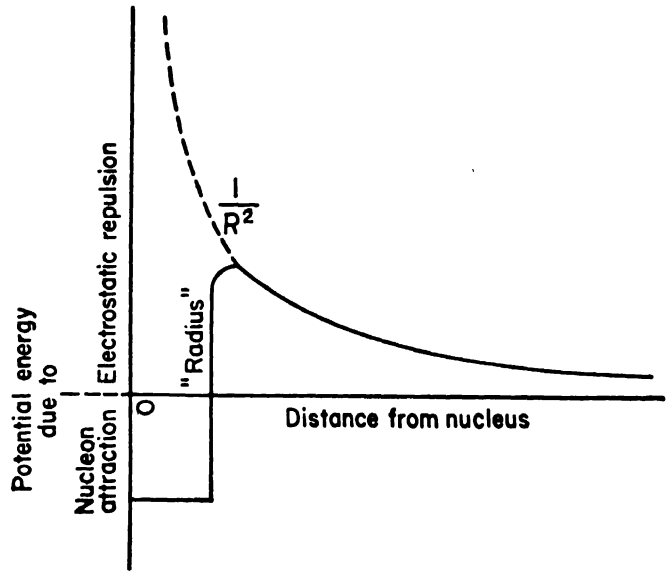


Fig. 3-2. Nuclear potential energy diagram.

nucleus an incoming charged particle will experience the retarding force of the positively charged nucleus. This force will vary as the inverse square of the distance from the nucleus and will of course increase with Z.

The *potential barrier* will have a height of a few Mev and an incoming particle must have this much energy in order to enter readily. Particles of less energy can "tunnel" through the barrier but the chance of this is relatively small.

Once past the potential barrier an incoming particle comes under the influence of the attractive nuclear force. The particle will be bound to the nucleus and at the instant of binding the new, or *compound nucleus,* has, in excess, the binding energy of the new particle. This excess energy will be radiated as electromagnetic waves (gamma rays) or a particle may be ejected from the compound nucleus.

The presence of the potential barrier stimulated the development of high-energy accelerators as tools for initiating nuclear reactions with greater effectiveness. Neutrons, on the other hand, do not need high energies to penetrate the potential barrier since they do not experience the electrostatic repulsion of the nuclear charge. Many neutron-induced reactions have a probability inversely proportional to the neutron velocity, the so-called $1/v$ law, so slow-energy neutrons are strongly favored.

Since nuclear forces are independent of charge, a neutron inside the potential barrier behaves much like a charged particle. The incoming nucleon will be bound and the excess binding energy released by a variety of possible mechanisms.

3.04 CHARGED PARTICLE REACTIONS

With a given target nucleus and bombarding particle several competing nuclear reactions may be possible. Only typical reactions will be discussed here, without considering details of relative yields.

As the first example consider the reaction of B^{10}, the less abundant isotope in a boron target, bombarded with a proton beam. The first stage of the reaction is

$$ {}_5B^{10} + {}_1p^1 \rightarrow {}_6C^{11*} \qquad (3\text{-}1) $$

The asterisk (*) indicates that the compound nucleus is in an excited state, which will be promptly relieved by gamma-ray emission.

$$ {}_6C^{11*} \rightarrow {}_6C^{11} + \gamma \qquad (3\text{-}2) $$

It is seldom necessary to consider the compound nucleus and so the reaction would usually be written

$$ {}_5B^{10} + {}_1p^1 \rightarrow {}_6C^{11} + \gamma \qquad (3\text{-}3) $$

Note that both Z and A must balance on the two sides of the equa-

tion. It is usually not necessary to write out the reaction as in Eq. (3-3); in customary notation this would be $B^{10}(p, \gamma)C$. The final product of a nuclear reaction may or may not be radioactive. In the example given, C^{11} is a short-lived radioactive isotope of carbon.

An example of a (p, n) reaction is the formation of A^{37} from the heavy isotope of chlorine.

$$_{17}Cl^{37} + {}_1p^1 \rightarrow {}_{18}A^{37} + {}_0n^1 \tag{3-4}$$

The product A^{37} is radioactive.

Deuterons have been much used as bombarding particles and enter into both (d, p) and (d, n) reactions. Typical reactions are

$$_{15}P^{31} + {}_1d^2 \rightarrow {}_{15}P^{32} + {}_1p^1 \tag{3-5}$$

$$Pd^{105}\,(d, n)\,Ag^{106} \tag{3-6}$$

3.05 NEUTRON-INDUCED REACTIONS

The most common reaction induced by slow neutrons is radiative capture, or (n, γ). This gives a product which is an isotope of the original starting material as $Na^{23}(n, \gamma)Na^{24}$. A most important (n, p) reaction produces radioactive carbon from nitrogen.

$$N^{14} + n \rightarrow C^{14} + p \tag{3-7}$$

An entirely different process takes place when a neutron enters one of the heavy nuclei capable of undergoing *fission*. Consider the case of fissionable $_{92}U^{235}$. In this case the compound nucleus does not get rid of the binding energy by particle or photon emission. Instead the nucleus splits into two large fragments with the release of a few free neutrons, which may enter other U^{235} nuclei to perpetuate the process.

Each fission is a chance phenomenon so a wide variety of *fission products* are produced. A typical reaction is

$$_{92}U^{235} + {}_0n^1 \rightarrow {}_{52}Te^{135} + {}_{40}Zr^{97} + 4\,{}_0n^1 \tag{3-8}$$

Both fission products Te^{135} and Zr^{97} lie well above the line of stability, Fig. 3-1, and so both would be expected to be highly radioactive. In fact each gives rise to a *fission chain* or series of radioactive nuclides which finally attain stability.

3.06 NATURE OF THE RADIATIONS

We must now consider in detail the nature of the radiations emitted by either naturally occurring radioactive materials or those produced by nuclear reactions. Early workers found that three distinct types of radiation were emitted by radioactive nuclides. Figure 3-3 shows the effect of a magnetic field on the emissions from a radium sample placed in a lead container *R*. A narrow beam of radiation escapes from the opening and is subjected to a strong magnetic field directed into the plane of the paper. One type of radiation, called *alpha,* is bent by the magnetic field in the direction to be expected of positively charged particles. The *beta* radiation is deflected in the opposite direction and hence must be negatively charged. The *gamma* radiation is not deflected by the field and so has no net electric charge.

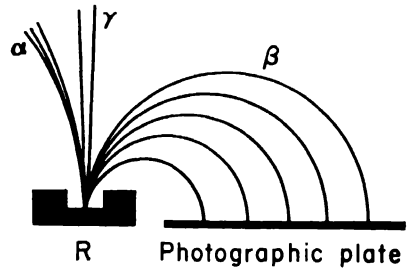


Fig. 3-3. The effect of a magnetic field on the three types of radiation from radium.

Several bits of evidence indicated that the alpha particles were doubly charged ions of helium gas, He^{++}. Perhaps the most convincing experiment demonstrating this was the one devised by Rutherford, Fig. 3-4. A small sample of an alpha-particle emitter was sealed in the inner glass tube, which had walls thin enough to

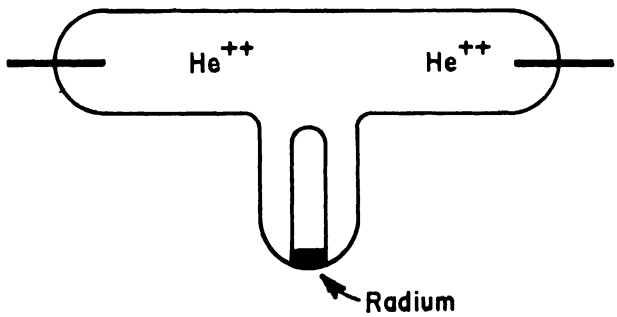


Fig. 3-4. Discharge tube for the identification of alpha particles.

be penetrated by the alpha particles. The space surrounding the inner tube was evacuated to a point where it would no longer support an electrical discharge. After several days, however, an electrical discharge could be passed through the tube and the excited gas emitted the characteristic lines of the helium spectrum.

Beta particles were found to have charge and mass equal to those of high-speed electrons. Although beta particles are energetic electrons, ejected from radioactive nuclides, it must be emphasized that they do not come from the orbital electron structure surrounding the nucleus. Early theories postulated the existence of free electrons inside the nucleus and beta-particle emission was assumed to be the ejection of one of these. It is now known that there are no free electrons inside the nucleus and a beta particle can have only a virtual existence prior to emission.

Negative beta-particle emission can be thought of as the conversion of a nuclear neutron to a proton according to

$$_0n^1 \rightarrow {}_1p^1 + \beta^- \tag{3-9}$$

This reaction, which is energetically possible, would leave the total number of nucleons unchanged, and would raise the atomic number by 1.

The gamma rays have been positively identified as electromagnetic radiation. Since the quantum energies of gamma rays range up to about 3 Mev they coincide with a well-known X-ray region. Once emitted, there is no difference between an X-ray photon and a gamma-ray photon of equal energy, and only occasionally need distinction be made between them.

3.07 ALPHA-PARTICLE EMISSION

Since an alpha particle consists of a tightly bound combination of two protons and two neutrons, a nucleus emitting an alpha particle must lose two units of positive charge and a total of four nucleons. Symbolically

$$_Z\mathrm{X}^A \rightarrow {}_{Z-2}\mathrm{Y}^{A-4} + \alpha + Q \tag{3-10}$$

where X represents the *parent* nuclide, Y the *daughter*, and Q is the energy released in the reaction.

As a specific example consider $_{92}\mathrm{U}^{238}$, the most abundant isotope

of uranium and the head of the uranium series. U^{238} is known to emit an alpha particle so

$$_{92}U^{238} \rightarrow \alpha + {}_{90}Th^{234} + Q \qquad (3\text{-}11)$$

Thus the emission of an alpha particle changes or transmutes a nucleus of U^{238} to a nucleus of Th^{234}. This transformation is shown schematically on an *A-Z* plot, Fig. 3-5. Another useful representation is the *Z-N* plot, also shown in Fig. 3-5.

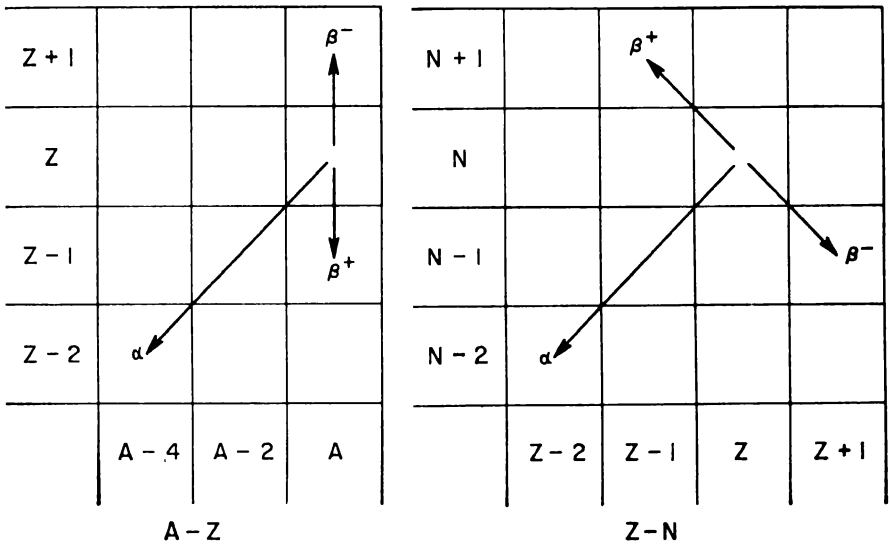


Fig. 3-5. Changes of Z and N in radioactive decay.

As the ejected alpha particle loses energy by collisions it slows down and eventually captures two electrons to become a neutral helium atom. The daughter nucleus must lose two of its orbital electrons to remain electrically neutral and hence the end products will involve the same total number of electrons as the original structure.

Most alpha-particle emissions are not as simple as that of U^{238}. For example Ra^{226}, the isotope of radium first extracted by Mme. Curie, emits alpha particles of either 4.795 Mev or 4.611 Mev and also a gamma ray of 0.188 Mev. Figure 3-6 shows the *decay scheme* * for Ra^{226}. According to this scheme 93.5 per cent of the decays go

* This and other data pertaining to radioactive transformations obtained from "Nuclear Data," *Circular No. 499* of the National Bureau of Standards, Sept. 1950, with supplements. From Government Printing Office, Washington 25, D. C.

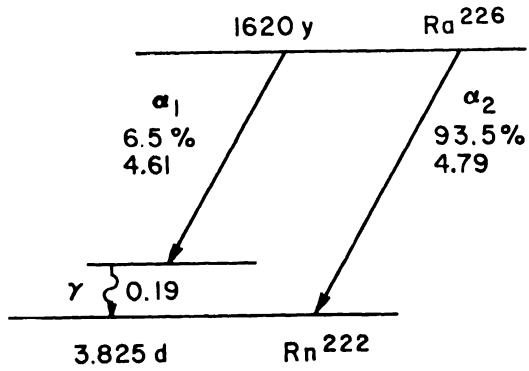


Fig. 3-6. Decay scheme of Ra^{226}.

from the ground state of Ra^{226} to the ground state of Rn^{222} with the alpha particle carrying off 4.795 Mev.

In the remaining 6.5 per cent of the Ra^{226} disintegrations the alpha particle carries away only 4.611 Mev and the Rn daughter is left in an excited state. This excited state is relieved by the prompt emission of a gamma ray. After this emission the daughter nucleus is in the same energy state as after the higher-energy alpha-particle emission. According to this scheme the sum of alpha-particle energy and gamma-ray energy in the second case should equal the alpha-particle energy of the first case. This relation is fulfilled within experimental error. For the second type of emission Eq. (3-10) must be modified to

$$ {}_{Z}X^{A} \rightarrow {}_{Z-2}Y^{A-4} + \alpha + \gamma + Q \qquad \textbf{(3-12)} $$

Detailed studies of alpha-particle emission provide strong arguments for the existence of energy levels inside the nucleus, somewhat analogous to the discrete energy states of orbital electrons.

3.08 NEGATIVE BETA-PARTICLE EMISSION

Th^{234}, the daughter product of U^{238}, is also radioactive but prefers to decay by beta-particle emission rather than by alpha emission. In beta emission a single negative charge is lost by the nucleus and so the atomic number must increase by one. The total number of nucleons remains unchanged by the decay and the general reaction is

$$_{Z}X^{A} \rightarrow {}_{Z+1}Y^{A} + \beta^{-} + \gamma + Q \tag{3-13}$$

In those cases in which the daughter nucleus is left in the ground state the γ term in Eq. (3-12) will be missing. Beta transitions appear as vertical lines on the *A-Z plot.*

In the specific case of Th^{234} Eq. (3-13) becomes

$$_{90}Th^{234} \rightarrow \beta^{-} + {}_{91}Pa^{234} + 0.205 \text{ Mev} \tag{3-14}$$

According to the decay scheme, Fig. 3-7, 80 per cent of the beta

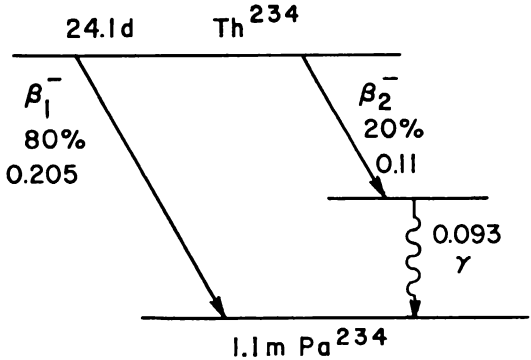


Fig. 3-7. Decay scheme of Th^{234}.

particles emitted by Th^{234} might be expected to have an energy of 0.205 Mev, and 20 per cent an energy of 0.110 Mev, with each of the latter accompanied by an 0.095 Mev gamma ray. Experimentally, a *continuous* spectrum of beta-particle energies is observed, ranging, in the case of Th^{234}, from 0 to 0.205 Mev. This continuous spectrum is not a peculiarity of Th^{234} but is observed in all *pure beta decays,* processes which are describable by Eq. (3-13).

The discovery of continuous beta-particle spectra raised serious questions as to the validity of the concept of discrete energy states of parent and daughter nuclei. When the beta particles are absorbed in a calorimeter the energy transfer amounts to only about $\frac{1}{3}$ of that to be expected if each particle was emitted with the full energy of the transition. Thus $\frac{2}{3}$ of the energy release expected from energy level considerations remains to be accounted for.

Theoretical physicist W. Pauli suggested that the discrepancy could be removed by assuming a second particle emitted simultaneously with each beta emission. According to this concept the full energy of transition will be lost by the parent nucleus at disintegra-

tion, with this energy divided in varying proportions between the beta particle and the new proposed particle.

Since electric charge in a beta transition is already conserved, the new particle must be electrically neutral; hence the name *neutrino*, ν. Since there is no consistent mass discrepancy associated with beta decay the neutrino must have a mass that is small even when compared to the mass of an electron. A particle having these properties will interact very weakly with the matter through which it passes, and thus experimental detection of the neutrino becomes very difficult. For the same reason it is of no direct biological importance, contributing nothing to the energy absorbed from a beta-particle beam.

In spite of the inherent difficulties involved, Reines and Cowan * have succeeded in demonstrating the existence of the neutrino beyond any reasonable doubt. To do so they made use of the intense radiation associated with the operation of high-power nuclear reactors, such as are used for the large scale production of radioactive isotopes.

It should be noted that tables of data pertinent to radioactive decay always list the maximum beta-particle energy associated with the transition. In calculations of energy delivered by beta particles to any absorbing medium the mean energy rather than the maximum is needed. Mean beta energy varies between 0.2 and 0.4 of maximum. The isotope table in the appendix lists both maximum and mean beta particle energies for some biologically important isotopes. A mean value of $\frac{1}{3}$ maximum can usually be taken without serious error in those transitions in which the mean is not known.

3.09 POSITRON EMISSION

In some artificially produced radioactive nuclides the nuclear instability requires the emission of a positron rather than a negative beta particle. Positron spectra show continuous energy distributions much like those seen in negatron distributions. It is again necessary to invoke a second emitted particle, the anti-neutrino, to account for the observed spectra. The type reaction for positron decay is

$$ {}_{Z}X^{A} \rightarrow {}_{Z-1}Y^{A} + \beta^{+} + \gamma + \nu + Q \qquad (3\text{-}15) $$

* Reines, F., and C. L. Cowan, Jr. "Neutrino Physics," *Physics Today* **10**, 12, 1957.

Like its counterpart, the anti-neutrino carries off energy, has zero charge, and a negligibly small mass. It interacts weakly with matter and has no direct biological significance. The division of energy between positron and anti-neutrino is slightly different from that between electron and neutrino, but the mean positron energy is about ⅓ maximum.

Any energy removed from a nucleus must come from a decrease in nuclear binding energy, which will appear as a loss in mass of the daughter nucleus. Negative beta emission is particularly simple.

Illustrative Example

Stable S^{32} of atomic mass 31.98227 amu is produced by the emission of a 1.72 Mev beta particle from P^{32}. Calculate the atomic mass of the radioactive parent.

The reaction is $_{15}P^{32} \rightarrow \beta^- + {}_{16}S^{32}$

Atomic mass of daughter	31.98227 amu
Mass equivalent of beta energy 1.72/931	0.00185
Atomic mass of parent	31.98412

One electron mass was lost from the system when the negative beta particle was ejected. This mass was exactly compensated by the one additional orbital electron required by the daughter. Because of this compensation no account of electron masses need be taken in negatron emission.

In positron emission one electron mass is lost from the nucleus and a second is lost because the daughter must release one orbital electron to maintain neutrality. Thus the atomic mass of the daughter must be at least $2\ m_e$ less than the parent, and the energy equivalent of this mass does not appear as kinetic energy of the positron or the anti-neutrino. The energy relations for Na^{22} are shown in the decay scheme, Fig. 3-8.

Illustrative Example

Calculate the atomic mass of Na^{22} from the decay scheme of Fig. 3-8 and the knowledge that the atomic mass of Ne^{22} is 21.998382 amu.

Atomic mass of daughter	21.998382 amu
Mass equivalent of beta energy 0.575/931	0.000616
Mass equivalent of gamma energy 1.28/931	0.001370
Two electron masses	0.001098
Atomic mass of parent	22.001466

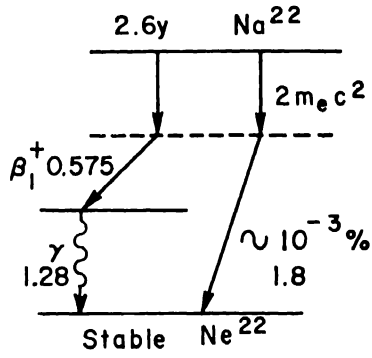


Fig. 3-8. Decay scheme of positron emitter Na^{22}.

3.10 ORBITAL ELECTRON CAPTURE

It may happen that a given nuclide lies below the line of stability and hence requires an increase in Z to achieve stability, but has a daughter nucleus whose mass is too great to permit positron emission. In these cases the required atomic-number increase is obtained by the nuclear capture of an orbital electron. Since K electron capture is most probable this is known as K *capture*. The general reaction is given by

$$ {}_zX^A + e^- \rightarrow {}_{z-1}Y^A + h\nu \qquad (3\text{-}16) $$

A specific case of K capture is Cr^{51} whose decay scheme is shown in Figure 3-9. Even when positron emission is energetically possible K capture may occur as a competing mode of decay. The decay of Zn^{65} is a case in point, Fig. 3-10.

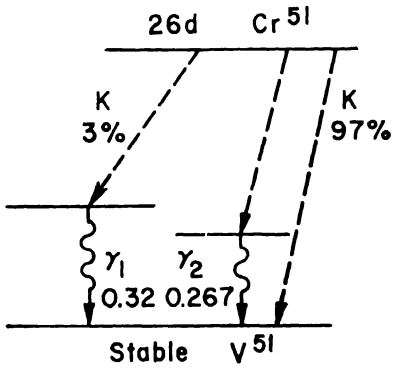


Fig. 3-9. Decay scheme with K capture, Cr^{51}.

Following K capture the daughter nuclide will emit a characteristic series of X-ray lines as the electron gap is filled from above. These X-ray photons provide the only means for assaying nuclides which decay by K capture only.

3.11 INTERNAL TRANSITION

In most cases radioactive nuclides decay by emitting a charged particle or capturing an electron to produce a change in atomic number. Occasionally, however, a nuclide is in an excited state and decays by gamma-ray emission to a lower state of the same nuclide (isomeric transition). A second decay process may or may not follow *internal transition,* designated by IT. Antimony 122 is a case in which internal transition is followed by beta emission, Fig. 3-11.

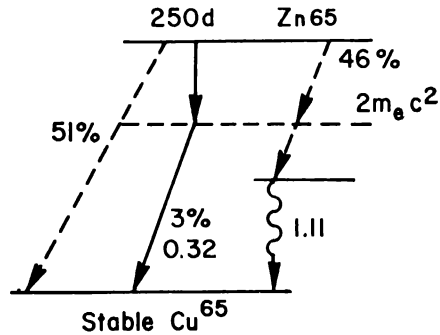


Fig. 3-10. Combined K capture and positron emission.

3.12 CONVERSION PROCESSES

Many cases of isomeric transitions show a line spectrum of beta particles in addition to the continuous distribution of energies characteristic of pure beta decay. The line spectrum may be thought of as arising from the *internal conversion* of nuclear gamma rays, acting to eject orbital electrons. The gamma-ray spectrum will have a small number of discrete energies and each orbital electron has a definite value of binding energy. Consequently, internal conversion electrons will have a series of discrete energies and no neutrino emission will be involved.

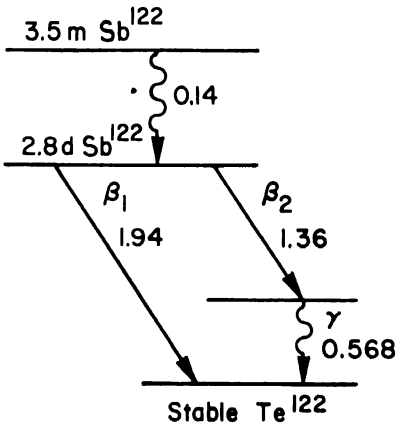


Fig. 3-11. Internal transition followed by beta emission.

In general only a fraction of the isomeric transitions will produce conversion electron emission. The

ratio N_e/N_γ is known as the *conversion coefficient.* Characteristic X-ray spectra will be emitted following internal conversion as the electron defects are filled from outer levels.

Low-energy *Auger electrons* are also ejected as the orbitals undergo the energy rearrangements associated with the other radiative processes. Energetically, these Auger electrons can be thought of as arising from the internal conversion of characteristic X-rays.

3.13 RATE OF RADIOACTIVE DECAY

Each radioactive decay process is characterized by the fact that only a definite fraction of the potentially unstable nuclei decay in a given time. Suppose that at a given instant there are N atoms of a radioactive species. Each of these atoms is capable of spontaneous disintegration and eventually will do so. In unit time only a fraction λ, or total number λN will decay. The fraction λ is known as the *decay constant* or the *disintegration constant.*

In a very short time Δt the number of disintegrations ΔN will be

$$\Delta N = -\lambda N \, \Delta t \tag{3-17}$$

The minus sign is required, since the decay process acts to decrease N rather than to increase it. Integration of Eq. (3-17) gives the expression for N as a function of time t.

$$N = N_0 e^{-\lambda t} \tag{3-18}$$

where N_0 = number of atoms at $t = 0$
e = base of natural logarithms.

Alternate forms of Eq. (3-18), sometimes more suitable for numerical calculations are

$$\ln N = \ln N_0 - \lambda t \tag{3-18A}$$

$$\ln\left(\frac{N_0}{N}\right) = \lambda t \tag{3-18B}$$

According to Eq. (3-18) there will be some parent atoms remaining at any finite value of t and so it is not possible to specify the life of any radioactive species. It is possible to specify the *half life* T, which is the time required for one-half the original number of nuclei to decay. To calculate T put $N = N_0/2$ in Eq. (3-18B). Then

$$\ln 2 = \lambda T$$

and

$$T = \frac{0.693}{\lambda} \tag{3-19}$$

Each radioactive nuclide has a characteristic half life which is unaltered by changes in any of the usual variables such as temperature, pressure, chemical combination, or state of aggregation.* Known half lives range from more than 10^{10} years to less than 10^{-6} sec. Half life is customarily expressed in years, days, hours, minutes, or seconds, abbreviated y, d, h, m, and s respectively.

The unit of radioactivity is the *curie,* defined as that quantity of any radioactive nuclide undergoing 3.7×10^{10} disintegrations per second. The choice of this figure is the result of an original definition based on the activity of a sample of Ra^{226}, Section 4.07. Note that the number of radiations emitted need not be equal to the number of nuclear disintegrations. The *millicurie,* mc (10^{-3} c) and the *microcurie,* μC (10^{-6} c) are commonly used subunits. In some cases the *megacurie,* Mc (10^{6} c) is the most convenient unit.

3.14 SERIAL RELATIONSHIPS

Most artificial radioactive nuclides decay in a single transition to a stable configuration. This is not the case with either the naturally occurring series elements, or the fission chains produced from U^{235} or Pu^{239}. The serial transformations are complicated by the fact that the source of one decaying nuclide depends upon the preceding decay.

The equations are derived on the assumption that at $t = 0$ there are N_{10} atoms of a parent radioactive nuclide and no trace of any daughter products. The following notation is used:

Parent nuclide	decay constant λ_1,	N_1 atoms at time t
First daughter	λ_2,	N_2
Second daughter	λ_3,	N_3
Third daughter	λ_4,	N_4

* This statement is not strictly true in all cases. In some cases of transitions involving orbital electrons, very small changes in decay rate can be detected as physical conditions are varied.

The first transformation proceeds independently, but all subsequent decays depend upon preceding reactions. We have

$$N_1 = N_{10}e^{-\lambda_1 t} \tag{3-20}$$

$$N_2 = N_{10}(a_1 e^{-\lambda_1 t} + a_2 e^{-\lambda_2 t}) \tag{3-21}$$

$$N_3 = N_{10}(a_3 e^{-\lambda_1 t} + a_4 e^{-\lambda_2 t} + a_5 e^{-\lambda_3 t}) \tag{3-22}$$

$$N_4 = N_{10}(a_6 e^{-\lambda_1 t} + a_7 e^{-\lambda_2 t} + a_8 e^{-\lambda_3 t} + a_9 e^{-\lambda_4 t}) \tag{3-23}$$

where

$$a_1 = \frac{\lambda_1}{\lambda_2 - \lambda_1}, \qquad a_2 = -\frac{\lambda_1}{\lambda_2 - \lambda_1} \tag{3-24}$$

$$a_3 = \frac{\lambda_1\lambda_2}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)}, \qquad a_4 = \frac{\lambda_1\lambda_2}{(\lambda_1 - \lambda_2)(\lambda_3 - \lambda_2)},$$
$$a_5 = \frac{\lambda_1\lambda_2}{(\lambda_1 - \lambda_3)(\lambda_2 - \lambda_3)} \tag{3-25}$$

$$a_6 = \frac{\lambda_1\lambda_2\lambda_3}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)(\lambda_4 - \lambda_1)}, \qquad a_7 = \frac{\lambda_1\lambda_2\lambda_3}{(\lambda_1 - \lambda_2)(\lambda_3 - \lambda_2)(\lambda_4 - \lambda_2)}$$

$$a_8 = \frac{\lambda_1\lambda_2\lambda_3}{(\lambda_1 - \lambda_3)(\lambda_2 - \lambda_3)(\lambda_4 - \lambda_3)}, \qquad a_9 = \frac{\lambda_1\lambda_2\lambda_3}{(\lambda_1 - \lambda_4)(\lambda_2 - \lambda_4)(\lambda_3 - \lambda_4)} \tag{3-26}$$

Relations for more than four series members can be derived but are not needed for present purposes.

3.15 SPECIAL CASES

The serial relationships given above are general and hold for any values of the decay constants. There are a few special cases in which approximations can be made with a negligible loss of accuracy.

1. *Very long-lived parent,* $\lambda_1 << \lambda_2$. In this case λ_1 is so small compared to λ_2 that for the times under consideration $e^{-\lambda_1 t} = 1$. Then Eq. (3-21) becomes

$$N_2 = N_{10}\frac{\lambda_1}{\lambda_2}(1 - e^{-\lambda_2 t}) \tag{3-27}$$

As time elapses the exponential term in Eq. (3-27) decreases and N_2 approaches the secular equilibrium value

$$N_{2\,\text{eq.}} = N_{10}\frac{\lambda_1}{\lambda_2} \tag{3-28}$$

2. *Comparatively long-lived parent,* $\lambda_1 < \lambda_2$. After some time has

elapsed the second term in Eq. (3-21) becomes negligible compared to the first and

$$N_2 = N_{10}\frac{\lambda_1}{\lambda_2 - \lambda_1}e^{-\lambda_1 t} \tag{3-29}$$

which, by Eq. (3-19) becomes

$$N_2 = N_1\frac{\lambda_1}{\lambda_2 - \lambda_1} \tag{3-30}$$

Thus an equilibrium ratio between N_2 and N_1 is established, and then both parent and daughter decay at the rate characteristic of the parent.

3. *Comparatively short-lived parent*, $\lambda_1 > \lambda_2$. In this case the first exponential term in Eq. (3-21) eventually becomes negligible compared to the second, and after this the daughter decays with its own characteristic half life.

An immediate application of the serial relationships arises in the use of 77 h Te^{132} as a source of 2.4 h I^{132}. For many purposes I^{132} can replace the more commonly used I^{131} with a substantial reduction in the radiation dose delivered to the patient. The short half life makes direct supply of I^{132} impractical, so it is customarily obtained as the radioactive daughter produced by the beta decay of Te^{132}. This parent nuclide is formed in good yield as a fission product in nuclear reactors. When needed the I^{132} daughter is separated from the Te parent by chemical methods. Chemical separation must be complete for any Te^{132} contaminant in the iodine will continue to provide I^{132} with a 77 hour half life.

PROBLEMS

3-1. Will the radioactivity of fission products consist of negative or positive beta emission? Why?

3-2. Estimate the number of members in the decay chain before the fission products of Eq. (3-8) obtain stability.

3-3. Calculate the atomic mass of A^{37} as formed by reaction Eq. (3-4).
Ans. 36.97683 amu.

3-4. Reaction Eq. (3-7) can take place with a slow neutron so no account need be taken of its kinetic energy. Calculate the energy of the ejected proton, neglecting the energy of recoil of the C^{14} nucleus.

3-5. Neutron beams are frequently produced by the bombardment of a deuterium target with deuterons, H^2 (d, n) He^3. What will be the energy released if the deuteron beam has an energy of 5 Mev?

Ans. 8.27 Mev.

3-6. If relativity considerations do not enter the reaction energy Q will divide between an ejected particle p and the residual nucleus according to $Q = E_p(1 + m_p/m_r)$. Assume this relation and calculate the kinetic energy of the ejected neutron and of the recoiling nucleus in Prob. 3-5.

3-7. Another common source of neutrons is obtained by bombarding a tritium target with deuterons, H^3(d, n)He^4. What reaction energy is available if the deuterons are incident at 3.5 Mev? What will be the neutron energy? *Ans.* 21.1 Mev, 16.9 Mev.

3-8. Write the type equation describing positron decay.

3-9. In August, 1911 Mme. Curie prepared an international standard containing 21.99 mg of $RaCl_2$. What is the radium content of this standard as of August, 1960? *Ans.* 16.77 mg.

3-10. What is the mass of a pure sample of Ra^{226} which has an activity of 1 curie?

3-11. What is the mass of a 15 mc sample of pure I^{131}?

Ans. 0.121 microgram.

3-12. An accident has contaminated a laboratory with Na^{24} to a radiation level 20 times tolerance. How long must the room be isolated before the tolerance level is reached?

3-13. Neglect relativity considerations and calculate the recoil energy of the N^{14} nucleus resulting from the ejection of a 150 Kev beta particle from C^{14}. *Ans.* 5.9 ev.

3-14. Calculate and plot the growth curve of 3.825d Rn^{222} from an initially pure sample of Ra^{226}.

3-15. Po^{210} decays with a 138d half life to stable Pb^{206} by the emission of an alpha particle. What volume of He^4 at NTP will be produced in 1 year by a 50 curie source of Po^{210}? What volume of He^4 will be produced by the total decay of the source?

Ans. 0.027 ml, 0.116 ml.

3-16. The average potassium content of living tissue is 0.35%. Calculate the number of microcuries of K^{40} in an 80 kg man. Half life of K^{40} 1.31×10^9 y.

3-17. A 15 mc sample of Te^{132} is to be used as a source of I^{132}. Assume that 40% of the available I^{132} can be chemically separated. For how long a time can this source be used to obtain 5μC samples of I^{132}? *Ans.* 515 hours.

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4

NATURAL RADIOACTIVITY

4.01 IMPORTANCE OF NATURAL PRODUCTS

Although clinical and research medicine, and industry, are using ever-increasing amounts of artificial radioactive nuclides, the importance of natural radioactive elements has not waned. Indeed, the production of artificial radioactive nuclides depends for the most part on nuclear reactors operating on uranium as a fuel. With the added demands on uranium for the production of power and nuclear weapons, world requirements have gone up and workable deposits are being sought in all parts of the world.

From the beginning the uranium series has been the most important of the four. Uranium had been mined extensively long before Becquerel's discovery; it was used primarily in the glass industry. Uranium ores are widespread, with a mean concentration in the earth's crust of about 4×10^{-6} grams per gram of rock, but relatively few deposits are rich enough to warrant commercial exploitation. In sea water the concentration ranges from 0.3×10^{-6} to 2.3×10^{-6} gm/liter, varying with the salinity.

It seems necessary to assume that the naturally radioactive nuclides are concentrated in a relatively thin layer of the earth's crust. Most of the considerable energy carried off by the radiations will be converted to heat in the material close to the emitter. The measured heat flow from the interior of the earth to the crust can be accounted for if the surface concentrations of radioactive nuclides are maintained to a depth of about 20 miles. More radioactive material than this would lead to excessive heat production and a gradually warming earth.

Each radioactive series is headed by a long-lived nuclide; a necessary requirement if these radioactive substances were laid down at the time of formation of the earth's crust. A starting element with a half life that is short compared to the age of the earth would long since have decayed to undetectable amounts.

Another common factor is that each series includes one member which is a gas. Each of these gaseous nuclides is an isotope of the noble gas radon, the heaviest member of the helium, neon, argon, . . . family. Three of the series end with a stable isotope of lead and one with a stable isotope of bismuth.

4.02 THE URANIUM SERIES

Because of its relative importance, only the uranium series will be considered in detail. Various members of this series were chemically isolated and named long before their true isotopic relationships were recognized. In Table 4-1 both the original name and the modern isotopic characterization are given, since both are frequently seen in the literature.

The nuclide Po^{218} exhibits the phenomenon of *branching*, which means that there are two possible modes of decay. Alpha emission to Pb^{214} is the preferred mode (99.96 per cent) with 0.04 per cent of the decays by beta emission to At^{218}. The series reconverges at Bi^{214} since Pb^{214} decays by beta emission and At^{218} by alpha emission. Branching is graphically demonstrated by either an A-Z or a Z-N plot.

The ratio $99.6/0.04 = 2500$ is known as the *branching ratio*. Examination of Table 4-1 shows branching at Bi^{214} also, and by chance the branching ratio is again 2500.

Table 4-1. THE URANIUM SERIES

Nuclide	Half life	EMISSION ENERGY, MEV α	β	γ
U^{238}–UI	4.50×10^9 y	4.18	–	–
Th^{234}–UX_1	24.1 d	–	0.192	0.090
Pa^{234}–UX_2	1.22 m	–	2.32	0.82
U^{234}–UII	2.3×10^5 y	4.78	–	0.065
Th^{230}–Io	8.0×10^4 y	4.6	–	0.068
Ra^{226}–Ra	1.62×10^3 y	4.79	–	0.19
Rn^{222}–Em	3.825 d	5.49	–	–
Po^{218}–RaA	3.05 m	6.00	–	–
At^{218}–	2. s	6.7	–	–
Pb^{214}–RaB	26.8 m	–	0.72	0.29
Bi^{214}–RaC	19.7 m	5.5	3.15	1.8
Po^{214}–RaC′	1.6×10^{-4} s	7.68	–	–
Tl^{210}–RaC″	1.32 m	–	1.8	–
Pb^{210}–RaD	25 y	–	0.029	0.046
Bi^{210}–RaE	4.85 d	–	1.08	–
Po^{210}–RaF	138 d	5.30	–	0.8
Pb^{206}–RaG	Stable –	–	–	–

4.03 NON-SERIES RADIOACTIVE NUCLIDES

All radioactive nuclides occurring as members of a series are heavy elements, $Z = 81$ or greater. In addition to these heavy elements there are a few lighter, unrelated radioactive nuclides located apparently at random throughout the periodic table. Table 4-2 lists those non-series radioactive nuclides whose identity is reasonably

Table 4-2. NON-SERIES, NATURALLY OCCURRING RADIOACTIVE NUCLIDES

Nuclide	Per cent abundance	Half life, years	Emission	Energy, Mev
H^3	–	12.4	β^-	0.018
C^{14}	–	5568.	β^-	0.16
K^{40}	0.0119	1.31×10^9	β^-,γ,K	1.3
Rb^{87}	27.8	6.0×10^{10}	β^-,γ	0.27
In^{115}	95.8	$\sim 10^{14}$	β^-	0.63
Te^{130}	34.5	10^{21}	$2\beta s$	–
La^{138}	0.09	7×10^{10}	β^-	1.0
Sm^{147}	15.07	7×10^{10}	α	2.18
Lu^{176}	2.6	4.6×10^{10}	β^-,γ,K	0.4
Re^{187}	62.9	4×10^{12}	β^-	0.04
Bi^{209}	100	2.7×10^{17}	α	3.15

well established. Future research may add other nuclides to the list and may change some of the presently listed radiation constants.

Each member of a radioactive series decays by either alpha or negative beta emission, either of which may or may not be followed by gamma-ray emission. Some of the non-series nuclides require a decrease in atomic number to attain stability, and hence K capture will occur.

With the exception of H^3 and C^{14} all the nuclides in Table 4-2 have half lives which are long compared to the age of the earth; hence, these could have been laid down at the time of formation of the earth's crust. H^3 and C^{14}, on the other hand, are being formed continuously by the cosmic radiation which reaches the earth from outer space. H^3 is formed by a variety of processes, whereas C^{14} comes mainly from the neutron bombardment of atmospheric nitrogen, according to Eq. (3-7). Some C^{14} is formed from atmospheric nitrogen at the time of a nuclear detonation.

H^3 and C^{14} concentrations vary somewhat with the origin of the sample. H^3 activity amounts to about 1.5×10^{-4} disintegrations per second (dps) per gram of hydrogen, whereas C^{14} activity is about 0.25 dps per gram of carbon.

Background radiation, to which man has apparently been exposed throughout his existence, arises from all the sources of natural radioactivity. Cosmic radiation, K^{40}, C^{14}, and penetrating radiations from radioactive nuclides in the earth all contribute to an inescapable background. Detailed discussion of this radiation can be made with more profit later.

4.04 AGE DETERMINATIONS BY RADIOACTIVITY

The presence of radioactive nuclides and the apparently immutable values of the characteristic decay constants permit the determination of several important time intervals. One of the earliest applications of radioactive dating was the determination of the age of minerals from the Pb/U or He/U ratios.

An examination of Table 4-1 shows that the sum of the disintegrations in the U^{238} series is equivalent to

$$_{92}U^{238} \rightarrow 8\,\alpha + 6\,\beta^- + {}_{82}Pb^{206} + Q \qquad (4\text{-}1)$$

The longest intermediate half life is 25 years for RaD, so after a few centuries the Pb^{206} content of a mineral should be a measure of the amount of U^{238} that has decayed if all other sources of Pb^{206} can be excluded.

Illustrative Example

Calculate the amount of Pb^{206} formed by the decay of U^{238} over a period of one million years.

For U^{238}

$$\lambda = \frac{0.693}{4.50 \times 10^9} = 1.54 \times 10^{-10}\ y^{-1}$$

From 1 gm of U^{238}

$$1 \times 1.54 \times 10^{-10} \times \frac{206}{238} = 1.33 \times 10^{-10}\ \text{gm } Pb^{206} \text{ per year}$$

Disregarding the small decrease in Pb^{206} production due to the decreasing amount of U^{238}

$$Pb^{206} \text{ production} = 1.33 \times 10^{-4}\ \text{gm per million years}$$

Age determinations from the He^4/U^{238} ratio agree quite well with the ages as determined from geological data.

Age determinations from the He^4/U^{238} ratio serve as a useful check when there is some doubt about the amount of radiogenic lead present. In some cases age determinations by He/U ratios are too low, indicating a loss of He by diffusion through porous rock. Fine-grained minerals appear to give the most satisfactory results.

For more recent times the carbon dating methods developed by Libby * are yielding some most interesting results. This method rests on the plausible but unproven assumption that the present rate of C^{14} production by cosmic radiation is the same as that throughout the dating period.

The radioactive C^{14} produced in the upper atmosphere by cosmic radiation will be distributed throughout the atmosphere by diffusion and turbulence. Existing primarily as $C^{14}O_2$, some of this radioactive carbon will be picked up by living organisms since the chemical behavior of C^{14} is no different from that of stable carbons C^{12} and C^{13}. During life, therefore, all living things will contain a small, constant amount of C^{14}.

Upon death the incorporation of C^{14} ceases and the amount

* Libby, W. F. *Radiocarbon Dating.* University of Chicago Press, Chicago, 1952.

present will decay with the characteristic half life of 5568 years. The age of an old organic material can then be determined by comparing its C^{14} concentration with that in living things. The half life of C^{14} is short on a geological time scale, limiting C^{14} dating to a period of about 25,000 years.

Because of differences in carbon metabolism one may expect some differences in the C^{14} content of contemporary samples. Thus, Libby, Anderson, and Arnold * find the specific C^{14} activity of contemporary wood to be 15.3 ± 0.5 dpm/gm while for a shell the value was 16.5 ± 0.5 dpm/gm.

4.05 THE CURIE UNIT

Radium, with a half life of 1620 years, was early recognized as a desirable standard for measurements of radioactivity. At the 1910 Congress of Radiology and Electricity a committee was formed to arrange for a standard of radioactivity, and in 1911 Mme. Curie prepared a sealed glass ampoule of radium chloride, which was deposited in the Bureau International des Poids et Mesures at Sèvres, France. In August 1911 this ampoule contained 21.99 mg of $RaCl_2$. Since that time a number of secondary standard solutions have been prepared and compared with the Sèvres standard, and now all major countries have one or more radiation standards which are intercompared at frequent intervals.

The 1910 Congress also defined the *curie* or unit of radioactivity, as the activity of the amount of radon gas that is in equilibrium with one gram of radium-226. This disintegration rate is the same as the rate of decay of the parent radium, since at equilibrium radon is being formed from radium at the same rate that it is decaying to polonium-218.

A long series of measurements has tended to converge on 3.7×10^{10} dps as the activity of the equilibrium quantity of radon. The exact number can be expected to change as more accurate measurements are made; hence the definition is not entirely satisfactory for a standard.

In 1954 the International Congress of Radiology redefined the

* Libby, W. F., E. C. Anderson, and J. R. Arnold. *Science* **109**, 227, 1949; Anderson, E. C., and W. F. Libby. *Physical Review* **81**, 931, 1951.

curie as that amount of any radioactive nuclide undergoing 3.7×10^{10} dps. This definition gives a fixed number, independent of future measurements of radon activity. Another unit of activity, the *rutheford*, rd, has been defined as 10^6 dps but this unit has not been widely accepted.

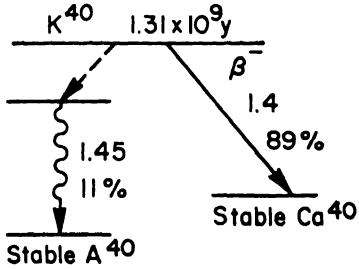


Fig. 4-1. Decay scheme of K^{40}.

4.06 SPECIFIC ACTIVITY

Specific activity or the activity per unit mass is an important quantity which frequently determines the usefulness of a sample of radio-active material. In using specific activity values care must be taken to state precisely the terms in which the values are expressed. The case of K^{40}, Fig. 4-1, is a good example of possible ambiguities.

Illustrative Example

Calculate the specific activity of K^{40}, $T = 1.31 \times 10^9$ y.

$$\lambda = \frac{0.693}{1.31 \times 10^9 \times 3.15 \times 10^7} = 1.68 \times 10^{-17}\ \text{s}^{-1}$$

Since there is branching, there are really two decay constants. From the branching ratio

$$\lambda_\beta = 0.89\lambda = 0.89 \times 1.68 \times 10^{-17} = 1.49 \times 10^{-17}\ \text{sec}^{-1}$$

$$\lambda_K = 0.11\lambda = 0.11 \times 1.68 \times 10^{-17} = 0.19 \times 10^{-17}\ \text{sec}^{-1}$$

In 1 gram of K^{40} there are

$$\frac{6.02 \times 10^{23}}{40} = 1.52 \times 10^{22}\ \text{atoms}$$

In 1 gram of K^{40} there are

$$1.52 \times 10^{22} \times 1.49 \times 10^{-17} = 2.26 \times 10^5\ \text{dps}\ \beta^-$$

In 1 gram of K^{40} there are

$$1.52 \times 10^{22} \times 0.19 \times 10^{-17} = 2.74 \times 10^4\ \text{dps K}$$

Hence the specific activities are

$$2.26 \times 10^5\ \beta^-\ \text{dps/gm}\ K^{40}$$
$$2.74 \times 10^4\ K\ \text{dps/gm}\ K^{40}$$

Another pair of specific activity figures can be obtained, based on naturally occurring potassium, which contains only 0.0119 per cent K^{40}.

In 1 gram of K there are

$$\frac{6.02 \times 10^{23}}{39.1} = 1.55 \times 10^{22}\ \text{atoms}$$

In 1 gram of K there are

$$1.55 \times 10^{22} \times 1.19 \times 10^{-4} = 1.84 \times 10^{18}\ \text{atoms of}\ K^{40}$$

In 1 gram of K there are

$$1.84 \times 10^{18} \times 1.49 \times 10^{-17} = 27.4\ \text{dps}\ \beta^-$$

In 1 gram of K there are

$$1.84 \times 10^{18} \times 0.19 \times 10^{-17} = 3.5\ \text{dps K}$$

The corresponding specific activities are

$$27.4\ \beta^-\ \text{dps/gm K}$$
$$3.5\ K\ \text{dps/gm K}$$

Another set of figures is obtained if the activities are expressed in microcuries instead of in disintegrations per second.

4.07 MEDICAL USES OF RADIUM

Medical uses have claimed over 80 per cent of all the radium that has been extracted from the native ores. Something over 10 per cent has been mixed with various phosphors to produce self-luminous paints, and the remainder has been used in industrial radiography and in various laboratory applications. The world supply of separated radium is probably about 1500 grams, so over 1000 grams are being used for medical purposes, primarily in the treatment of cancer.

Medical demands for radium have been reduced recently by the availability of artificially produced radioactive nuclides such as Co^{60}, Cs^{137}, and Ir^{192}. However, radium, and particularly its daughter products have some advantages, so they will probably never be completely supplanted by the newer sources.

Radium, as such, is not always used in therapy. Radium is expensive, dangerous to handle, and because of its long half life, must be removed when treatment is complete. The gaseous daughter product Rn^{222} can be pumped off from a radium solution into tiny capillary tubes called *seeds* or needles. These radon seeds can be made up daily, or at any other convenient intervals, from a centrally located radon plant.

The use of radon seeds permits flexibility in treatment, since various strength needles can be made up to provide each particular case with the best possible radiation dose distribution. Because of the short half life of radon the radiation dose will decrease rapidly with time. This permits implanted seeds to be left in place in cases where a second operative procedure for recovery seems inadvisable.

Radon has a higher specific activity than radium, and so a radon seed can be smaller than a radium source of equal activity. In actual practice the concentration of radon as calculated from the gas laws cannot be attained because of the presence of inert gases, but a concentration substantially greater than that of radium is readily obtained. In making calculations involving radium one must remember that the pure metal is never isolated and used as such. Radium is a highly chemically reactive element, entirely apart from its radioactivity, and is always used as a soluble salt such as $RaCl_2$ or $RaBr_2$. The definition of the curie refers of course to the mass of pure radium.

4.08 THE USEFUL RADIATIONS

Although alpha particles produce dense ionization they can penetrate only very small distances, and cannot escape from any container rugged enough for clinical application. Alpha particles, therefore, contribute nothing to the radiation effects obtained with either radium or radon.

For a given energy beta particles are more penetrating than alphas but still have a range of only a few millimeters in tissue. Some of the more energetic betas will escape from thin-walled needles but lose so much energy that they make only a small contribution to the total tissue ionization. In most cases, therefore, the radiation effects can be considered as due to gamma rays only.

An examination of Table 4-1 shows only four gamma-emitting

nuclides in the decay series from Ra^{226} to Pb^{206}. Radium itself emits a gamma ray in only 1 per cent of the transitions so it makes a negligible contribution to external radiation effects. As a result, the radiations from Ra and Rn are qualitatively identical, and the two sources differ only in their rates of decay.

The gammas from Pb^{210} are soft and originate in a long-lived nuclide so that their rate of emission is low and their dosage contribution negligible. The 0.8 Mev gamma ray from Po^{210} is penetrating but it is emitted in only about 0.1 percent of the transitions since most Po^{210} decays go directly to the ground state of Pb^{206}. This leaves only Pb^{214} and Bi^{214} to account for the gamma-ray dosage from a radium source.

The relative contributions of Pb^{214} and Bi^{214} can only be determined from a detailed study of the two decay schemes, which are much more complex than is indicated by Table 4-1. Gamma rays from these two nuclides have energies ranging from 0.24 to 2.2 Mev and therefore the relative contributions will depend to some extent upon the absorptive properties of the container. Bi^{214} accounts for 70–90 per cent of the gamma-ray effects, three energies of 0.6, 1.4, and 1.8 Mev being the most important.

4.09 SECULAR EQUILIBRIUM

Consider radium as the chloride in a weak HCl solution in flask F_1, Fig. 4-2. At zero time assume a pure solution of $RaCl_2$ with no Rn or other daughter products present. This state can be obtained only in principle, since radon is being constantly produced by the alpha decay of radium. The rate of production of Rn atoms is $\lambda_1 N_{10}$, where $\lambda_1 = 1.36 \times 10^{-11}$ sec^{-1} is the decay constant of radium and N_{10} is the number of Ra atoms at $t = 0$. Since λ_1 is very small the number of Ra atoms is essentially constant over long periods of time and Rn will then be produced at a nearly constant rate.

As soon as some radon atoms are formed they will start to decay at a rate characterized by $\lambda_2 = 2.097 \times 10^{-6}$ sec^{-1}. At first production will exceed decay and the amount of radon will increase. As it does so the number of decays (but not the fractional rate) will increase, and eventually a state will be reached where decay equals production. This state is known as *secular equilibrium*. It is not a true equilibrium, for now both Ra and Rn will decay at rate λ_1.

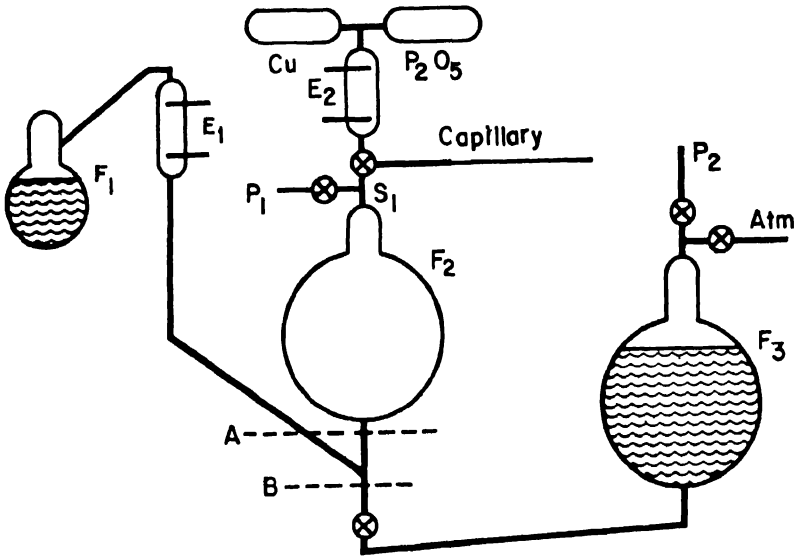


Fig. 4-2. Typical radon plant: F_1—flask with radium solution; E_1, E_2—sparking electrodes for recombination of H_2 and O_2; F_2, F_3—mercury filled Toepler pump; Cu, P_2O_5—purification train.

At any time t the number of radon atoms will be given by Eq. (3-27) which is

$$N_2 = \frac{N_{10}\lambda_1}{\lambda_2}(1 - e^{-\lambda_2 t}) \tag{4-2}$$

Since the number of decays per unit time is $A = \lambda N$

$$A_2 = N_{10}\lambda_1(1 - e^{-\lambda_2 t}) \tag{4-3}$$

The corresponding equilibrium values are

$$N_{2\,eq} = \frac{N_{10}\lambda_1}{\lambda_2} \tag{4-4}$$

$$A_{2\,eq} = N_{10}\lambda_1 \tag{4-5}$$

Direct substitution of values into the growth equation, Eq. (4-3) will give the activity in disintegrations during whatever time unit is used in the exponential. In the special case of 1 gram of radium the equilibrium value will be 1000 mc by definition; the growth curve can be plotted in these units instead of in dps, Fig. 4-3.

4.10 RADON PRODUCTION

The growth curve of Fig. 4-3 or, more accurately, calculations from Eq. (4-3) can be used to determine the theoretical yield from

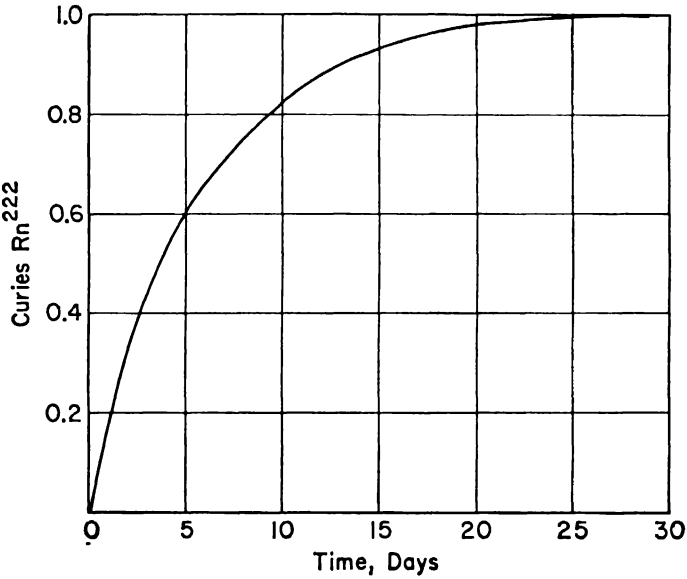


Fig. 4-3. Buildup of radon from radium.

a radon plant. Suppose, for example, that the radon has been completely pumped off of a 1 gram radon plant at $t = 0$. From Fig. 4-3 there will be 166 mc of radon produced one day later, and with daily pumpings a total of $7 \times 166 = 1162$ mc becomes available in one week. If, on the other hand, no radon is pumped until the seventh day, only 719 mc will be obtained. The theoretical maximum yield of 1000 mc in a single pumping can only be obtained at infinite time, although 99 per cent of this activity is reached in 25 days.

It is evident that the amount of radon obtainable from a plant depends upon the pumping schedule. If a large single sample is required there is no choice but to wait until it accumulates. If, as is more usual, smaller amounts are needed, more frequent pumpings will increase the total available output.

The figures given are actual Rn production from a Ra solution. In general only 80–90 per cent of the theoretical amounts can be

realized because of dead volume in the plant, solubility of Rn in the solution, and a variety of other causes. It should be noted that the figures given refer only to the amount of Rn available and not to the γ ray activity of each pumped-off sample. The gamma-ray activity of each sample depends on the buildup of Pb^{214} and Bi^{214} from the gas.

4.11 GAMMA ACTIVITY OF RADON SEED

The instant at which a radon seed is filled becomes a new zero of time to be used in calculating the buildup and decay of the gamma activity. The serial relationships of Sec. 3.13 apply. Any convenient time unit can be used in these relationships provided that the units of each λ and t are self-consistent. In the case of Rn the hour is the most convenient time unit. Then the pertinent constants become:

Rn^{222}	$\lambda_1 = 0.00755\ h^{-1}$	Pb^{214}	$\lambda_3 = 1.55\ h^{-1}$
Po^{218}	$\lambda_2 = 13.6\ h^{-1}$	Bi^{214}	$\lambda_4 = 2.11\ h^{-1}$
a_3	$= 0.00489$	a_7	$= -0.000085$
a_4	$= 0.00624$	a_8	$= -0.0153$
a_5	$= -0.00553$	a_9	$= 0.0117$
a_6	$= 0.00361$		

Figure 4-4 shows the time course of the activity of a sealed-off radon needle, plotted as a fraction of the maximum activity. This curve was calculated from Eqs. (3-22) and (3-23) giving a weight of 1.0 to Bi^{214} and 0.1 to Pb^{214}.

After the initial buildup to a maximum in about 5 hours the activity will decrease with the half life characteristic of Rn. The disintegration rate can be converted readily to millicuries and this is known as the *curiage* of the source. Practically, it is usual to measure the activity of a needle at any convenient time after seal-off, and to use Fig. 4-4 to determine the strength at any later time.

Illustrative Example

A radon needle was sealed off at 1000 hours (note use of 24-hour notation) on Tuesday, and 1.5 hours later had a measured activity of 15.6 mc. Calculate the activity at the time of implantation planned for 1500 hours on the following Wednesday.

From Fig. 4-4

Activity at 1.5 hours	73.5 per cent
Activity at 29 hours	83.4 per cent
Activity at implantation	$15.6 \times \frac{83.4}{73.5} = 17.7$ mc

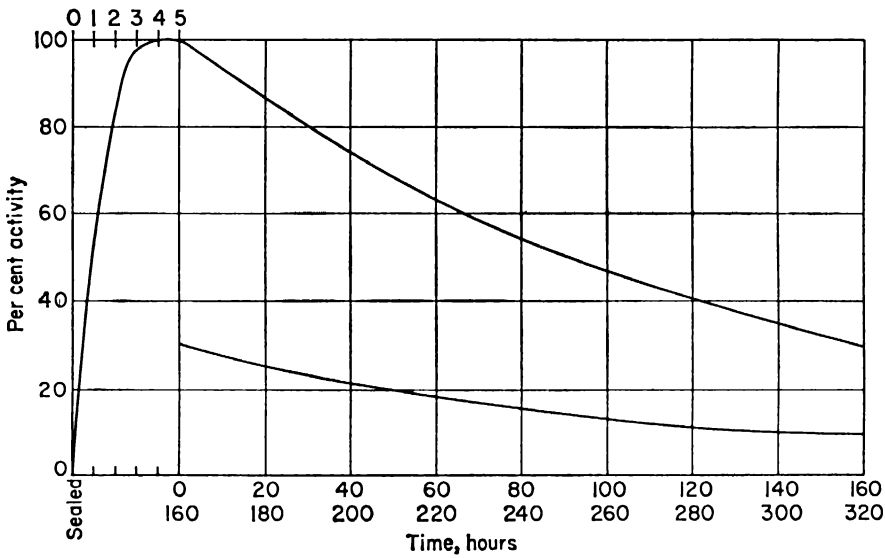


Fig. 4-4. Buildup and decay of gamma-ray activity in a radon needle.

4.12 RADIUM EQUIVALENT OF RADON

The total gamma-ray energy received by a tissue from a radium source will be proportional to the strength of the source and the time of treatment. Although properly the tissue dose must be given in rads (see 7.02) it is convenient to express radium treatments in *millicurie hours,* mch. In the case of radium, source strength is essentially constant and mch can be obtained by simple multiplication. More detailed calculations are required for a radon source to take account of the changes in source strength with time.

To simplify the calculations consider, as is customary, that the radon seed will not be used until after the gamma-ray activity has passed its maximum value. With this restriction the source strength will decrease according to the decay constant of radon, and the discussion can be carried out in terms of *average lifetime* $\overline{T}$ of the source.

Consider any radioactive substance initially consisting of N_0

atoms and governed by a decay constant λ. Then at any later time t there will be $N_0\lambda e^{-\lambda t}\,\Delta t$ atoms decaying in the short interval Δt and these decaying atoms will have had a *total* life of $N_0 t\lambda e^{-\lambda t}\,\Delta t$. If this expression for total life is integrated over all values of t and divided by N_0 the value of average lifetime is obtained. This is

$$\overline{T} = \frac{1}{\lambda} \tag{4-6}$$

or

$$\overline{T} = \frac{T}{0.693} \tag{4-7}$$

In the case of radon $T = 3.825$ days and $\overline{T} = 5.519$ days $= 132.4$ hours.

According to this result a radon seed having an activity of 1 mc at implantation, and left in situ to decay completely, will deliver an irradiation of 132.4 mch. Now assume that the 1 mc implant is removed when it has decayed to 0.1 mc. By a repetition of the previous argument the source is still capable of an irradiation of $0.1 \times 132.4 = 13.24$ mch, so the amount already delivered is $0.9 \times 132.4 = 119.16$ mch. This gives the important result that radon will deliver an irradiation equal to 132.4 times the number of millicuries lost by decay during the treatment.

Explicitly,

$$\text{mch} = \frac{S_0}{\lambda}(1 - e^{-\lambda t}) \tag{4-8}$$

where S_0 = initial source strength in mc.

Figure 4-5 is a plot of Eq. (4-8) evaluated for $S_0 = 1$ mc. This plot agrees with the previous conclusion that 1 mc of radon can deliver a maximum irradiation of 132.4 mch, and this only in an infinite time.

PROBLEMS

4-1. Calculate the number of microcuries of C^{14} in an 80 kg man, assuming a specific activity of 15.3 dpm/gm of C, like contemporary wood. *Ans.* 0.087 μc.

4-2. The oceans of the earth are estimated to contain a total of 1.37×10^{18} cu m of water. Assume an average concentration of 1.86×10^{-6} gm of U^{238} per liter and secular equilibrium, and estimate the total activity in megacuries.

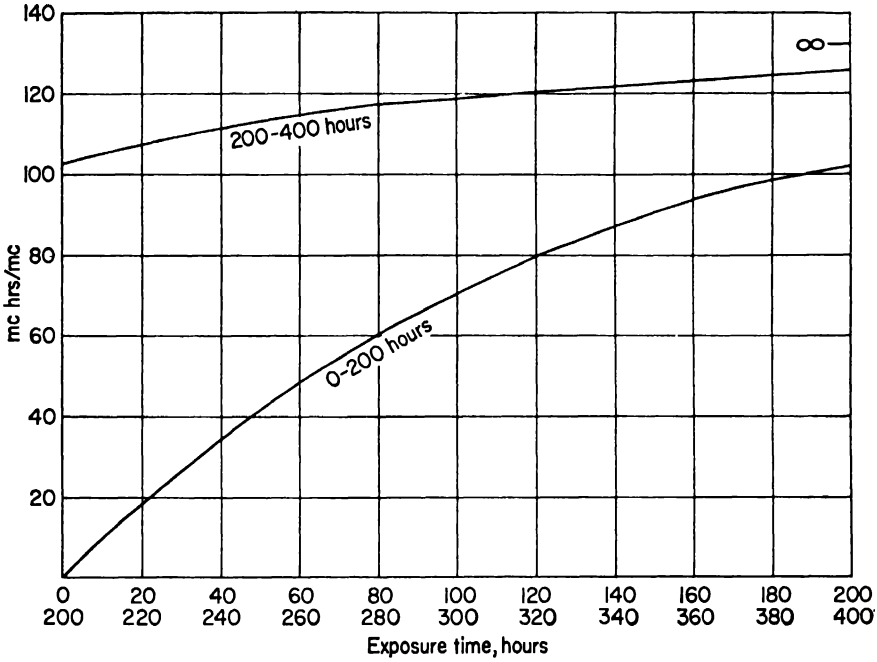


Fig. 4-5. Integral gamma-ray dose from a radon needle.

4-3. The Pb^{206}/U^{238} ratio in a sample of pitchblende was found to be 0.095. Estimate the age of the ore. *Ans.* 715 million years.

4-4. Assume the mean concentration of U^{238} in the earth's crust to exist to a depth of 20 miles in rock of density 2.5 gm/cm^3. Estimate the total U^{238} content in grams and in curies. What is the rate of energy production from the α particle emission of U^{238}, in erg/sec? Radius of earth 6.3×10^3 km.

4-5. Calculate the volume at NTP of the He^4 produced in 1 year from an old 1 gm sample of U^{238}. *Ans.* 1.16×10^{-3} ml.

4-6. Calculate the mass of a 1 curie sample of Po^{214}.

4-7. Using Eq. (4-3) calculate the number of mc of Rn produced in 3 days by a plant containing 500 mg of Ra. *Ans.* 209 mc.

4-8. A plant contains 600 mg of Ra and 83 per cent of the Rn produced can be pumped off. At what intervals can 250 mc samples of Rn be obtained?

4-9. Assume that all of the alpha-particle energy from a solution of Ra goes into the decomposition of water into H_2 and O_2, with one

molecule of water disrupted for each 30 ev expended. Calculate the volume at NTP of the H_2 produced in 24 hours by 600 mg of Ra.
Ans. 11.4 cm^3.

4-10. A pure sample of a member of the uranium series has a mass of 2 mg and emits 5×10^9 beta particles per second. Identify the nuclide.

4-11. In a mineral sample presumed to be in equilibrium a chemical analysis gave a U/Ra concentration ratio of 3×10^6. Determine the half life of U^{238} from the known half life of Ra^{226} *Ans.* 4.86×10^9 y.

4-12. Calculate and plot the time course of the growth of Po^{218} from an originally pure sample of Rn^{222}.

4-13. A radon needle is required to have an activity of 50 mc 24 hours after seal-off. What must be the measured activity of this needle at 1 hour after seal-off? *Ans.* 30.6 mc.

4-14. Two hours after seal-off a radon needle was measured as 36.7 mc. It is suspected to be improperly sealed and hence leaking radon. A measurement made 10 hours after seal-off shows 38.1 mc. Is the source leaking, or is it properly sealed?

4-15. A radon needle measures 10.5 mc 2.5 hours after seal-off and is to be implanted 18 hours later. How many hours must the needle be left in position to deliver 500 mch? *Ans.* 52 hours.

4-16. A radon needle has an activity of 55 mc at time of implantation. How many hours will be required to deliver an irradiation of 600 mch?

4-17. A manufacturer of luminous instrument dials formerly used zinc sulphide, ZnS, excited by the alpha particles from Ra^{226}. He desires to replace the Ra^{226} with Po^{210} because of the escape of Rn gas from the paint. If 1 μc of Ra^{226} was required for each dial how much Po^{210} will be required to obtain equal luminosities two years after manufacture? *Ans.* 2.04 μc.

4-18. Ca^{47} (T 4.7d) decays to a radioactive daughter Sc^{47} (T 3.3d). Assume an initially pure sample of 100 mc of Ca^{47} and calculate and plot the time course of the individual and combined activities of the sample.

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5

PHOTON ABSORPTION

5.01 ENERGY TRANSFER PROCESSES

Radiation effects in any substance, living or dead, are the results of large numbers of ionizations and excitations in the constituent atoms. Charged particles such as electrons and alpha particles are *ionizing radiations*, because in their passage through matter they leave a trail of closely spaced ions and excited atoms. Energy transfer from the moving particle to the orbital electrons takes place in small amounts, usually measured in electron volts.

Photons, on the other hand, are a non-ionizing radiation. A photon leaves no trace of its passage through matter until it enters into a cataclysmic event involving a large energy transfer, usually measured in Mev, to one or more electrons. Because of the large energy exchange the electron involved will have a high kinetic energy, and will produce ionizations and excitations until all its energy is expended.

Photons interact with orbital electrons and nuclei in a variety of ways; a complete description of all possible processes is too involved for presentation here. Fortunately only three of the processes make appreciable contributions to the total energy transfer in the usual range of photon energies and only these three need detailed discussion for biological systems. Before describing these mechanisms in detail it is necessary to consider the gross features of attenuation of a photon beam as it passes through matter.

5.02 NARROW-BEAM ABSORPTION

Consider a source of gamma radiation at *A*, Fig. 5-1, with the

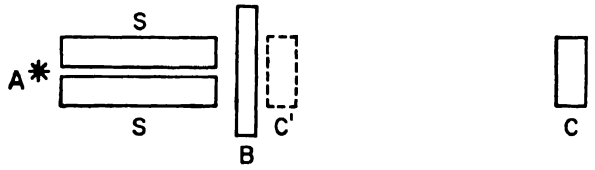


Fig. 5-1. Geometrical arrangement for measuring narrow-beam attenuation. Detector at *C*: good geometry—measures total absorption. Detector at *C'*: poor geometry—measures true absorption

radiation restricted or *collimated* into a *narrow beam* by the lead slits *S*. Assume that the photon beam is *monoenergetic* or *monochromatic*, which is to say that each photon has an equal energy. A gamma-ray detector is located at *C*, a considerable distance away from the slits, and absorbers of known thickness can be placed at *B*, well away from the detector.

An arrangement such as that shown is inefficient in that only a small fraction of the gamma rays pass the slits and enter the detector. The arrangement is, however, said to have *good geometry* because the detector will properly measure the beam intensity as it is attenuated by the absorber.

As we shall see later an absorber at *B* will absorb some energy from the incident beam, and will scatter some photons at all angles. If none of the scattered photons reach the detector it will properly measure the total attenuation of the beam by the absorbers. From these data a factor known as *total-absorption coefficient* can be cal-

culated. With good geometry a negligible amount of scattered energy reaches the detector and conditions for measuring total absorption are fulfilled.

Now imagine a detector placed so as to receive all scattered and transmitted radiation C', Fig. 5-1. Such an arrangement cannot be realized in practice because some of the radiation will be scattered backwards, but an approximation is obtained by putting the detector close behind the absorber. This system has *poor geometry;* measurements made with it lead to the *total true-absorption coefficient.* With idealized poor geometry the detector measures all the beam energy except that deposited directly in the absorber.

Both total absorption and true absorption are important concepts with immediate practical applications. In considering shielding of a photon source one is interested in the total energy removed from the original beam. This is seldom a narrow-beam situation but modified total absorption constants can be used. In calculating the energy delivered to some test object such as an experimental animal or a tumor one is interested in the local deposition of energy and then true absorption constants are involved.

5.03 EXPONENTIAL ABSORPTION

With the good geometry arrangement of Fig. 5-1 let the gamma-ray intensity at the detector be I_0 when there is no absorber in the beam. As used here *intensity* refers to the amount of gamma-ray energy crossing a unit area perpendicular to the beam direction in unit time. Common units of intensity are ergs/cm^2/sec or Mev/cm^2/sec. In the special case of a monoenergetic beam, intensity may be expressed in photons/cm^2/sec.

As absorbers are introduced the intensity at the detector will decrease according to an exponential law:

$$I = I_0 e^{-\mu_x x} \tag{5-1}$$

where I = intensity with absorber thickness x
μ_x = constant.

The *linear-absorption coefficient* μ_x, is a constant for a given absorber material and photon energy but varies with both of these variables

over wide limits. Some computations are more easily made if Eq. (5-1) is written in logarithmic form:

$$\ln I_0 - \ln I = \mu_x x \tag{5-2}$$

$$\ln\left(\frac{I_0}{I}\right) = \mu_x x \tag{5-3}$$

These relations are merely alternate form of Eq. (5-1) and add nothing new beyond convenience of use.

A relation of the type of Eq. (5-1) results from the fact that each thin slab of absorber Δx, removes a *constant fraction* of the radiation incident upon it. The energy, ΔI, taken from the beam by the thin slab can be expressed as

$$\Delta I = -\mu_x I \, \Delta x \tag{5-4}$$

where the minus sign is required since absorption of ΔI acts to reduce I rather than to increase it. Eq. (5-4) can be rearranged to give

$$\mu_x = -\frac{\Delta I/I}{\Delta x} \tag{5-5}$$

If Δx is set equal to unity Eq. (5-5) shows that μ_x is equal to the *fraction* of the beam removed by unit thickness of absorber. If Eq. (5-4) is again rearranged, put in differential form, and integrated one obtains Eq. (5-1).

That absorber thickness $x_{1/2}$ which reduces the beam intensity to one-half of its original value is known as the *half-value layer,* HVL. When $x = x_{1/2}$ $I = I_0/2$ and

$$\ln\left(\frac{1.0}{0.5}\right) = \mu_x x_{1/2} \tag{5-6}$$

and since $\ln 2 = 0.693$

$$x_{1/2} = \frac{0.693}{\mu_x} \tag{5-7}$$

It is evident from Eq. (5-7) that μ_x has the dimensions of a reciprocal length, usually cm^{-1}.

Another useful term is the *mean free path,* x_M, of the photons. Mean free path is defined as the average distance travelled by a photon before it is removed from the beam. By an argument similar to that which led to Eq. (4-6) we get

$$x_M = \frac{1}{\mu_x} \tag{5-8}$$

When the absorber thickness is equal to one mean free path $I = I_0/e$, or about 37 per cent of the original intensity.

5.04 THE ATTENUATION COEFFICIENTS

Linear-absorption coefficients are convenient for calculating shielding thicknesses but for some purposes other coefficients are more useful. To a good approximation, ability to absorb radiation depends only upon the constituents of the absorber and not upon their physical or chemical state. Thus a given mass of hydrogen and oxygen gas will show no change in total absorption after it is burned to form water or frozen into ice, although the three values of μ_x will be quite different.

Because of this independence *mass-absorption coefficient*, μ_m, is a commonly used parameter. Mass-absorption coefficient is defined by

$$\mu_m = \frac{\mu_x}{\varrho} \tag{5-9}$$

where ϱ = density of absorber.

Eq. (5-1) now becomes

$$I = I_0 e^{-\mu_m(x\varrho)} \tag{5-10}$$

where the most usual unit for μ_m is cm²/gram.

Theoretical calculations are frequently made in terms of the absorption per atom of absorber, ${}_A\sigma$. Eq. (5-1) can be written

$$I = I_0 e^{-{}_A\sigma x N} \tag{5-11}$$

where N = atoms per cm³ of absorber
${}_A\sigma$ = atomic cross section for absorption.

All exponents, such as that in Eq. (5-11) must be dimensionless numbers and this requires that ${}_A\sigma$ have the dimensions of an area. Thus ${}_A\sigma$ is a sort of target area for radiation absorption and is called a *cross section*. The usual units are cm².

Another coefficient used in theoretical calculations is the absorption coefficient per electron, ${}_e\sigma$. From the definition we may write

$$I = I_0 e^{-{}_e\sigma NZ.x} \tag{5-12}$$

where Z = atomic number of absorber.

In general an absorber is a complex material instead of a single element and a weighted mean value of Z must be used in Eq. (5-12).

5.05 ABSORPTION COMPONENTS

Numerical values of absorption cross sections are of considerable practical importance since they enter into all calculations of shielding and radiation dosage. These values may be obtained either by direct measurement or from a theoretical treatment of the absorption processes. Many good experimental data are available but there are many gaps where accurate values have not been obtained.

Results of theoretical calculations are in good agreement with experimental results in most cases and it seems desirable to use the mathematical relations wherever they can be applied. The theoretical treatment can be generalized in atomic number and in photon energy and thus complete and self-consistent values of the absorption constants can be obtained.

The "classical" calculation of J. J. Thomson, Eq. (5-13) was based on the idea that an orbital electron was set in oscillatory motion by the electromagnetic field of the primary photon. Energy was absorbed from the field and re-radiated by the electron. This mechanism leads to a "classical" cross section

$${}_e\sigma_0 = \frac{8\pi}{3} \frac{e^4}{m_0{}^2c^4} = 6.65 \times 10^{-25} \text{ cm}^2/\text{electron} \tag{5-13}$$

All symbols in Eq. (5-13) have their usual meaning, with e to be expressed in esu. The simple Thomson model is now known to be inadequate, giving proper results only when essentially zero energy is imparted to the electron. The classical cross section appears, however, as one factor in more sophisticated treatments.

Equation (5-13) is based on a single mode of interaction between photon and electron, and this results in a cross section which is independent of photon energy and atomic number. There are in fact three main absorption mechanisms, each having a unique dependence on $h\nu$ and Z. Direct measurement, as depicted in Fig. 5-1, permits the determination of only the total cross section for all

processes. Collateral measurements must be made to establish the individual contributions of the three components.

5.06 PHOTOELECTRIC ABSORPTION

In photoelectric absorption the incident photon gives up its entire energy to one of the orbital electrons in an absorber atom as in Fig. 5-2(A). Any orbital electron can be involved in photoelectric

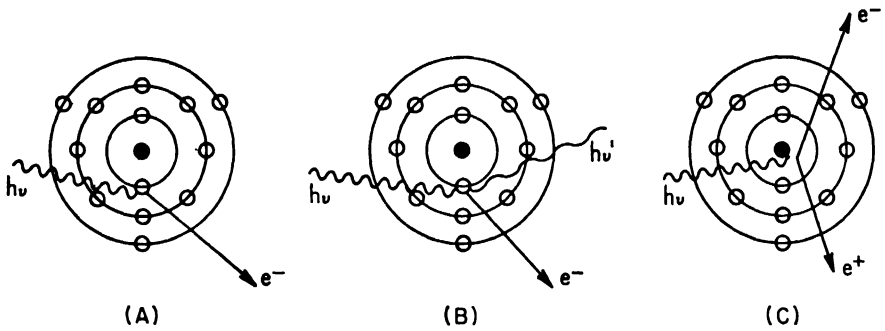


Fig. 5-2. The three chief modes of photon-electron interaction. (A) Photoelectric absorption. (B) Compton scattering. (C) Pair production.

absorption, but interaction with K electrons is most probable. The involved electron will be ejected from the atom with an energy equal to that of the photon, less the energy required to free the electron from its orbital structure. The energy relations are

$$\text{KE} = h\nu - \phi \tag{5-14}$$

where ϕ is the energy binding the electron to its nucleus.

Photoelectric absorption is the most probable process at low photon energies but for the present we must exclude discussion of photon energies only slightly greater than ϕ. When hν is nearly equal to ϕ resonance phenomena cause the absorption to change rapidly with energy; a separate discussion is required, sec. 5.12.

Except at extremely high energies, the range of an electron is much less than the mean free path of a photon of equal energy. The ejected photoelectron will then expend its energy close to its place of origin, and therefore energy imparted to this electron is energy truly given up to the absorber.

After the photoelectron is ejected the absorber atom will emit its characteristic X-ray spectrum as the orbital electron defect is removed. The process is exactly the same as in X-ray emission but now the secondary photons are called *fluorescent radiation* because they are excited by a primary photon instead of a bombarding electron.

In the case of a high atomic number absorber, ϕ is large (88 Kev for lead) and the fluorescent radiation is quite penetrating. The fluorescent radiation gives up its energy at a large distance from its point of origin, which means that energy ϕ cannot be included in the energy of true absorption. Living tissues on the other hand are for the most part composed of low Z elements and here ϕ will be less than 1 Kev. In this case the very soft fluorescent radiation will be absorbed very close to the point of emission, and true energy absorbtion is $KE + \phi$ instead of KE alone. The very fact that ϕ is small in this case makes the distinction of little practical importance.

5.07 PHOTOELECTRIC CROSS SECTION

A complete representation of photoelectric cross section cannot be given in a single mathematical expression. Calculations agree satisfactorily with measurement, however, if the theory is used only in its range of validity.

Photoelectric cross section due to a single K electron has been deduced * as

$$ {}_e\sigma_{PE(K)} = 2\sqrt{2}\ {}_e\sigma_0 \frac{Z^5}{(137)^4}\left(\frac{m_0c^2}{h\nu}\right)^{7/2} \tag{5-15} $$

A factor of 2 will give the cross section due to both K electrons; an additional factor of 1.25 accounts for absorption by L electrons. The effects of screening are taken care of by replacing Z by $(Z - 0.3)$. Finally, it is possible to remove some of the approximations entering into Eq. (5-15) by applying a correction factor S, obtained from Fig. 5-3. With these changes we have

$$ {}_A\sigma_{PE} = 5\sqrt{2}\ \ {}_e\sigma_0\ \ S\frac{(Z - 0.3)^5}{(137)^4}\left(\frac{m_0c^2}{h\nu}\right)^{7/2} \tag{5-16} $$

* Heitler, W. *The Quantum Theory of Radiation*, 2nd ed., 123, Oxford University Press, 1944.

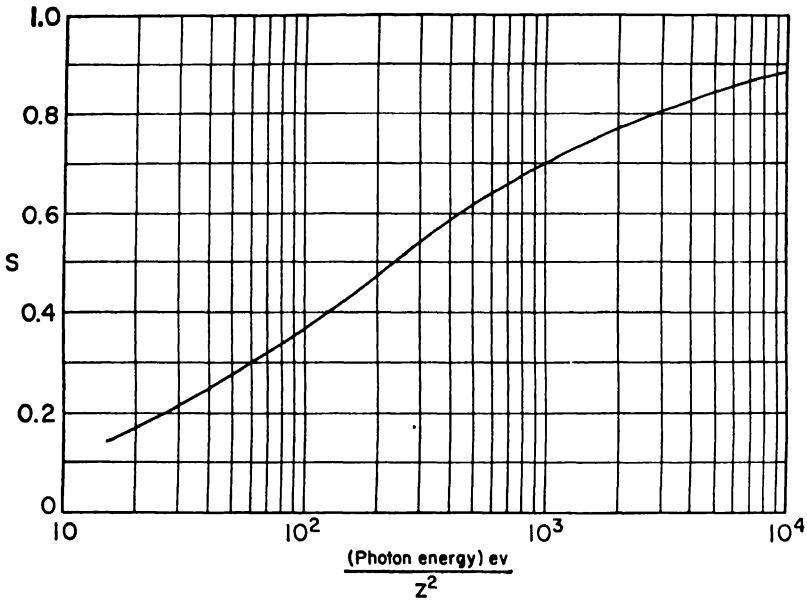


Fig. 5-3. Correction factor for calculation of photoelectric absorption. (Rearranged from page 311 of *Experimental Nuclear Physics*, E. Segre, Ed., Vol. I, Wiley, New York, 1952.)

Equation (5-16) gives an increasingly poor approximation as photon energies increase and relativistic effects in the ejected electron become more important. However, at high photon energies the photoelectric cross section may become negligible compared with other cross sections because of the presence of $(h\nu)^{7/2}$. If this is the case a considerable error in σ_{PE} will have little effect on the overall cross-section calculation.

In high-Z absorbers σ_{PE} may be important even at high photon energies because of the $(Z - 0.3)^5$ term. At the high energies an expression for σ_{PE} originally derived by Sauter * can be used. In biological systems most constituents have low values of Z and σ_{PE} becomes small before high relativistic energies are reached.

The angular distribution of the photoelectrons is given by

$$\Delta N = \frac{\sin^2\theta}{(1 - \beta\cos\theta)^4}\,\Delta\Omega \qquad (5\text{-}17)$$

where ΔN = number of electrons in the small solid angle $\Delta\Omega$ ejected at angle θ to the photon

$\beta = v/c$ for the electron.

* E. Segre, Ed. *Experimental Nuclear Physics*, Vol. I, 310. Wiley, New York, 1953.

At low photon energies β will be small and the second term in the denominator can be neglected. The distribution of electrons is then given by $\sin^2\theta$ which has a maximum at $\theta = 90°$, Fig. 5-4. At higher

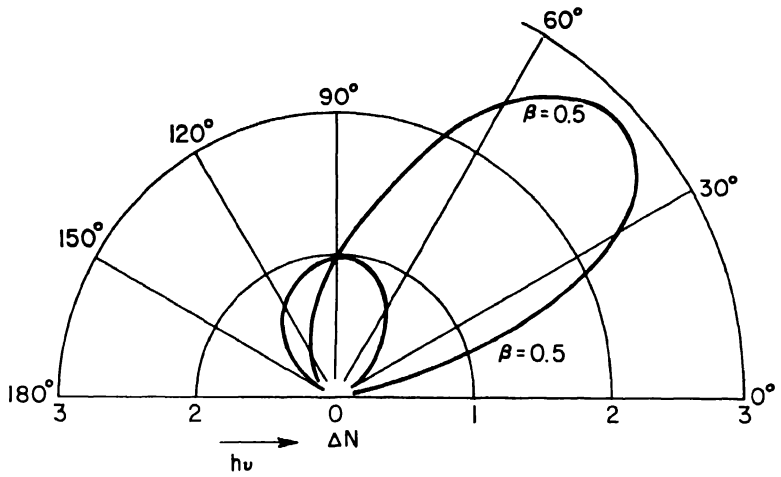


Fig. 5-4. Spacial distribution of ejected photoelectron. The curve for $\beta = 0.5$ was calculated by the non-relativistic relationship but is still a reasonable approximation to the proper distribution.

energies the electrons tend to be emitted in a more sharply defined, forward direction.

5.08 COMPTON SCATTERING

Compton scattering, named after its discoverer, A. H. Compton, becomes important at photon energies where σ_{PE} is falling off because of the $(h\nu)^{-7/2}$ term in Eq. (5-16). In Compton scattering, Fig. 5-2B, a primary photon interacts with an electron to free it, and produce a secondary, scattered photon of lower energy. Figure 5-5 shows the geometrical relations involved.

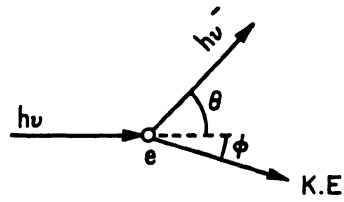


Fig. 5-5. The geometrical relationships in a Compton process.

The Compton process can be described by applying the laws of con-

servation of energy and momentum to the photon-electron collision, using relativistic forms of the laws because of the high energies involved. The resulting expression is

$$\Delta\lambda = \frac{c}{\nu} - \frac{c}{\nu'} = \frac{h}{m_0 c}(1 - \cos\theta) \tag{5-18}$$

where θ is the angle associated with the scattered photon as shown.

Equation (5-18) shows that the energy division between the Compton electron and the scattered photon depends strongly upon the original photon energy. At low energies the scattered photon carries away a large fraction of the available energy; at high energies there is a strong photon degradation.

Illustrative Example

Calculate the energy of an X-ray photon scattered through an angle of 90° for a primary photon of (a) 100 Kev, and (b) 1 Mev.

$$\frac{h}{m_0 c} = \frac{6.6 \times 10^{-27}}{9.1 \times 10^{-28} \times 3 \times 10^{10}}$$
$$= 2.42 \times 10^{-10} \text{ cm} = 0.0242 \text{ A}$$

This is known as the Compton wavelength, since it is a common factor to be multiplied by the proper cosine term. For 90° scattering $\cos\theta = 0$ and

(a)

$$\lambda = \frac{12.4}{100} = 0.124 \text{ A}$$
$$\lambda' = 0.124 + 0.0242 = 0.148 \text{ A}$$
$$E' = \frac{12.4}{0.148} = 83.6 \text{ Kev}$$

(b)

$$\lambda = \frac{12.4}{1000} = 0.0124 \text{ A}$$
$$\lambda' = 0.0124 + 0.0242 = 0.0366 \text{ A}$$
$$E' = \frac{12.4}{0.0366} = 339 \text{ Kev}$$

Equation (5-18) gives the energy relations in a Compton collision but says nothing about the probability for scattering into various values of θ. This probability is an important function since from it one can obtain the cross sections by integration. The proper probability functions were derived by Klein and Nishina * using quan-

* Klein, O., and Y. Nishina. *A. f. Physik* **52**, 853, 1929.

tum mechanical concepts of the interaction process. The Klein-Nishina equations are among the earliest and most completely verified results of quantum mechanics.

The cross section for scattering photons into a small solid angle $d\Omega$ at angle θ to the original beam is

$$d_e\sigma_{CT} = \frac{3\sigma_0}{16\pi} \frac{1}{[1 + \alpha(1 - \cos\theta)]^2}\left(1 + \cos^2\theta + \frac{\alpha^2(1 - \cos\theta)^2}{1 + \alpha(1 - \cos\theta)}\right) d\Omega \quad \textbf{(5-19)}$$

where $\alpha = h\nu/m_0c^2$. The differential cross section must have the subscript e, since the original calculation was based on a single scattering electron. It must also have the subscript T, for total absorption, since Eq. (5-19) gives the probability for the removal of photons from the beam into angle θ.

If, now, the probability for photon removal is multiplied by the energy carried off by each scattered photon, one obtains a new differential cross section for the *energy* scattered into a small solid angle $d\Omega$ at angle θ. This is

$$d_e\sigma_{CS} = \frac{3\sigma_0}{16\pi} \frac{1}{[1 + \alpha(1 - \cos\theta)]^3}\left[1 + \cos^2\theta + \frac{\alpha^2(1 - \cos\theta)^2}{1 + \alpha(1 - \cos\theta)}\right] d\Omega \quad \textbf{(5-20)}$$

since $$\frac{h\nu'}{h\nu} = \frac{1}{1 + \alpha(1 - \cos\theta)}$$

The differential cross section in Eq. (5-20) must have the subscript S, since this relation gives the energy removed from the beam and scattered into angle θ.

Figure 5-6 shows the angular distribution of scattered energy for several photon energies. At low energies the distribution is symmetrical about 90 degrees but at higher energies forward scattering predominates and in the betatron region (20 Mev) the beam becomes relatively sharp in the forward direction.

5.09 COMPTON CROSS SECTIONS

When Eq. (5-19) is integrated over all possible values of θ an expression for the total probability of *photon removal* is obtained. This is

$${}_e\sigma_{CT} = \frac{3\sigma_0}{4\alpha^2}\left[\frac{2 + 8\alpha + 9\alpha^2 + \alpha^3}{(1 + 2\alpha)^3} - \frac{2 + 2\alpha - \alpha^2}{2\alpha} \ln (1 + 2\alpha)\right] \quad \textbf{(5-21)}$$

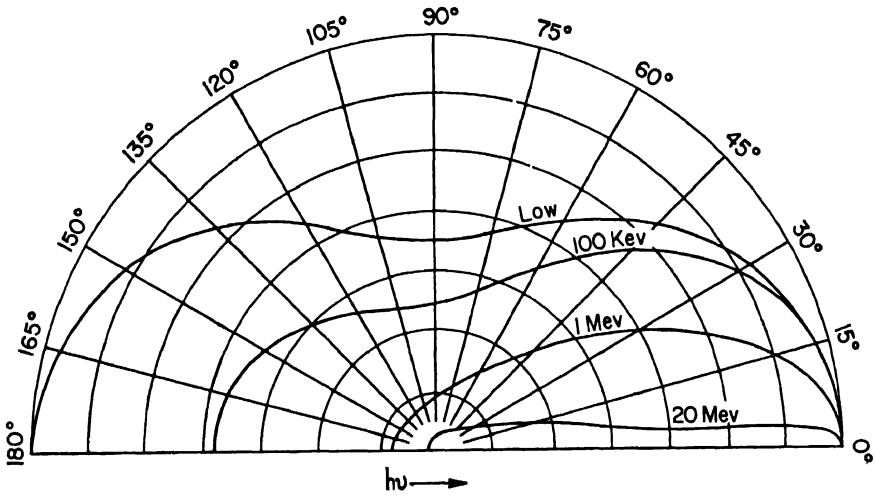


Fig. 5-6. Angular distribution of Compton scattered photon energy

Similarly an integration of Eq. (5-20) gives an expression for the probability of *energy removal* by Compton scattering. This is

$$_e\sigma_{CS} = \frac{3\sigma_0}{4\alpha^2}\left[-\frac{3 + 15\alpha + 18\alpha^2 - 6\alpha^3 - 16\alpha^4}{3(1 + 2\alpha)^3} + \frac{1}{2\alpha} \ln (1 + 2\alpha)\right] \quad (5\text{-}22)$$

The difference between the two integrated equations will give the cross section for *true* energy deposition in the absorber because of Compton processes. This is

$$_e\sigma_{Ca} = \frac{3\sigma_0}{4\alpha^2}\left[\frac{9 + 51\alpha + 93\alpha^2 + 51\alpha^3 - 10\alpha^4}{3(1 + 2\alpha)^3} - \frac{3 + 2\alpha - \alpha^2}{2\alpha} \ln (1 + 2\alpha)\right] \quad (5\text{-}23)$$

These three equations look formidable but actually are not. Care is required to avoid numerical errors but application is perfectly straightforward. Figure 5-7 shows a plot of the three coefficients as a function of photon energy.

In using the Klein-Nishina expressions for Compton cross sections it is not necessary to distinguish between electrons in different shells of the absorber. Compton scattering becomes important at photon energies which are high compared even to that binding the *K* electrons to the nucleus. All electrons are essentially free and no distinction need be made between them.

Numerical values obtained from Eqs. (5-21 to 5-23) will be expressed in cm^2 per electron, Values of μ_r and μ_m are obtained by

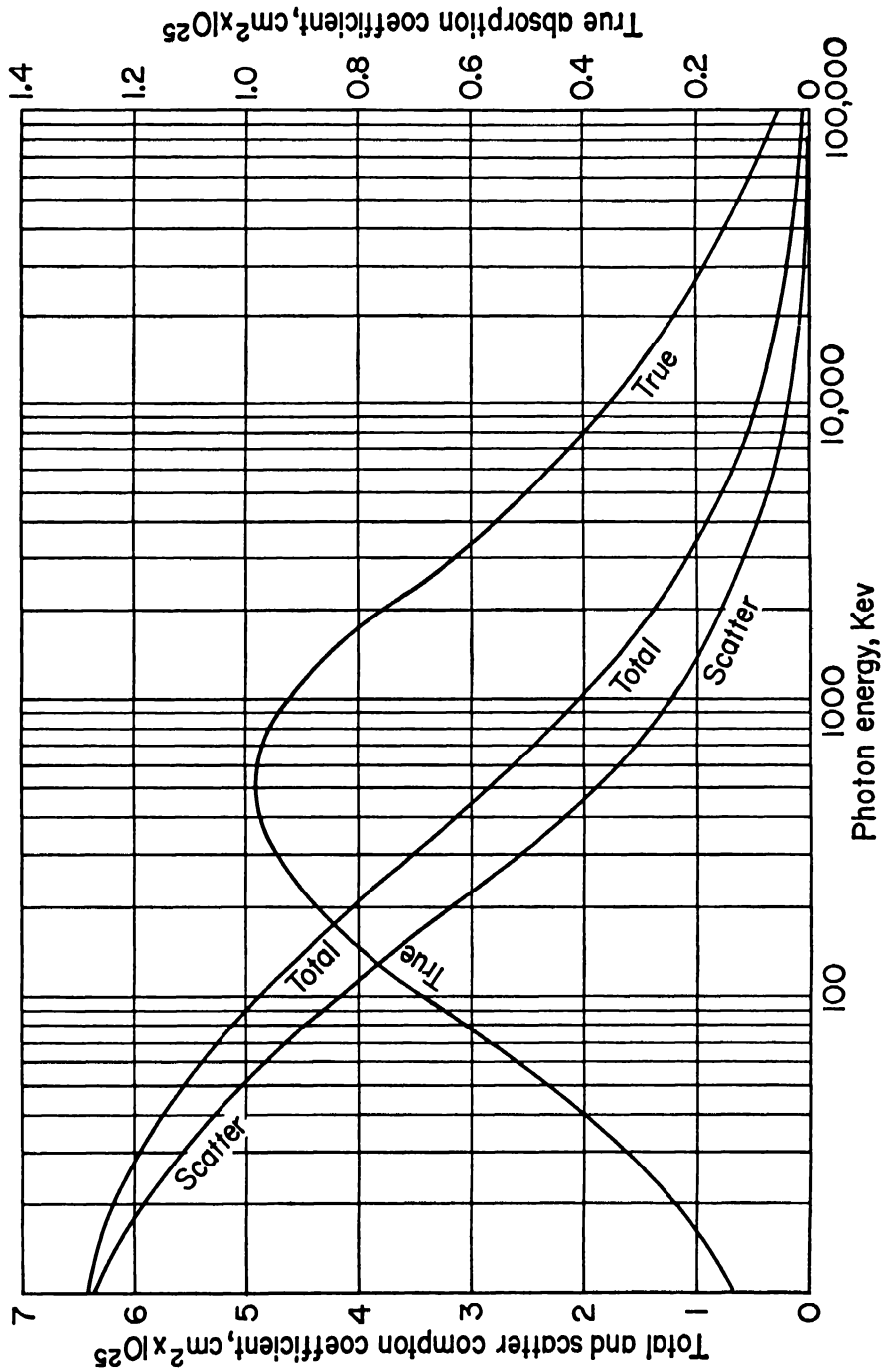


Fig. 5-7. The three Compton cross sections as a function of photon energy.

multiplying the cross sections by the number of electrons per cm^3 or per gm, respectively.

5.10 PAIR PRODUCTION

An entirely new absorption process takes place at photon energies greater than 1.02 Mev. Here, a photon can interact with an atomic nucleus and give up all its energy in the process of *creating* a negative electron-positive electron pair, Fig. 5-2C. The interaction actually creates the two electrons and therefore pair production must have a threshold equal to the energy equivalence of the two created masses, which is 1.02 Mev. Any photon energy above the threshold goes into kinetic energy of the electrons, with the positron receiving slightly more than the negatron. The created electrons tend to move off in the direction of the photon, a tendency which becomes more pronounced at high photon energies.

As the negatron proceeds it loses energy to ionizations and excitations and is eventually captured to become an orbital electron. The positron loses energy by the same processes but meets a quite different eventual fate. When most, or all of the positron energy is lost, it will combine with a negative electron to produce two oppositely directed gamma rays, each having an energy of 0.51 Mev. These gamma rays are called *annihilation radiation* since the negatron-positron pair disappears in the process.

The theory of pair production is well understood but the results are not expressible in simple mathematical forms. Cross sections are low just above 1.02 Mev and increase to a maximum value at higher photon energies. Except at high atomic numbers and high photon energies the cross section varies nearly as Z^2.

For most situations of biological interest cross sections for pair production can be calculated from Fig. 5-8. Ordinates given in Fig. 5-8 are to be multiplied by

$$\frac{3\sigma_0 Z^2}{8\pi \times 137} = 5.79 \times 10^{-28}\ Z^2 \qquad (5\text{-}24)$$

to obtain the cross section per atom ${}_A\sigma_{PP}$. Linear or mass absorption coefficients are then obtained by muliplying these cross sections by the number of atoms per cm^3 or per gram, respectively.

Pair-production cross sections are based on the probabilities of

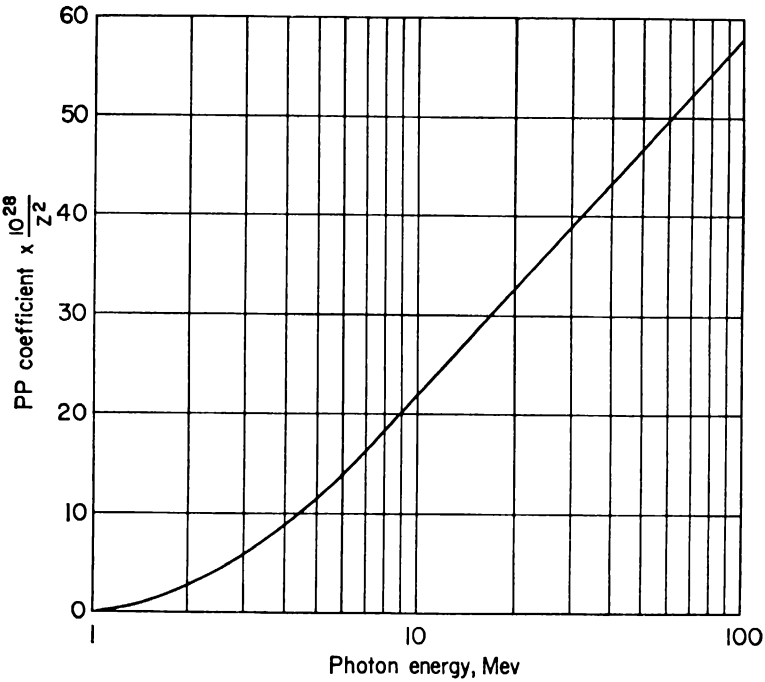


Fig. 5-8. Pair-production cross section as a function of photon energy and atomic number of absorber.

photon-nucleus interactions and so give values for the removal of energy from the beam. This removal will be greater than the deposition of energy in the absorber since each pair production process requires 1.02 Mev for the production of the electron masses. Thus the pair-production cross section for true absorption is obtained by multiplying the value calculated from Fig. 5-8 by

$$\frac{h\nu - 1.02}{h\nu} \tag{5-25}$$

where $h\nu$ must be expressed in Mev. In either case the calculated cross section will be an atomic cross section, ${}_A\sigma$, because of the presence of the Z^2 factor in Eq. (5-24).

5.11 COMBINED ABSORPTION

In general, all three absorption mechanisms are simultaneously operating, the relative importance varying with photon energy and

atomic number. Since each absorption process obeys a relation similar to Eq. (5-4) the combined cross section will be the sum of the three component cross sections.

There will be two relations, one corresponding to energy removal and one for energy deposition. The first is

$$_A\sigma_T = {}_A\sigma_{PE} + Z_e\sigma_{CT} + {}_A\sigma_{PP} \tag{5-26}$$

From Eq. (5-26) values of μ_x and μ_m can be readily obtained for calculating the attenuation of the primary photon beam.

The expression for true energy absorption is

$$_A\sigma_a = {}_A\sigma_{PE} + Z_e\sigma_{Ca} + {}_A\sigma_{PP}\left(\frac{h\nu - 1.02}{h\nu}\right) \tag{5-27}$$

and again the corresponding absorption coefficients are readily calculated by multiplying the cross section per atom by the number of absorbing atoms per centimeter or per gram.

It must be remembered that all the relations given above apply strictly only to narrow-beam situations. In a broad beam there may be an appreciable absorption of Compton scattered photons within the beam, and thus the energy deposited will be greater than that calculated by Eq. (5-27). Radiation hazards arise more frequently under broad-beam conditions (see the Appendix).

Other absorption processes are known and if necessary can be taken into account by adding the appropriate cross sections to either Eq. (5-26) or (5-27). One of these less important processes is *coherent scattering*, described in sec. 1.03. In coherent scattering some geometrically regular structure is required so that the scattered photons can reinforce and deliver energy in certain definite directions. Compton scattering, on the other hand, is *incoherent* since each event is unique and independent of other scattering events. In most biological systems there is little material having the regular structure of a crystal lattice and so here the cross section for coherent scattering is small in comparison with the three main cross sections.

Another process omitted in Eqs. (5-26) and (5-27) becomes increasingly important at high photon energies. Instead of interacting with an orbital electron a photon may initiate a nuclear reaction (γ, n) by entering a nucleus and ejecting a neutron from it. At low photon energies the cross section for a (γ, n) process is vanishingly small but at about 20 Mev the reaction becomes sufficiently probable to provide a useful method for generating neutrons. A (γ, n) reaction

cross section has been omitted from the combined equations because at energies where these processes become appreciable, other complications enter the cross-section calculation. For example, at high energies the range of the Compton electrons becomes comparable to the mean free path of the photons, and thus our assumption of local energy deposition is no longer valid.

5.12 ABSORPTION EDGES

In the infra-red, visible, and ultra-violet regions an atom or molecule absorbs preferentially exactly those photon energies which it emits upon suitable excitation. By analogy one might expect a considerable increase in X-ray absorption when the incident photons have energies equal to those of the K, L, . . . emission lines of the absorber. Failure to observe this resonance type of absorption can be explained in terms of the mechanism of X-ray production and the Pauli Principle.

Consider an absorber with monoenergetic photons incident upon it and initially let these photons have an energy well below that of the L emission lines. At this energy the absorption cross section will be large because of photoelectric and Compton processes. As the photon energy is increased the absorption cross section decreases and is low even at the energies of L emission.

To understand this lack of L shell absorption recall that an L_α line is emitted when an M electron drops into a vacancy in the L shell. The inverse, or absorption process, would require that an L electron be raised into an M shell vacancy. In general there will be no vacancy in the M shell and therefore by the Pauli Principle the inverse process cannot take place. L electrons, therefore, become involved in absorption only when they can be completely ejected from the atom by the incident photons. At this energy, which is of course greater than that of L emission, a sharp increase in absorption would be expected, and is observed. This energy is known as the L *absorption edge.*

As photon energies increase above the L edge, absorption cross section decreases in accordance with the usual photoelectric and Compton mechanisms. When the photons have sufficient energy to remove K electrons there will be another sharp increase in absorption at the K absorption edge. Above the K edge absorption cross

sections decrease smoothly as photon energies increase, Fig. 5-9. *M* and even higher order absorption edges are known, but in general these occur at such low energies that detection is difficult.

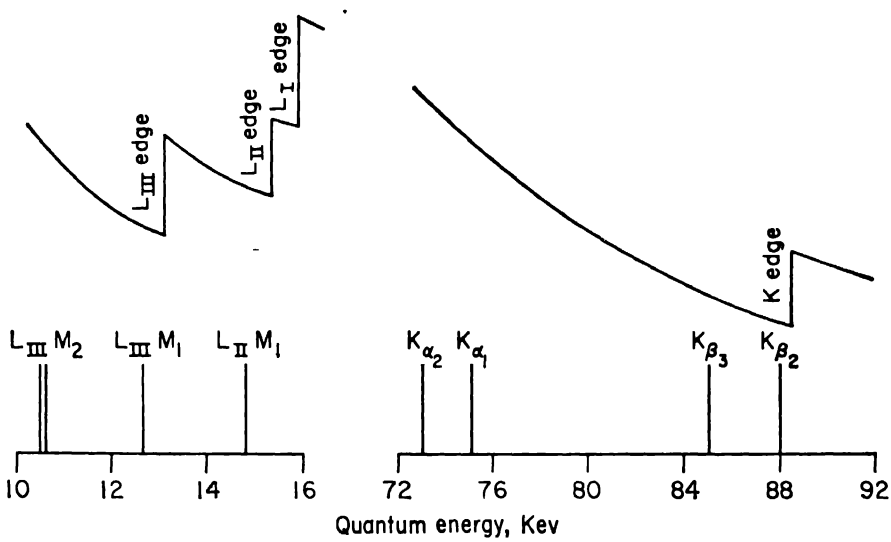


Fig. 5-9. The X-ray emission and absorption frequencies of lead. Note that the *L* edge is deep enough to show up several sub-levels in the *M* shell.

The sharp change in absorption at an edge can be used to isolate a narrow energy band from a broad X-ray emission spectrum. A *Ross filter* consists of two absorbers composed of elements of nearly adjacent atomic number. By carefully adjusting the thicknesses, absorption at energies away from the absorption edges can be equalized in the two components. Measurements made with first one component and then the other will differ only by the effect of the narrow band between the two edges.

A common Ross filter has a $_{38}$Sr component (*K* edge 0.768 A) and a $_{40}$Zr component (*K* edge 0.687 A). The differential transmission of this combination will be the band 0.687—0.768 A. In particular this band includes the K_α emission line of Mo at 0.712 A. Mo is a very satisfactory target material and in combination with an Sr-Zr filter provides an intense narrow-energy band of X-radiation.

A higher degree of energy selection can be achieved by utilizing an X-ray beam diffracted from a crystal. The diffracted beam has a low intensity and can only be used for special purposes.

5.13 FLUORESCENT RADIATION

After an absorbed photon has ejected an orbital electron, a series of characteristic X-ray lines will be emitted as the electron defect is filled from outer orbits. This *fluorescent radiation* is not accompanied by a continuous spectrum, as are X-rays produced by electron excitation, since there are no decelerated charged particles involved. Fluorescent radiation is poorly absorbed by the absorber itself since the emissions lie just outside the absorption edges. An element of atomic number lower than that of the fluorescent emitter will, however, absorb effectively, and this fact is used in filters designed to harden X-ray beams.

As a practical example consider the hardening of a beam produced by an X-ray tube operated at 200 kvp. As generated this beam will have a large component of low-energy photons which will be strongly absorbed in the superficial layers of an irradiated object. Usually this superficial dose is undesirable and filters are used to reduce it.

A filter of copper 0.2–0.5 mm thick will effectively remove the soft components of the beam by photoelectric absorption, and will produce a much smaller loss of the high-energy portion. The absorption process produces a strong copper fluorescent radiation, however, so there is little beam hardening by a copper filter alone. A second filter of 0.2–0.5 mm aluminum will strongly absorb the copper fluorescence with little attenuation of the remaining primary beam. If aluminum fluorescent radiation is troublesome it can be removed by a carbon absorber, which usually consists of a sheet of bakelite. The same principles of beam hardening are applied at higher initial photon energies where the first filter would be either tin or lead.

To be effective the individual components of a beam-hardening filter must be in the proper sequence. Any reversal of the Cu-Al-C order would seriously reduce the absorbing effectiveness of the combination.

Some of the fluorescent radiation will be absorbed in the fluorescing atom before the photon escapes, to produce low-energy electrons known as *Auger* electrons after the discoverer of the effect. In the example cited above, absorption of a primary photon might eject

a K electron from a copper atom. When this defect is filled from the L shell a copper K_α photon will be emitted. This photon may leave the emitting atom and be absorbed in the aluminum filter, or it may be absorbed in the $L, M, \ldots$ levels of the emitting atom itself. Auger electrons ejected from these shells will have low energies because only K_α energy is available, and $L, M, \ldots$ binding energy must be supplied from this.

5.14 EFFECTIVE ENERGY

In practice, photon beams are seldom monoenergetic and even if initially so are rapidly made heteroenergetic by Compton scattered and fluorescent photons. Absorption processes tend to harden the beam because of the preferential absorption of the lower-energy components. Compton scattering and fluorescent emission tend to soften the beam by introducing low-energy photons and the combined effect in a thick absorber is a softening rather than a hardening.

Since absorption cross sections vary with photon energy a linear (log intensity) depth relation would not be expected for a heteroenergetic beam. In fact, the cross sections vary slowly with energy in some regions so that in many experimental situations a reasonably good semilogarithmic relation is obtained from a heteroenergetic beam.

In this situation an absorption coefficient can be calculated from the slope of the log-intensity-depth curve. From tabulated values a single photon energy can be found having the same absorption coefficient as that of the complex beam, and this single energy is the *equivalent energy* of the beam.

The concept of effective energy is a useful one for describing the hardness of a photon beam. It must not be used indiscriminately because in many respects the monoenergetic and heteroenergetic beams may not be equivalent.

5.15 ABSORPTION COEFFICIENTS

The mathematical expressions given in this chapter permit the calculation of total and true absorption coefficients over a wide range of photon energies. Extensive tabulations of these coefficients have

been made * for many pertinent elements. For many purposes absorption coefficients can be obtained with sufficient accuracy from plotted values, Fig. 5-10.

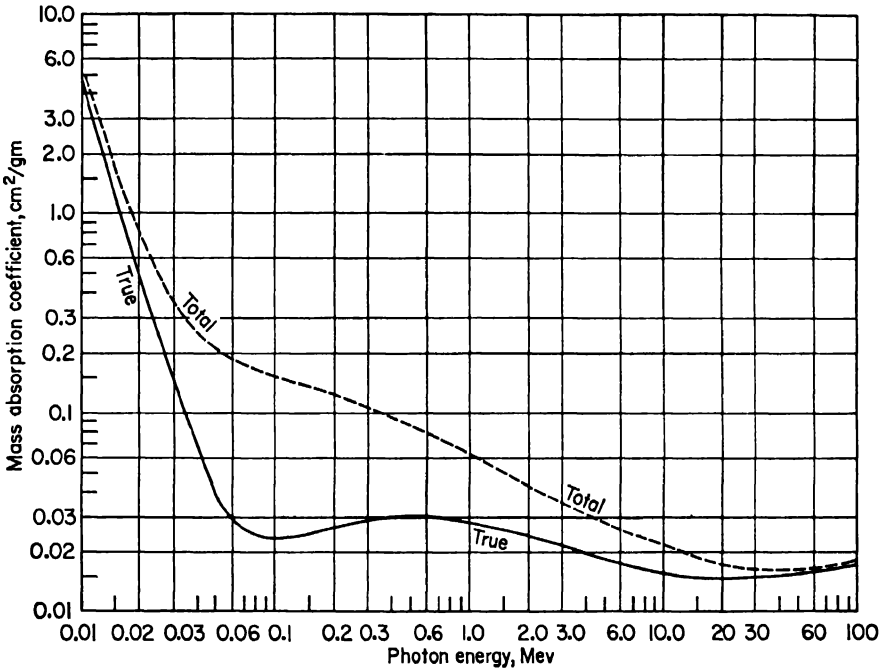


Fig. 5-10. Total and true mass absorption coefficients for air.

Values of total and true mass-absorption coefficients shown in Fig. 5-10 were calculated for a composition of 78 per cent N_2, 21 per cent O_2, and 1 per cent A. Each of these elements has a low atomic number and hence all absorption edges lie at energies below the plotted range. Note that the true absorption curve is quite flat for an energy range of 0.06–2.0 Mev, a fact of considerable importance in the use of ionization chambers for radiation measurements.

Figure 5-11 shows the true mass-absorption coefficients of water, (a good approximation to muscle) fat, and bone. The curve for fat was calculated for a composition of CH_2. Bone composition was taken as 30 per cent H_2O, 30 per cent C, and 40 per cent inorganic matter. The latter was calculated as 23 per cent Ca, 15 per cent P, and 62 per cent O.

* Hine, G. J., and G. L. Brownell, Eds. *Radiation Dosimetry*. Academic Press, New York, 1956.

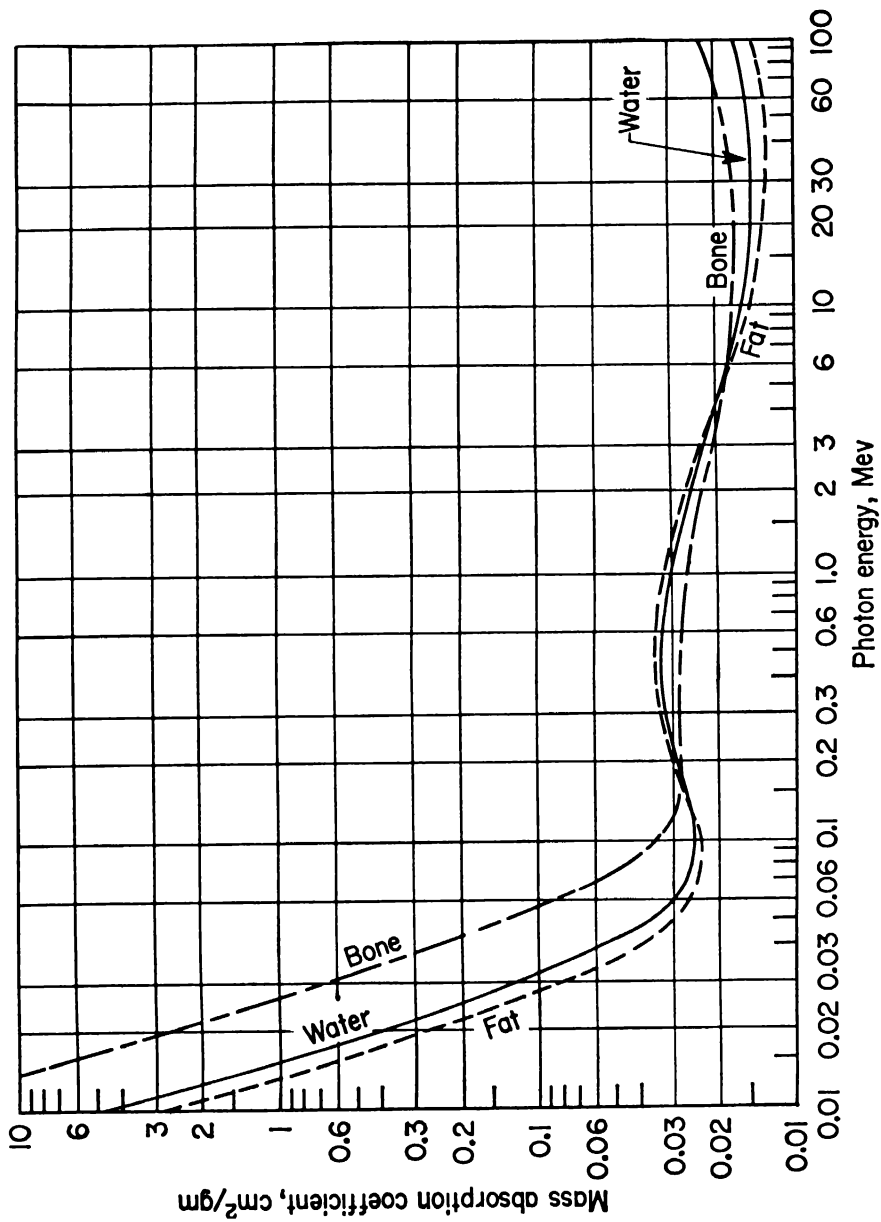


Fig. 5-11. True absorption coefficients for water, fat, and bone.

The curve for bone shows the effect of moderately high atomic-number elements on the absorption coefficients. The presence of Ca and P raises the absorption at both low and high photon energies, but has little effect in the mid-energy range.

Differential values of absorption coefficients are essential if internal structures are to be visualized by X-ray fluoroscopy or radiography. From Fig. 5-11 it is evident that bone can best be visualized at photon energies below 100 Kev. Fat and muscle will show little contrast at any energy. Because of the relatively small differences in absorption coefficients, *contrast media*, which contain high atomic number elements, are used wherever possible to display body cavities.

Some medical visualizations can be made to advantage at 1–2 Mev, where the absorption coefficients for bone, soft tissue, and air are nearly identical. At these energies the equal absorptions greatly reduce the interference from the bony structures which are usually seen at lower photon energies. Contrast differences result, then, from differences in density rather than from differences in absorption.

Modern electronics offers considerable promise to medical radiology by increasing the contrast of X-ray images produced on fluorescent screens. Using techniques adapted from the television industry, an *image intensifier* can be set to examine any desired limited range of contrast and expand it to the full contrast of the television screen. This method results in improved visualization at a reduced radiation dose to the patient.

5.16 INDUSTRIAL RADIOGRAPHY

High-energy photons are routinely used in the examination of a variety of metal products for hidden flaws. Castings, for example, can be examined for voids with photons in the 1–2 Mev range. Most metals have a z value considerably greater than that for air and will have correspondingly greater values of μ_m. Contrast is achieved by differences in both μ_m and ϱ.

High energies are required to obtain the penetration needed for the examination of thick sections. Multi-curie sources of Ra^{226} or Co^{60} have been used, as well as X-ray tubes activated by resonant transformers or Van de Graaff generators.

Since a radiograph is essentially a type of pin-hole photograph, good resolution requires the use of the (geometrically) smallest possible source. Sizes in radioactive sources are limited by the available specific activities. X-ray generators can incorporate adjustable magnetic fields for focusing the electron beam to produce a very small focal spot on the anode.

PROBLEMS

5-1. What thickness of lead is required to reduce the intensity of a 1 Mev gamma-ray beam by a factor of 500? Linear coefficient of absorption for lead at 1 Mev 0.791 cm^{-1}. *Ans.* 7.85 cm.

5-2. What additional thickness of lead is required to reduce the gamma-ray intensity in Prob. 5-1 by an additional factor of 10?

5-3. The linear attenuation coefficient of air for 2 Mev photons is 0.000030 cm^{-1}. Calculate the half-value layer and the mean free path for these photons. *Ans.* 231 meters, 333 meters.

5-4. An X-ray unit operating at an effective energy of 100 Kev has been adequately shielded with 15 cm of concrete (μ_m = 0.170 cm^2/gm). The unit is to be replaced by another having a photon beam with 1.5 Mev effective energy. How much additional concrete (μ_m = 0.0519 cm^2/gm) will be required to obtain a beam attenuation equal to the original?

5-5. The following readings were taken with an arrangement similar to that of Fig. 5-1. Intensity figures are given in arbitrary units.

Absorber thickness, cm	0.0	0.1	0.2	0.3	0.4	0.6	0.8	1.0	1.2	1.4
Intensity	152	143	133	125	112	97	89	75	66	58

Plot these data and calculate half-value layer and mass-absorption coefficient of the iron absorber for density 7.8 gm/cm^3.
Ans. HVL 1.02 cm, μ_m = 0.087 cm^2/gm.

5-6. The following data were taken with lead absorbers using an arrangement similar to that of Fig. 5-1.

gm/cm^2	0.0	1.0	2.0	3.0	4.0	5.0	6.0	8.0
Intensity	210	200	185	185	178	163	155	142

Plot the absorption curve and determine the effective energy of the X-ray beam.

5-7. The K electrons in lead are bound with an energy of 88.2 Kev. Calculate the energy of a photoelectron ejected from the K shell in lead by a gamma ray of wavelength 0.0127 A. *Ans.* 887.8 Kev.

5-8. The K absorption edge of tin is located at 0.4239 A. Calculate the energy of an electron ejected from the K shell of tin by a 1.17 Mev gamma ray from radioactive Co^{60}.

5-9. Assume a monoenergetic beam of 0.100 Mev photons scattered by a copper filter. Calculate the energy of the scattered photons as a function of scattering angle, determining enough points so that a curve of energy against angle can be plotted.

5-10. Repeat the calculations and plot of Prob. 5-9, assuming 2 Mev photons.

5-11. Calculate the energy range of the Compton electrons produced by the scattering of 1.5 Mev gamma rays. *Ans.* 0.0 to 1.28 Mev.

5-12. Show that the energy imparted to a Compton electron, in usual notation is

$$E = \frac{(h\nu)^2(1 - \cos\phi)}{m_0c^2 + h\nu(1 - \cos\phi)}$$

5-13. Radioactive sodium, Na^{24}, emits 2.758 Mev gamma rays. Calculate the velocity of the electrons produced from one of these gamma rays by pair production, assuming the available energy to be equally divided between the electrons. *Ans.* 2.79×10^{10} cm/sec.

5-14. A 10-Mev photon from a betatron suffers Compton scattering through 90 degrees and the scattered photon is then absorbed by pair production. Assume an equal negatron-positron energy and calculate the energies of the three ejected electrons.

5-15. Calculate the half-value layer and mean free path for 0.60 Mev photons in air of density 0.00129 gms/cm^3.

Ans. 29.1 meters, 42.0 meters.

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6

PHOTON DOSIMETRY

6.01 ELECTRON RANGE

As we have seen, photons are non-ionizing and produce no direct effect upon the matter through which they pass. All the important mechanisms by which photons are absorbed lead to the production of free, high-speed electrons, which interact strongly with the electric charges in the absorbing medium. In general an electron will lose energy at each interaction and will be deflected from its previous course. The tortuous path traversed by the electron is marked by a trail of ions and excited atoms and molecules.

Unlike a photon an electron has a definite path length which depends upon the original particle energy. At each ionization or excitation the electron slows down until finally, at a very low energy, it is captured and incorporated into some neutral atom or molecule. Because of the devious path followed by the electron, *path length,* or total distance travelled before capture, must be distinguished

from *range*, which is the linear distance from point of origin to point of capture. The range is roughly 70 per cent of the path length.

To a good approximation, the range of an electron is independent of the atomic number and the chemical and physical state of the material through which it passes. Since range depends almost entirely on the mass of material traversed it is convenient to express range, R, in mg/cm^2 or gm/cm^2. For energies above about 0.8 Mev an empirical expression developed by Glendennin and Coryell can be used to relate range and energy.

$$R = 0.540\,E - 0.103 \qquad \textbf{(6-1)}$$

where R = range in gm/cm^2
E = energy in Mev.

At low energies the linear relationship between E and R no longer holds and a curve plotted from experimental data must be used, Fig. 6-1.

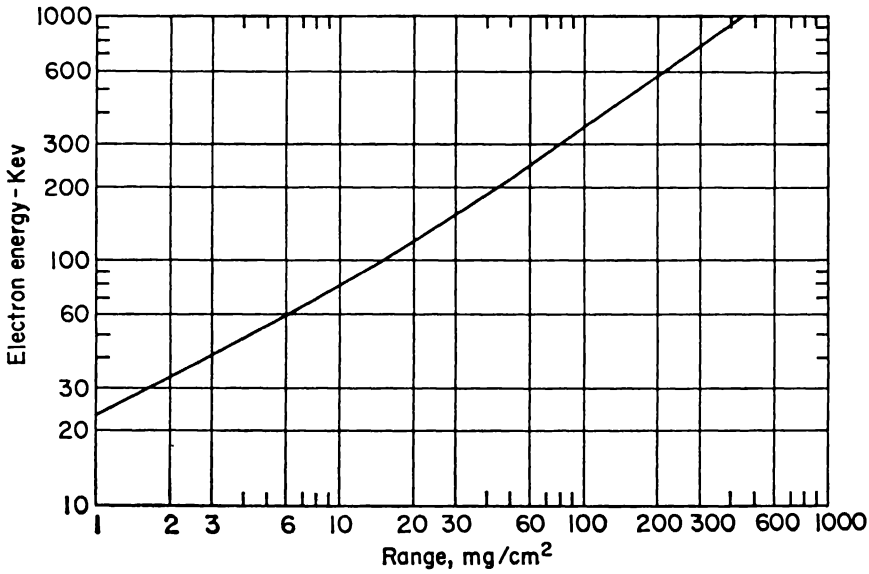


Fig. 6-1. Range of electrons at low energies.

From Eq. (6-1) we see that at the more commonly encountered energies electrons expend their energy relatively close to the point of origin, although on a cellular scale the range is rather long. Thus a 1 Mev electron has a range in tissue of about 4 mm.

6.02 ROENTGEN AND RAD

Prior to 1928 a number of rather ill-defined dosage units were in vogue, resulting in uncertainties which make much of the older literature meaningless. This confusion began to disappear in 1928 with the definition and acceptance of the *roentgen, or* r, as the unit of photon dosage. The roentgen served a very useful purpose for many years but became inadequate as energy ranges were extended and beams of high-speed particles became available from accelerators and nuclear reactions. Two basic dosage units were adopted by the Eighth International Congress of Radiology in 1956 to meet the complexities resulting from the newer radiations.

1. *Exposure dose* of X- or gamma radiation at a given place is a measure of the radiation flux based upon its ability to produce ionization at that place. The unit of exposure dose of X- or gamma radiation is the *roentgen,* r. One roentgen is that quantity of X- or γ radiation such that the associated corpuscular emission (electrons and ions) per 0.001293 gm of air produces, in air, ions carrying 1 electrostatic unit of charge of either sign. At 0° C and 760 mm pressure (NTP) 0.001293 gm is the mass of air in a volume of 1 cm^3.

2. *Absorbed dose* of any ionizing radiation is the energy imparted by ionizing particles to a unit mass of material at the point of interest. The unit of absorbed dose is the *rad*, which is the deposition of 100 ergs per gram.

These two units are basic to all radiation measurements; the differences between them must be clearly understood. In the definition of the roentgen a standard absorbing substance is specified, so exposure dose is a characteristic of the radiation beam and not of an absorber. Since ionization is specified in the definition, exposure dose can be measured directly in electrical quantities.

A standard material is *not* specified in the definition of the rad and the number of rad absorbed from a given radiation beam will depend upon the exposed material. In a photon beam of fixed quality, for example, the roentgen–rad relationship is determined by the relative values of the true absorption cross section in air and in the substance of interest.

A direct measurement of absorbed dose cannot be made by purely electrical methods since some absorbed energy is degraded into forms having no electrical manifestations. Direct measurement

of absorbed dose requires a calorimeter and the use of more refined techniques than are needed for measuring ionization.

The most commonly used multiples are the *milliroentgen,* mr, and the *millirad,* mrad. Occasionally the *kiloroentgen,* kr, and the *megaroentgen,* Mr, are used. Both r and rad are quantities and not rates, but the latter are frequently used, as r per day or mrad per hour.

6.03 STANDARD AIR CHAMBER

The roentgen can perhaps be best appreciated in terms of the instrument designed to measure it. A *standard air chamber,* Fig. 6-2,

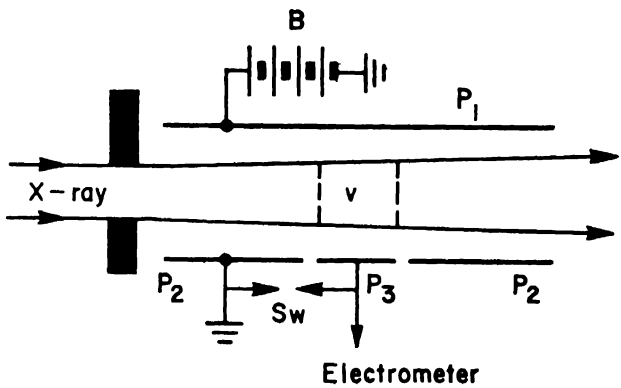


Fig. 6-2. Schematic arrangement of a standard air chamber for determining photon-exposure doses in roentgens.

consists essentially of three charge-collecting electrodes P_1, P_2, P_3. A battery B maintains a potential difference between P_1 and P_2 and P_3 so that positive ions formed by the radiation will be attracted to P_1, negative particles to P_2 and P_3. Only the charge collected by P_3 is measured. P_2 is maintained at a potential as close to that of P_3 as possible to serve as a *guard ring* and to maintain an undistorted electric field in the chamber.

A photon beam, collimated with lead slits, produces ionization in the air along its path. All the negative ions formed in the small volume v can be collected on P_3 and measured by an electrometer. Some of the ionization in v will be produced by electrons originating

outside and conversely some electrons originating in v will produce ionization elsewhere. In a properly designed chamber these two effects will exactly balance and the charge collected by P_3 can be attributed to the calculable volume v.

If the definition of the roentgen is to be fulfilled, the electrons resulting from photon absorption must expend all their energy in the air, and must not strike any of the metal parts of the chamber. This requirement fixes minimum chamber dimensions which depend upon the photon energy to be measured. A 100 Kev electron has a range of about 15 mg/cm^2, which corresponds to $0.015/0.001293 = 11.6$ cm range in air. Thus a standard air chamber is unwieldy even at 100 Kev, and becomes correspondingly cumbersome at higher energies.

To measure exposure dose properly, all the negative (or positive) ions formed in v must be collected. With a low battery voltage the ions will move slowly toward the respective collecting electrodes and an appreciable *recombination* into neutral atoms will take place. As the collecting voltage is raised the charged particles will reach the electrodes more quickly, recombination will be reduced, and the ion current measured from a given beam will be greater than before.

With a constant-intensity photon beam a plot of charge collected as a function of chamber voltage appears as in Fig. 6-3. At point S

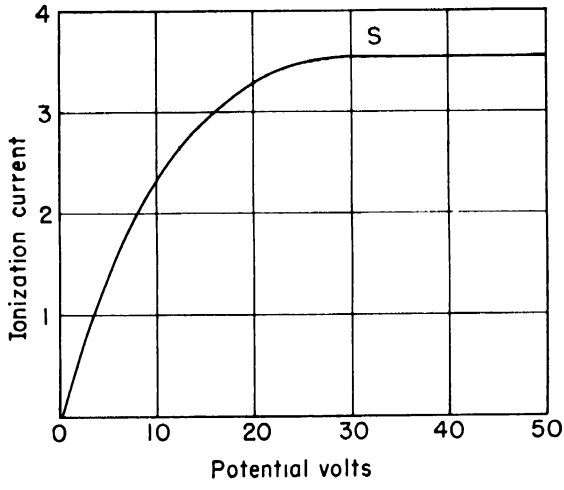


Fig. 6-3. Variation of current in an ionization chamber at constant-exposure dose rate.

the ionization current has reached its maximum value and the chamber is *saturated*. Under saturation conditions there is no appreciable recombination and ionization chambers must be so operated. The voltage required to obtain saturation increases with the rate of ionization in the air, and care must be taken to insure saturation at the highest dose rates measured.

Details of instruments for measuring the charge collected are described in Chap. 7. It is sufficient to note here that exposure dose can be determined from a measurement of the total charge collected on P_3 over a suitable time interval. In an alternative scheme electric current (rate-of-charge collection) is measured and exposure dose rate determined.

6.04 ENERGY FLUX AND THE ROENTGEN

Consider a beam of monoenergetic X-rays of intensity such that a standard air chamber measures 1 r/min. This means that 1 esu of charge will be collected in one minute from 0.001293 gm of air and that $1/0.001293 = 773$ esu/min will be collected from 1 gram of air. Since each ion has a charge of 4.8×10^{-10} esu, 1 r is equivalent to

$$\frac{1}{4.8 \times 10^{-10}} = 2.08 \times 10^{9} \text{ ion pair/cm}^3$$

$$\frac{773}{4.8 \times 10^{-10}} = 1.61 \times 10^{12} \text{ ion pair/gm}$$

A long series of careful measurements * has shown that the energy required to produce one ion pair in a gas is almost independent of electron energy and ionization intensity, and is only slightly dependent on the kind of gas. Some disparate values appear in the older literature but recent measurements are tending to converge on a value of 34.0 ev/ion pair. Then one roentgen corresponds to the deposition of

$$1.61 \times 10^{12} \times 34.0 = 5.47 \times 10^{13} \text{ ev/gm}$$
$$5.47 \times 10^{13} \times 1.6 \times 10^{-12} = 87.6 \text{ ergs/gm}$$

According to the basic definitions then, the beam under discus-

* Jesse, W. P., and J. Sadauskis. *Phys. Rev.* **97**, 1228, 1955.
Weiss, J., and W. Bernstein. *Phys. Rev.* **98**, 1828, 1955.

sion produces an exposure dose rate of 1 r/min and, in the case of air, an absorbed dose rate of 0.876 rad/min. If substances other than air are put at the point of measurement, absorbed dose rate will change with the substance but exposure dose rate will be constant at 1 r/min.

The energy removed from a photon beam and deposited at the point of measurement can be expressed in terms of the true absorption cross sections, since these measure the fraction of the incident energy absorbed. If F is the beam intensity or *energy flux per unit cross section*, in ergs/cm^2

$$F = \frac{87.6\,\mathrm{r}}{N_{\mathrm{air}}({}_{A}\sigma_{a})_{\mathrm{air}}} \tag{6-2}$$

where N_{air} = number of atoms per gram and $({}_{A}\sigma_{a})_{\mathrm{air}}$ is the atomic absorption cross section calculated according to Eq. (5-27). The number of incident photons, P, can be readily calculated from Eq. (6-2) since, from a monoenergetic beam $F = Ph\nu$

$$P = \frac{87.6\,\mathrm{r}}{N_{\mathrm{air}}h\nu({}_{A}\sigma_{a})_{\mathrm{air}}} \tag{6-3}$$

Energy flux per roentgen (air) and rad (water) are plotted in Fig. 6-4 as functions of photon energy. These curves are essentially reflections of the true-absorption coefficient curves. The close relationship between the two curves except at the high energies shows that a measurement in air will be a close approximation to an absorbed dose in tissue. Figure 6-5 shows the photon flux per roentgen as a function of photon energy.

6.05 EXPOSURE AND ABSORPTION

Now consider one gram of any substance S, placed in the monoenergetic photon beam at the point where the standard air chamber measured an exposure dose rate of 1 r per min. The new substance will also receive an *exposure* at the rate of 1 r per min and the total exposure will be the product of this rate and the time of irradiation.

The absorbed dose rate will no longer be 87.6 erg per gm per min or 0.876 rad per min because in general the absorption cross sections for substance S will differ from those for air. These cross sections can be calculated if the photon energy is known. Since the

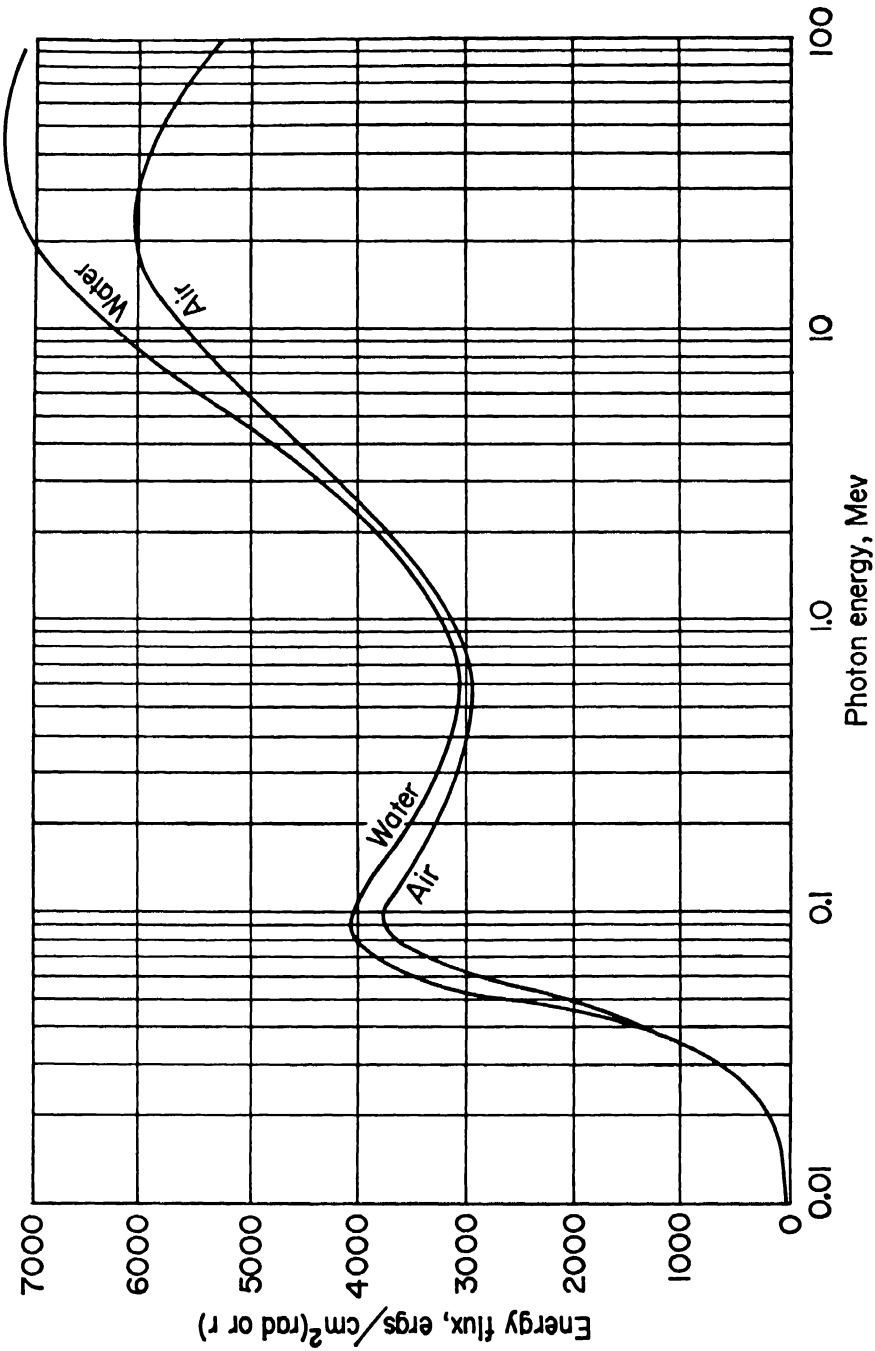


Fig. 6-4. Energy flux per roentgen (air) and per rad (water) as a function of photon energy.

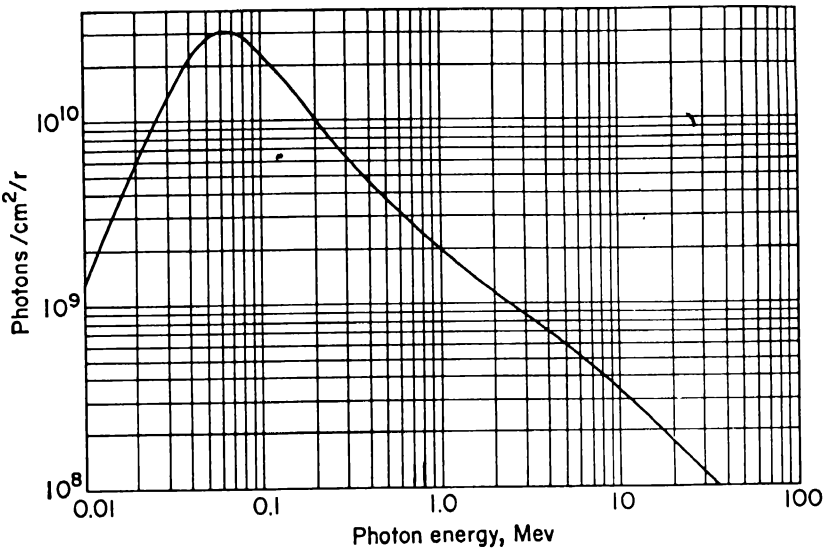


Fig. 6-5. Photon flux per roentgen as a function of photon energy.

energy flux can be determined from the standard air chamber measurement, absorbed energy E and absorbed dose D are readily calculated.

$$E = FN_S({}_A\sigma_a)_S \qquad \text{erg/gm} \tag{6-4}$$

$$D = \frac{E}{100} = \frac{FN_S({}_A\sigma_a)_S}{100}\text{rad} \tag{6-5}$$

where N_S is the number of atoms per gram of absorber S.

Absorbed dose can be expressed directly in terms of exposure dose without an explicit calculation of energy flux F. From Eq. (6-2)

$$D = \left(\frac{87.6\text{ r}}{100}\right)\left(\frac{N_S({}_A\sigma_a)_S}{N_{air}({}_A\sigma_a)_{air}}\right) \tag{6-6}$$

Figure 6-6 shows the absorbed dose in rads per roentgen of exposure dose for bone, fat, and muscle tissue. Bone and fat show big changes below 100 Kev but above this the ratios are nearly unity. Much bigger variations will be found in high-atomic-number materials. In a multi-element absorber the product $N_S({}_A\sigma_a)_S$ must be formed and added for each important constituent.

The discussion above is based on the implicit assumption that the substance introduced into the beam was not so large as to appreciably attenuate the beam, and to seriously degrade the photon

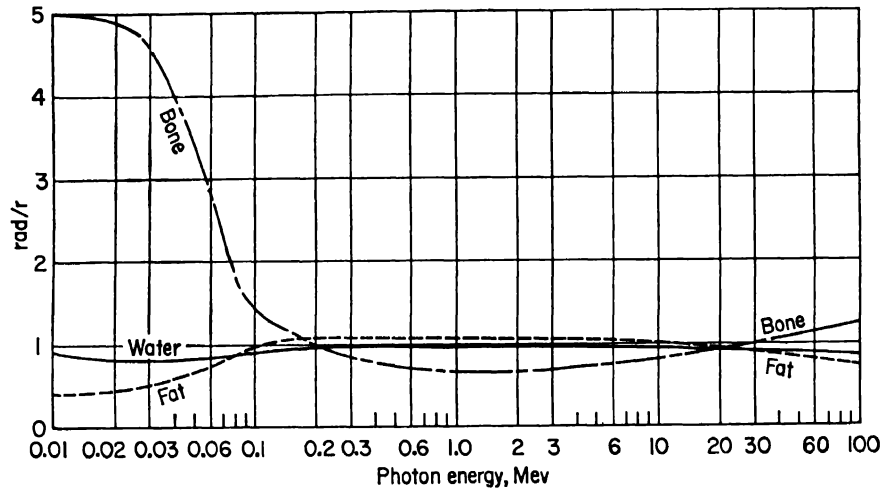


Fig. 6-6. Absorbed dose in rads per roentgen for water, fat, and bone.

energy by Compton scattered photons. In general both of these assumptions are violated to some degree.

With Grenz rays (X-rays of 5–30 Kev) the absorption cross sections are large; a few centimeters of air will appreciably attentuate the beam. In the more usual therapy range (250 KVP) sometimes called the *orthovoltage* region, dose may be considered constant through a small object such as a mouse. For an object as large as a man there is both appreciable absorption and degradation at 250 KVP, and calculations similar to that of Eq. (6-6) cannot be made. In this case both F and $({}_A\sigma_a)_S$ vary with depth and recourse must be had to *depth-dose* measurements rather than calculation. It is probable that future theoretical developments will permit more detailed calculations of depth dose.

At photon energies of 5 Mev and above the basic definition of the roentgen becomes progressively untenable. As photon energies increase, electron ranges increase more rapidly than the mean free paths of the photons, Table 6-1.

Table 6-1 RANGE OF PHOTONS AND ELECTRONS IN WATER

Energy, Mev	Mean free path, cm	Electron range, cm	Ratio
0.1	41.7	0.015	278
1.0	33.3	0.400	83.3
10.0	66.7	5.3	12.6
100.0	71.5	54.1	1.3

At the higher energies chambers must be made very large to completely absorb the electrons; an appreciable attenuation of the photon beam is thus introduced.

6.06 THIMBLE CHAMBERS

In principle, the standard air chamber can be used to measure exposure dose in any photon beam except for the high-energy restriction mentioned above. In practice, however, the standard air chamber is only applicable over a rather narrow range of energies. Below 20–30 Kev there is a large beam attenuation from the air between the defining slits and the measuring volume, so that substantial corrections must be applied to the chamber readings. Above 400 Kev the chambers become too large and cumbersome for routine operation. Even in the intermediate energy region a standard air chamber is a laboratory instrument scarcely suited for routine measurements of exposure dose.

Most routine measurements are made with a *thimble chamber*, Fig. 6-7, consisting of a small air volume with walls of some low-

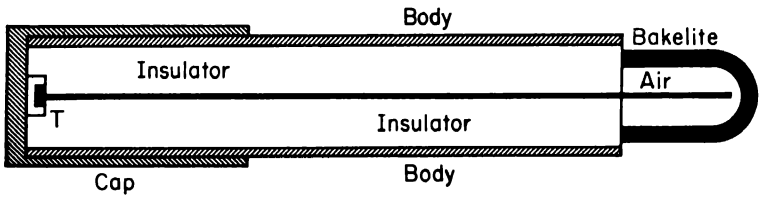


Fig. 6-7. Cross section of a thimble ionization chamber.

atomic-number material such as bakelite. Wall design is most important to the proper response of thimble chambers and will be discussed in detail later.

The inner surface of the chamber wall is made conducting, usually with a thin coating of colloidal graphite, and this coating is electrically connected to the metal body of the chamber. A central collecting electrode of low-atomic-number material is supported in the gas volume by a high-quality insulator. The conducting inner wall and this central electrode form the two plates of an electrical condenser whose charge can be measured with an electrometer. The chamber-electrometer combination is called a *condenser-r meter.*

In operation the protective cap is removed to expose the charging terminal T. The air volume surrounding T is made as small as possible to reduce the effects of ionizations not in the main chamber volume. The chamber is now connected to a source of 300–400 volts, V. If the chamber has an electrical capacitance C each electrode of the chamber will acquire a net charge Q.

$$Q = CV \tag{6-7}$$

With the protective cap replaced the chamber is placed in a radiation field for an appropriate time. Ions formed in the air in the chamber will be attracted, each to the electrode of opposite polarity. Each ion, upon reaching an electrode, will neutralize one of the deposited charges, which reduces Q and hence V. At the end of the exposure

$$Q' = CV' \tag{6-8}$$

and a measurement of $V - V'$ will be a measure of $Q - Q'$ and hence of the chamber ionization. Care must be taken that the lowest voltage V' is still sufficient to insure saturation current.

For accurate measurements a thimble chamber must be calibrated against a standard air chamber, but approximate sensitivity can be calculated from a knowledge of the capacitance and the chamber volume. Thimble chambers are simple, rugged, and can serve as secondary standards when used with a suitable electrometer.

Illustrative Example

A thimble chamber has a capacitance of 25 μμfd (25×10^{-12} farads) and a gas volume of 3 cm³. It is originally charged to 420 volts and after an exposure is found discharged to 280 volts. Calculate the number of ion pairs formed and the exposure dose in roentgens.

$Q = 25 \times 10^{-12} \times 420 = 1.05 \times 10^{-8}$ coulombs

$Q' = 25 \times 10^{-12} \times 280 = 0.70 \times 10^{-8}$ coulombs

Charge lost $= 0.35 \times 10^{-8}$ coulombs

$$\frac{0.35 \times 10^{-8}}{1.6 \times 10^{-19}} = 2.19 \times 10^{10} \text{ ions of either sign}$$

$$\frac{2.19 \times 10^{10}}{3} = 7.3 \times 10^{9} \text{ ions of either sign per cm}^3$$

$$\frac{7.3 \times 10^{9}}{2.08 \times 10^{9}} = 3.5 \text{ r exposure dose}$$

6.07 PHOTON-ELECTRON EQUILIBRIUM

In the illustrative example the calculation of ions collected was extended to a determination of exposure dose in roentgens. This can be done only if care is taken to make the chamber *air-equivalent* for the photons being measured. Air-equivalence can be nearly attained, at least over limited energy ranges, if the composition and thickness of the chamber walls satisfy certain criteria.

Restrictions on wall thickness arise from the fact that a solid wall material will not have exactly the same atomic composition as the surrounding air. Because of this the distribution between photoelectrons, Compton electrons, and those produced by pair production will be different in the two media, and the energy deposition will also be slightly different.

Consider a chamber wall with photons incident upon it. Let the most energetic photoelectron have a range R in the wall.

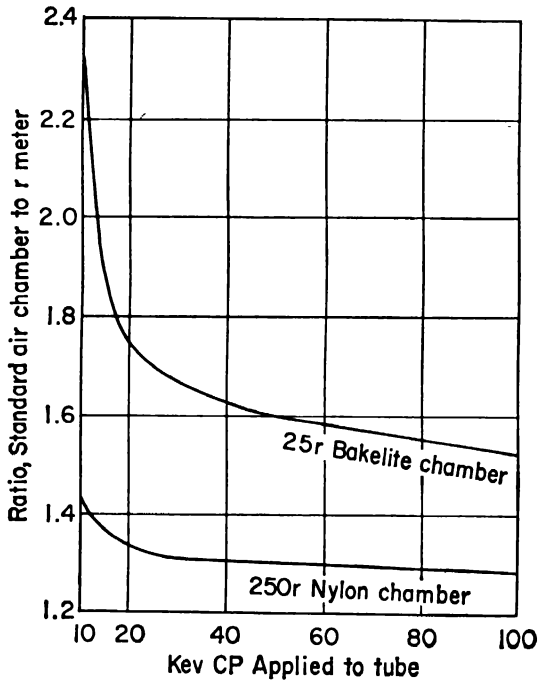


Fig. 6-8. Response of ion chambers to X-rays from a Be window tube. No added filtration. Data from F. H. Day, *N. B. S. Jour. of Research* **41**, 295, 1948.

Down to depth R the electron density will be somewhat variable since some electrons there will have originated outside the wall. At and below R we have electronic equilibrium or better, photon-electron equilibrium. If the chamber response is to be *energy independent* the wall thickness must be sufficient to insure photon-electron equilibrium at the highest quantum energy measured.

As a general rule the atomic-number mismatch is such that there is an electron buildup to depth R and so a chamber will read low if the walls are too thin. Auxiliary caps of suitable plastic are frequently used to extend the use of thimble chambers to energies higher than their design values.

There is also a maximum value of wall thickness acceptable for each energy. If there is an appreciable photon attenuation in the chamber wall the number of electrons traversing the gas will be reduced and again the chamber reading will be too low. Thus a given wall thickness is a compromise between oppositely directed requirements—satisfactory operation will be restricted to a range of photon energies. Figure 6-8 shows the rapid increase in the effect of wall attenuation as the photon energy drops below 100 Kev.

6.08 AIR-EQUIVALENT MATERIALS

For strict air-equivalence each component absorption cross section (σ_{PE}, σ_{CA}, σ_{PP}) must equal the corresponding value for air. Exact equality cannot be achieved, for the cross sections depend upon atomic number and there is no solid available with an atomic composition exactly like that of air.

Organic materials such as bakelite and some plastics with a high carbon content seem to offer the best approximation to air-equivalence. Many organics have a substantial hydrogen content, which is undesirable since this is the only element which has one electron for each unit of mass. In all other elements there is roughly one electron for each two atomic units of mass. Although exactly equivalent wall materials are not to be obtained, compromise materials are satisfactory. Several types of air-equivalent chambers are available.

It should be noted that air-equivalence is needed only when a chamber must measure exposure dose in roentgens. Ionization chambers are used for many other types of measurement; in these cases construction may be suited to each particular requirement.

6.09 ABSORBED-DOSE MEASUREMENT

Although the definition of the rad is straightforward, its realization by direct measurement is difficult. Ionization and excitation are the first effects that result from energy absorption from a radiation beam. As ions recombine and excitations decay, much of the absorbed energy is degraded into sensible heat and hence calorimetry appears to be the method of choice for absorbed-dose determinations.

At the dosage levels commonly used the temperature increases due to radiation absorption are small so that great care must be taken when using radiation calorimeters. The most sensitive temperature indicators are required and elaborate controls of unwanted heat transfers must be instituted.

Even calorimetry may not give a true measure of absorbed energy because radiation-induced chemical reactions may produce compounds with a different energy content than was present in the original state. In most practical cases this effect is small but one can conceive of cases where a considerable amount of energy is stored in the chemical products of irradiation. In any case it appears that most routine measurements of absorbed dose will be made by indirect methods instead of by radiation calorimetry.

6.10 TISSUE DOSE AND CAVITY IONIZATION

It is frequently necessary to determine the radiation dose delivered at various points in an extended solid or liquid body. This can seldom be done directly but ionization measurements can be made by the cavity ionization method * developed by L. H. Gray. In this method the ionization in a solid medium, such as tissue, can be deduced from the ionization in a gas-filled cavity formed by an ionization chamber with tissue-equivalent walls.

Assume an extended homogeneous medium into which has been introduced a thimble chamber with gas volume V with medium-equivalent walls so that the chamber wall is really an extension of the medium itself, Fig. 6-9. Let an electron ejected by photon absorption lose energy ΔE in traversing a short distance Δx in the medium. In the air-filled cavity a similar electron loses energy ΔE

* Gray, L. H. *Proc. Roy. Soc.* **156**, 578, 1936.

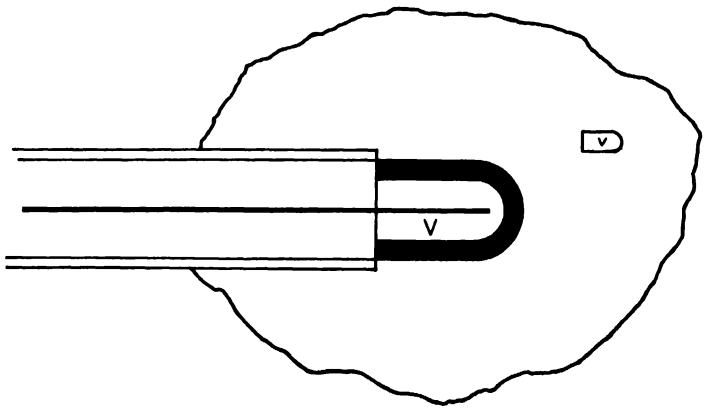


Fig. 6-9. Air-filled cavity for measuring energy deposition in a solid medium.

over a path length $S_m \Delta x$ where S_m is known as the *relative stopping power* of the medium.

Now consider the ionization in air volume V and in a volume of medium v, which is geometrically similar to V but with all dimensions reduced by a factor S_m. If V and v are in a uniform radiation field each electron passing through V will produce just as many ions as a corresponding electron passing through v. If the dimensions of V are small compared to the range of an electron in the gas, the presence of V will have a negligible effect on the number of electrons traversing it. Then the density of ionization in both V and v will be that characteristic of the medium.

Since volume V has a cross-section area $S^2{}_m$ times as large as the cross section of v the energy loss in V will be $S^2{}_m$ times that lost in v. Then the respective energy losses in V and v, E_A and E_m respectively, are related by

$$E_A = S^2{}_m \, E_m \tag{6-9}$$

and since

$$V = S^3{}_m \, v$$

$$\frac{E_A}{V} = \frac{E_m}{S_m \, v} \tag{6-10}$$

Eq. (6-10) shows that the energy absorbed *per unit volume* is S_m times as great in the medium as in the cavity. Relative stopping power can be obtained by independent measurements of electron

ranges and with this known E_m/v can be obtained from a measurement of E_A/V.

A direct determination of E_A/V presents all the problems associated with measurements of energy absorption. However, the number of ion pairs formed per unit volume of the cavity gas, J, is readily measured and if each ion pair requires an energy expenditure W

$$\frac{E_A}{V} = JW \tag{6-11}$$

and finally

$$\frac{E_m}{v} = JWS_m \tag{6-12}$$

Thus the cavity ionization principle permits a determination of energy absorption in a solid medium from the measured ionization in a small gas-filled cavity. The cavity must be small because if its presence seriously upsets the electron distribution in the solid the considerations leading to Eq. (6-12) no longer apply.

6.11 DEPTH-DOSE MEASUREMENT

The principles of cavity ionization are frequently applied in determining the radiation dose delivered at points inside an extended medium. Thus, a radiologist treating a malignancy with an external source of photon radiation must know the energy delivered at the site of the neoplasm. To obtain this information a *phantom* is constructed of some reasonably tissue-equivalent material such as rice, water, or pressed wood. Phantom construction may be simple or elaborate, with inserted bony structures, depending upon the accuracy desired. Cavity chambers can be placed at appropriate points in the phantom and *depth doses* calculated from the ionization measurements.

Depth-dose data are usually presented as curves of equal dose, or *isodose curves,* expressed as a percentage of the maximum, Fig. 6-10. This shows the buildup of dose until photon-electron equilibrium is reached, and the subsequent decrease in dose because of absorption.

In general, decrease in dose with depth results from attenuation by absorption and also from the increase in distance from the radi-

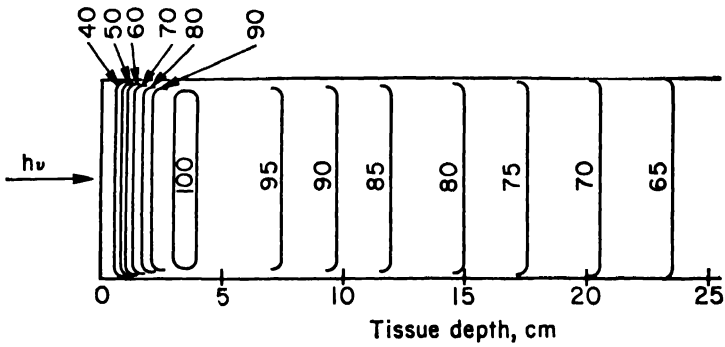


Fig. 6-10. Isodose curves at 20 MVP at infinite TSD.

ation source. Neglecting scatter, photons move outward from any source along diverging paths, and from purely geometrical considerations the energy flux crossing unit area must vary as the inverse square of the distance from the source. Thus depth-dose distributions depend upon the target-skin distance, TSD, as well as upon the absorber itself. The isodose curves in Fig. 6-10 have been corrected for inverse-square-law attenuation and hence represent variations due only to buildup and absorption processes.

Proper depth-dose determinations require that phantom measurements be made with the same *backscatter* conditions that exist with the patient in position. Backscatter is the term used, particularly by radiologists, for all Compton scattered photons, regardless of direction. An ionization chamber, placed say at the position occupied by the skin surface, will read higher with the phantom in position than in free air, because of backscatter.

At photon energies above 1 Mev, forward scattering becomes increasingly important and the dose increase due to backscatter is less than at energies of 100–500 Kev. At energies below 50 Kev backscatter is also reduced because the very soft scattered photons are strongly absorbed very near their point of origin. In the mid-energy region backscatter may increase the skin dose to 150 per cent of the free-air dose.

Skin-dose measurements, both at entrance and exit, are important since severe skin reactions may limit the amount of radiation that can be delivered to a deeper structure. Skin dose is usually determined with an *extrapolation* chamber, Fig. 6-11. This chamber consists of two parallel plates made extremely thin to reduce photon

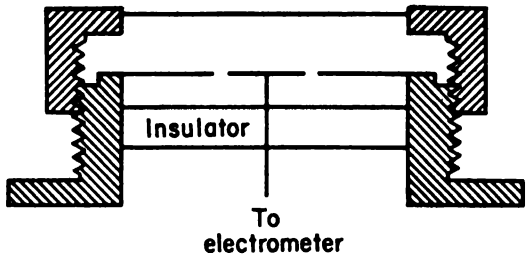


Fig. 6-11. Extrapolation ion chamber for measuring skin dose.

absorption to a negligible amount. One of the plates can be moved accurately parallel to the other with a micrometer screw so arranged that the plate separation can be measured. In use the chamber is placed on the surface of a phantom and a series of readings of ionization current taken as plate separation is decreased. From these data ionization per unit volume can be calculated, plotted against plate separation, and extrapolated to zero separation. This extrapolated value will be the skin dose.

6.12 PRACTICAL IRRADIATION PROBLEMS

Many biological effects of radiation are strong functions of radiation dose; considerable care must be taken to insure reliable results. Mammalian mortality is a case in point, where both environmental conditions and radiation parameters must be carefully controlled.

When groups of animals are irradiated, it is important that each one receive the same dose. Careful measurements will show that the radiation field from most X-ray tubes is non-uniform. At high energies this results from the anisotropic emission of bremsstrahlung, with forward production favored. At low energies with reflection targets there will be some attenuation of X-rays by the anode structure itself. Non-uniformity can be greatly reduced by the use of *field-flattening* filters inserted in the beam near the tube. In some cases the shape of these filters can be calculated but in others cut-and-try methods must be used. Further assurance of uniform dosage is obtained by slowly rotating the irradiation vessels in the beam.

All materials put in the beam, such as the irradiation vessels or supporting structures, should be made of low atomic number mate-

rials, so that radiation scattered from them will have the same quality as that scattered from the animals.

Backscatter should be kept as low as possible and arrangements should be made to compensate for variations in it. Small animals are customarily irradiated in plastic containers with 10 or even 20 individual compartments. If a full complement of animals is not irradiated, phantoms of wood or plastic should be put in the unused compartments so that adjacent animals receive the normal amount of scatter.

Care must be taken to maintain constant electrical conditions since bremsstrahlung production varies as the square of the tube voltage, and directly as the tube current. In some locations line-voltage fluctuations may require the use of automatic voltage regulators. Preferably, all doses are administered by electronic integrators energized from ion chambers, which continuously monitor the output beam.

When radioactive nuclides are used as photon sources there is no problem of variable output except for the calculable decay of the emitter. In the absence of scatter the gamma-ray output of a radioactive nuclide can be expressed in terms of its *emission constant* Γ. The rhm (pronounced rum) which is the number of roentgens per hour at one meter from a one curie source, is the usual unit of emission.

Values of Γ are readily calculable from the known gamma-ray energies and the true absorption coefficients for air. A curve of Γ as a function of energy (see Appendix) will be an inversion of Fig. 6-5.

PROBLEMS

6-1. A 250 Kev photon undergoes Compton scattering and produces a secondary photon at an angle of 60° to the original beam. What is the range in water of the electron ejected in this process? What would be the electron range in water if the original photon had undergone photoelectric absorption? *Ans.* 0.025 cm, 0.05 cm.

6-2. An electron-positron pair is produced by the absorption of a 3.8 Mev photon. Assume the available energy to be equally divided between the two particles and calculate the range in water. Repeat the calculation for a 70 Mev photon from a synchroton.

6-3. A thimble chamber has a wall thickness just sufficient to obtain photon-electron equilibrium at 200 Kev. Estimate the thickness of

a plastic (density 1 gm/cm^3) cap necessary to insure electronic equilibrium at 2.5 Mev. *Ans.* 1.20 cm.

6-4. What is the range and path length of a 1.8 Mev electron in air at NTP. How many ion pairs will be formed by this electron in coming to rest?

6-5. Calculate the energy in ev and in ergs deposited in 1 cm^3 of air at NTP by an exposure dose of 1 r of 200 Kev photons. Repeat the calculations for 1 gram of air. *Ans.* 7.08×10^{10} ev/cm^3, 0.113 ergs/cm^3. 5.48×10^{13} ev/gm, 87.6 erg/gm.

6-6. What is the temperature rise in a 2 gram sample of water receiving an absorbed dose of 950 rad?

6-7. An ionization chamber can be used to measure exposure rate if the associated circuit is arranged to measure electric current rather than charge. Calculate the volume of a chamber to produce an ionization current of 10^{-9} amperes in a radiation field of 10 r/min. Remember that 1 ampere = 1 coulomb/sec. *Ans.* 18 cm^3.

6-8. An ionization chamber has a capacitance of 35 μμfd, a volume of 9 cm^3, and is initially charged to 380 volts. Assume saturation and NTP and calculate the exposure dose required to drop the chamber voltage to 165.

6-9. At sea level normal background radiation from cosmic rays and natural radioactivity is about 0.02 mr/hr. An air-filled chamber used to detect this radiation is connected with an electrometer capable of measuring 3×10^{-15} amperes. Calculate the chamber volume needed. *Ans.* 1,620 cm^3.

6-10. In a Compton process a 350 Kev photon ejects an electron and a photon is scattered at an angle of 90 degrees. How many ion pairs will be produced in air by the electron before it comes to rest? Assume that the electron loses energy at a constant rate and calculate the number of ion pairs formed per mm of path.

6-11. An ionization chamber with a volume of 3 cm^3 is inserted in a water phantom and an electrometer circuit measures an ionization current of 7.2×10^{-11} amperes. Assume the relative stopping power of water to be 820 and calculate the rate of energy deposition per gram of water. *Ans.* 0.067 rad/sec.

6-12. It is desired to determine the total energy content of a 1.3 Mev gamma-ray beam by measuring the temperature rise in a lead calorimeter. How thick must the lead be if 99 per cent of the incident beam is to be absorbed?

6-13. A gamma-ray beam of 0.9 Mev has a measured exposure dose rate of 3.6 r/min. How many photons pass through 1 cm^2/sec and what is the energy flux rate through 1 cm^2?

Ans. 1.26×10^8 photons/sec, 183 ergs/sec.

6-14. An extrapolation chamber with a cross-section area of 7 cm^2 is used to determine skin dose. Calculate the exposure dose at the skin surface in r/min from the following data taken in a constant X-ray field.

Plate separation mm	2.0	1.5	1.0	0.8	0.6	0.4	0.2
Ion current, amps $\times 10^{-10}$	30	21	18	16	13	10	6.1

6-15. The following data were taken on axis in a water phantom with TSD = 50 cm. Correct the data to a constant distance, plot, and determine the HVL of the beam.

Depth, cm	2	4	6	8	10	12	15	20	25
Dose, rad	270	220	180	135	102	81	51	28	19

Ans. 7.2 cm of water.

6-16. Calculate and plot the on-axis doses in water to a depth of 25 cm for the beam used in Prob. 6-15, if the TSD is changed to 70 cm.

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7

RADIATION MEASURING INSTRUMENTS

7.01 IONIZATION CHAMBERS

Sensitive electroscopes and electrometers were available when Roentgen and Becquerel made their dramatic discoveries and most early radiation measurements were made with one of these instruments connected to an ionization chamber. New discoveries and the techniques of modern electronics have produced more sensitive and versatile equipment, but the electrometer-ion chamber still plays an important role in radiation measurements.

Ionization-chamber requirements for measuring exposure dose in roentgens have been discussed. Specifications for other applications are usually less severe and a wide variety of designs can be suited to particular requirements. In principle, an ionization chamber consists simply of an enclosed gas volume containing a collecting electrode mounted on a high-quality electrical insulator.

The insulator is the critical component in any ion chamber; the

greatest care must be taken to maintain its integrity. For many years amber, quartz, and cast sulphur were used for ion-chamber insulation but these materials are now largely supplanted by synthetics such as polystyrene or polyethylene. Injection molding into highly polished dies is preferable to machined shapes, which may have rough surfaces and internal stresses tending to increase *soak-in* and other undesirable effects.

Soak-in is a phenomenon distinct from electrical leakage, with which it is frequently confused. Leakage refers to the transport of charge either through the body of the insulator or along its surface. Soak-in refers to the gradual penetration of charge into the body of an insulator, a behavior closely simulating leakage. Charge thus acquired will gradually be released when the charging voltage is removed.

Leakage is increased by the accumulation of moisture on insulator surfaces and whenever possible precision ion chambers should be kept in a dessicator. An ion chamber designed to respond to external alpha particles must have an extremely thin *window* to permit the entry of the particles into the gas volume. Many of these thin windows permit moisture to enter the chamber and spoil the insulator.

Samples of soft beta and alpha emitters may be introduced directly into the chamber to improve the counting geometry and more fully utilize the ionizing capabilities of each particle. In the usual arrangement the sample is mounted at one end of the chamber in 2π *geometry*, Fig. 7-1, so-called because particles emitted in one-half the

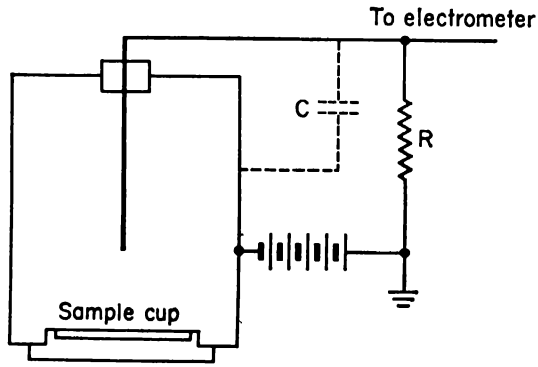


Fig. 7-1. Ion chamber with resistor connected to measure ionization current.

total possible solid angle of 4π are utilized. Samples deposited on extremely thin films may be mounted in the center of a chamber to attain essentially 4π geometry. To realize full ionization efficiency the chamber dimensions and gas density must be sufficient to permit full absorption in the gas. A dense gas such as argon is frequently used to reduce the chamber dimensions.

7.02 TIME CONSTANT

Figure 7-1 shows a circuit for measuring ionization rate using any suitable electrometer to measure the potential drop across the resistance R. The dotted portion of the circuit indicates that the chamber and the detecting device act like a condenser of capacitance C.

With no ionization there will be no current flow and both ends of R will be at ground potential. When a source of radiation is suddenly introduced, the voltage across R cannot instantaneously rise to its final value because of the presence of C. In fact, the voltage rise will be given by

$$V = V_F(1 - e^{-\frac{t}{RC}}) \tag{7-1}$$

where V is the voltage at time t and V_F is the final voltage. The product RC is known as the *time constant* of the circuit. If t is given in seconds R must be in ohms and C in farads. When $t = RC$ $V = V_F\,(1 - 0.37) = 0.63\ V_F$.

The sensitivity of an ion-chamber circuit can be increased by increasing R but at the same time a more sluggish response will result. Similarly, a slow system will result if C is not kept to a minimum.

Illustrative Example

An electrometer has a capacitance of 5 μμfd (5×10^{-12} farads) and will respond to a signal of 0.5 volts. What resistance must be used, and what will be the time constant of the circuit to detect an ionization current of 10^{-12} amperes in a chamber of 35 μμfd capacitance?

By Ohm's law $$R = \frac{V}{I} = \frac{0.5}{10^{-12}} = 5 \times 10^{11} \text{ ohms.}$$

Total capacitance $5 \times 10^{-12} + 35 \times 10^{-12} = 4 \times 10^{-11}$ farads.

Time constant $RC = 5 \times 10^{11} \times 4 \times 10^{-11} = 20$ seconds.

It is evident that, with a constant capacitance, sensitivity can only be achieved at the expense of fast response. A long time-constant circuit may be quite satisfactory for many assay measurements. In making surveys with portable instruments, however, it is quite possible to miss small contaminated areas if the meter response is too slow.

7.03 ELECTROSCOPES AND ELECTROMETERS

Many types of electroscopes and electrometers have been devised but only a few designs need be described here.

The Lauritsen electroscope, Fig. 7-2, combines the ionization

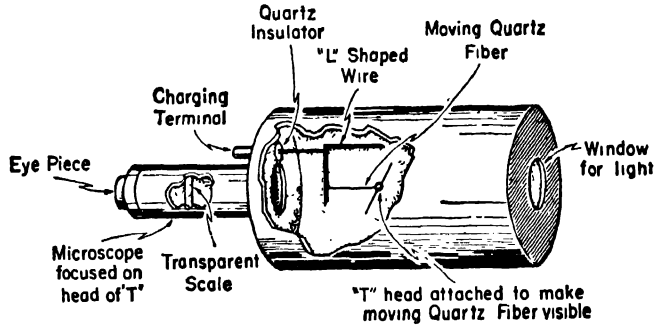


Fig. 7-2. Phantom view of Lauritsen electroscope.

chamber and detecting device in a single unit. When a battery of some 200 volts is connected to the charging terminal a charge will flow onto the stiff-wire support and the quartz fiber, which is only 3–5 microns in diameter. The fiber will be bent away from the stiff wire by the mutual repulsion of like charges. Gaseous ions produced inside the case will neutralize some of the charge and the fiber will return toward its uncharged position.

The position of the fiber is read with the microscope and scale and an ionization measurement is made by timing the passage of the fiber across some convenient scale divisions. Deflection is not linear with charge so all observations must be made over the same

scale range. The instrument shown in Fig. 7-2 is arranged to measure radiations originating outside the case. Slides can be arranged so that weak emitters can be put directly into the chamber.

Instruments more sensitive than the Lauritsen have been devised, but it is light, readily adapted to field work, and maintains its calibration well. For this reason Lauritsen electroscopes are frequently used for measuring strong radioactive samples.

The condenser r-meter uses a string electrometer shown schematically in Fig. 7-3. When the chamber and electrometer are

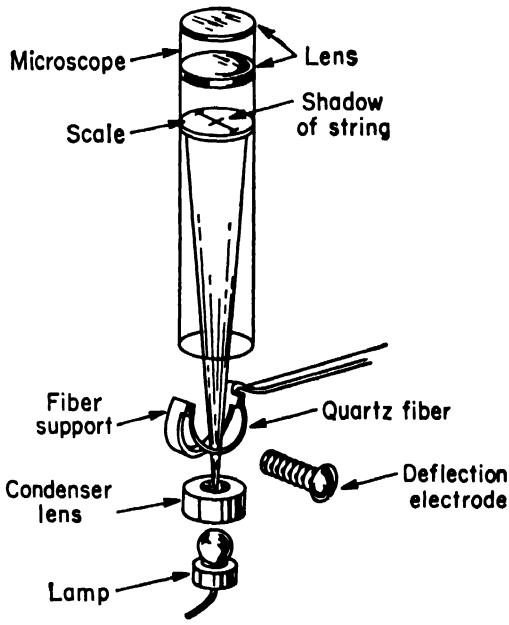


Fig. 7-3. String electrometer in the condenser r-meter. Courtesy of Victoreen Instrument Co.

charged, charges of opposite polarity appear on the quartz fiber and the deflecting electrode. The fiber (made conducting by a thin evaporated metal film) deflects toward the electrode. When a partially discharged chamber is connected to the electrometer the reduced charge will be shared by the two systems and the fiber will return toward its equilibrium position.

Most electrometers are sensitive to orientation but the Lindemann, Fig. 7-4, can be used in any position. The four quadrants

are cross-connected as shown in Fig. 7-4 to a source of 15–20 volts. The metal-coated quartz needle comes to equilibrium in the two electric fields at a point determined by the potential of the needle. In use the Lindemann is usually mounted on the stage of a compound microscope and the fiber position read on an eyepiece scale. The Lindemann electrometer is small and rugged but its sensitivity depends strongly on the quadrant voltages and care must be taken to maintain calibration.

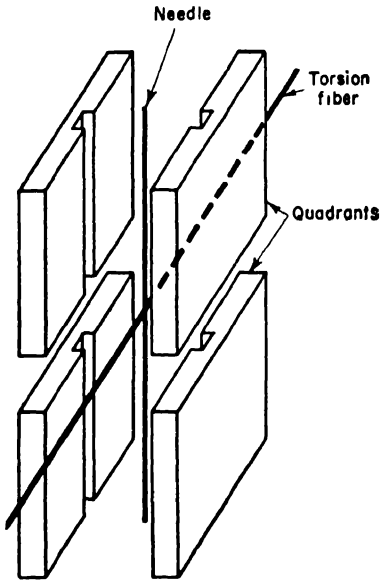


Fig. 7-4. Schematic diagram of Lindemann electrometer.

7.04 VACUUM TUBE ELECTROMETERS

As improved vacuum tubes have become available there has been a tendency to replace the quartz-fiber instruments with tubes connected to rugged indicating meters. This tendency has been particularly marked in portable survey-type instruments. A three-element tube, or triode, can be used as an electrometer since a voltage applied to the grid can control the plate current without drawing any appreciable current itself. Thus the grid circuit of a tube presents a very high resistance and may, for example, be connected across the high resistance R in Fig. 7-1 without seriously reducing R by shunting.

Vacuum tubes used in communication circuits may draw enough grid current to be unacceptable in the more sensitive circuits. In practice, four-electrode tubes, or tetrodes, are used and by special design and manufacture extremely low grid currents can be attained. These electrometer tubes are almost always used in a balance circuit, Fig. 7-5, to reduce the effects of varying battery voltage. With care, currents of 10^{-17} amperes can be measured with electrometer tubes.

The input circuit to a vacuum-tube electrometer consists of a capacitance and a high resistance with a time constant calculated as

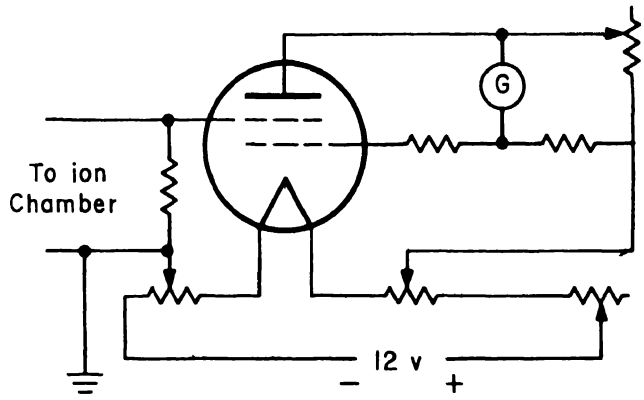


Fig. 7-5. Four-element electrometer tube in a balanced circuit

before. Vacuum-tube circuits can be devised, however, which permit substantial reductions in time constant. The electrometer tube can be followed by one or more stages of vacuum-tube amplification, and the increased sensitivity may permit a reduction in the input resistor, with a consequent decrease in time constant. Time constant can also be reduced by *feedback*, wherein a small portion of the amplified signal is returned to the input circuit.

7.05 VIBRATING-REED ELECTROMETER

Although the total ionization current in an ion chamber is the sum of many individual pulses, the long time constant results in an essentially steady, or DC signal, except for slow variations with radiation level. Unfortunately, high-gain amplification of DC signals presents real problems in circuit stability, although rapidly varying signals (AC) can be amplified with relatively stable circuits.

In the vibrating-reed electrometer the DC signal from an ion chamber is converted to AC, amplified, and reconverted to DC at the amplifier output. The vibrating-reed conversion is accomplished by an application of Eq. 6-7. With a constant charge obtained by ion collection a variable voltage will be produced if the capacitance is varied. This is readily done by cyclically changing the separation between two metal plates in the chamber circuit. The cyclic variation was first obtained by a vibrating metal reed, establishing the

generic name for the instrument. Vibrating-reed electrometers offer a very satisfactory compromise between sensitivity, speed, and stability.

7.06 BALANCE MEASUREMENTS

All the methods described imply that ionization current is measured by the deflection of some indicating meter in an electrometer of known and constant sensitivity. This is not always easy to achieve for electrometer sensitivity changes with many variables such as the voltage supplied to the deflecting electrodes. Problems of sensitivity change can be eliminated by using the electrometer only as a null indicator, and obtaining the ion current from some stable circuit element. Many null arrangements have been developed, one example being the Townsend *charge balance* circuit of Fig. 7-6, shown with a Lindemann electrometer as indicator.

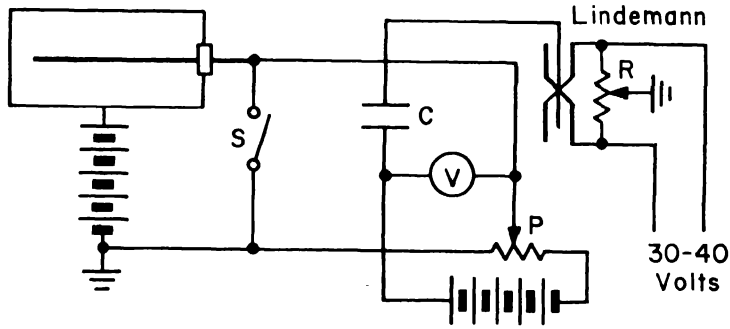


Fig. 7-6. Schematic diagram of charge-balance measurement with Lindemann electrometer.

With grounding switch S closed R is adjusted to produce no deflection of the electrometer fiber. When S is opened charge from the ion chamber flows onto condenser C, whose capacitance can be accurately determined by an independent measurement. As the condenser charges the electrometer fiber will deflect, but a null reading can be restored by applying a charge of opposite polarity from potentiometer P. A reading of precision voltmeter V at balance permits a calculation of total charge collected by Eq. (6-6).

Various schemes have been developed * to make the balance ad-

* Garfinkel, S. B. *R. S. I.* **30**, 439, 1959.

justment automatic; the balancing charge is sometimes obtained from a second ionization chamber and a fixed radiation source. Charge-balance circuits are useful for the differential measurement of different types of radiation. Two chambers may, for example, be balanced for gamma radiation, but have quite different responses to neutrons, so that the latter can be measured in the presence of a strong photon field.

7.07 PULSE COUNTERS

It is sometimes desirable to count the individual pulses of ionization associated with the arrival of each particle. This can be done with a chamber if the associated circuits are made sufficiently fast. Fast response can be obtained by reducing the series resistance across which the signal is developed. The loss in signal strength is offset by introducing a *linear pulse amplifier* to bring the pulse amplitudes up to the level needed to actuate counting devices.

Differential measurements can be made with a chamber-linear amplifier arrangement, since the terminal counter can be designed to discriminate against small signals and respond to large ones. Alpha particles, for example, can be counted in the presence of considerable photon radiation by using a flat ionization chamber fitted with a very thin window. An alpha particle that passes through the window will expend all its residual energy in the gas, producing on the order of 10^5 ion pairs. A beta particle, on the other hand, will expend only a fraction of its energy in the gas and may produce only 10^3 ion pairs. Recording circuits can readily distinguish between the two pulse sizes so that no response will be made to beta particles. Gamma rays will also be rejected since they are only detected by the ionization resulting from photon-electron interactions.

A similar arrangement is suitable for measuring fast neutrons. In this case the chamber is filled with hydrogen gas to which fast neutrons impart considerable energy. The recoiling protons leave a trail of densely ionized gas to which counting circuits will respond.

7.08 AVALANCHE IONIZATION

All the previous discussion was based on the tacit assumption that the ion chamber was operating at normal atmospheric pressure,

with saturation voltage. A greatly increased pulse amplitude can be obtained by applying voltages many times saturation, either at normal atmospheric or at reduced pressure. To simplify the discussion, assume a cylindrical ionization chamber with a fine-wire collecting electrode stretched along the axis of the cylinder. Further assume that the chamber is exposed to a radiation such that the same number of primary ions is formed by each ionizing particle.

Figure 7-7 is a schematic representation of pulse size as a func-

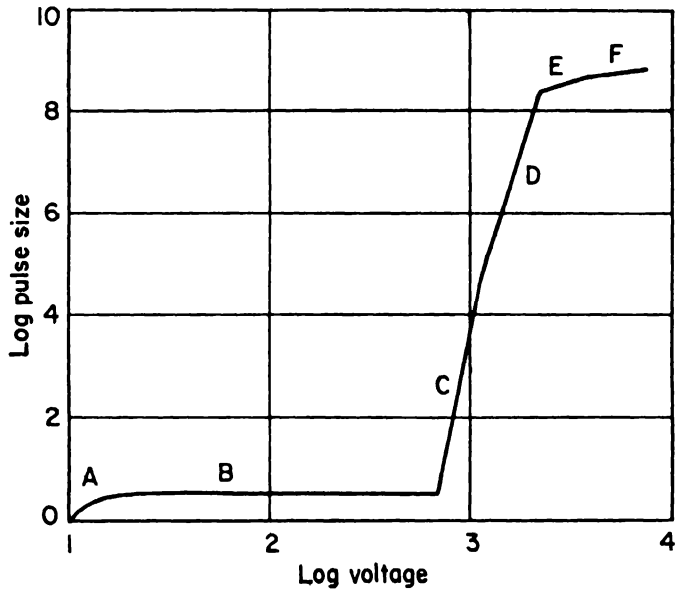


Fig. 7-7. Pulse size in a chamber as a function of applied voltage. Double log scale.

tion of voltage applied to the chamber. *A* and *B* form the regions of *recombination* and *saturation* respectively. *C*, where the pulse size is greater than that formed by primary ions alone, is the *proportional region*. This passes into the region of *limited proportionality, D*, and this in turn into the *Geiger region, E*. The highest voltage portion, *F*, is the region of *continuous discharge*.

Since all the ions produced by the primary particle are collected at saturation, in region *B*, large numbers of secondary ions must be formed at the higher voltages. The process by which primary ions are multiplied is known as *avalanche ionization*. A primary ion, attracted toward the electrode of opposite polarity, acquires enough

energy at the high voltages to produce secondary ions by collision with neutral gas molecules. These secondaries can in turn be accelerated sufficiently to produce tertiaries, and so on. With the assumed cylindrical symmetry the most intense electric field exists very close to the central wire, and the process of avalanche ionization takes place there.

The proportional region is a very useful one, because here the size of each total pulse is proportional to the number of primary ions formed by the initiating particle. As before, a discriminator circuit in the output will reject pulses formed by sparsely ionizing radiations. Since a *gas amplification* of 1000 can be attained, only a limited amount of vacuum-tube amplification is needed to bring pulses to usable size.

The other region of great practical importance is the Geiger region *E*. Here the gas amplification is very high and only the simplest electronic circuits are needed to detect the pulses. However, the pulses are no longer proportional to the ionization of the initiating particle. A single ion pair is sufficient to initiate ionization along the entire axis of the cylinder, so the chamber has lost its ability to discriminate.

Practical exploitation of the Geiger region is usually done with Geiger-Muller counter tubes filled with argon gas at a low pressure. Typically, a G-M tube will be filled with argon gas to a pressure of about 10 cm of mercury. For reasons to be discussed later, alcohol or xylene vapor may be added to an additional pressure of 1 cm of mercury. At the reduced pressure there will be only about $\frac{1}{7}$ as many gas molecules as at normal atmospheric pressure. Each ion travels farther between collisions and hence can pick up enough energy to produce avalanche ionization with only moderate applied voltages.

A G-M counter tube is always connected to some sort of an electronic circuit for counting the number of pulses. This circuit will necessarily have a threshold, and pulses below the threshold will not be recorded. Figure 7-8 shows the counting rate of a typical G-M circuit exposed to a constant radiation intensity. *A* is the threshold voltage below which no counts are recorded. Regions *B* and *C* correspond to the proportional region and the region of limited proportionality. The *plateau D* corresponds to region *E*, Fig. 7-7. Actually the plateau shows a small slope, perhaps 2–3 per cent per 100 volts in a well-made counter. A long plateau with a gentle

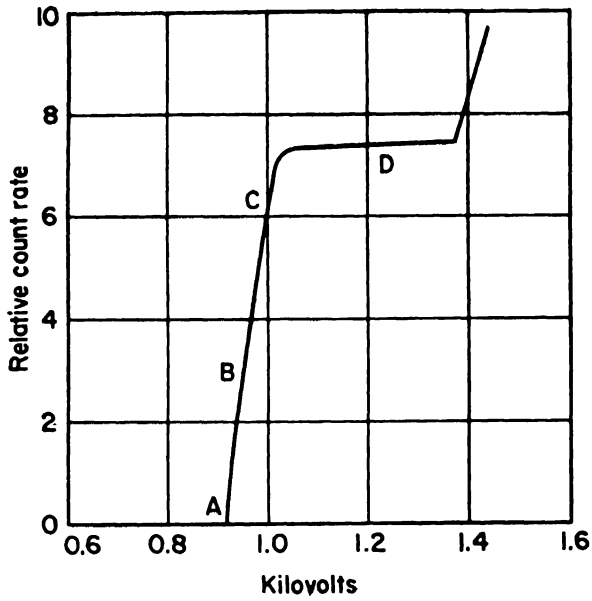


Fig. 7-8. Schematic of G-M tube characteristic.

slope is a desirable characteristic since it assures that the counting rate will be reasonably independent of the tube voltage.

7.09 QUENCHING THE DISCHARGE

The continuous-discharge region is not used for counting since a single pulse will trigger a series of closely spaced pulses originating in the tube itself. The same mechanisms operate less effectively at lower voltages and are of great importance in determining tube behavior.

G-M tubes are always operated with the central wire positive and the outer cylinder negative. With this polarity the negative electrons moving toward the central wire will see a continually increasing electric field and will be collected in a few microseconds. The heavier positive ions move through a decreasing field toward the cathode, and may not arrive until 100 μsec after the initial discharge.

The electric field of the approaching ions may raise some of the cathode atoms into excited states, which will be relieved by the

emission of visible and ultraviolet light. Some of these photons can eject photoelectrons from the cathode material or the filling gas; these electrons will immediately move toward the central wire. If the tube voltage is high a second avalanche will be initiated. Thus a self-perpetuating process is set up at a repetition rate determined by the characteristics of the tube and the associated circuit.

A resistance must be put in series with the G-M tube so that voltage pulses can be transmitted to the counting circuits. The voltage across the tube will decrease by any voltage developed across the resistor. If the resistance is made very large the voltage drop will be sufficient to prevent the formation of the second avalanche, and the discharge is *quenched.* The high resistance results in a long time constant, and resistance-quenched tubes are *slow.*

Tubes can be made *self-quenching* by using a material with poor photoelectric characteristics for the cathode, and by adding about 10 per cent of a *quenching gas* to the regular argon filling. A good quenching gas must have strong absorption bands in the ultraviolet, and must dissociate from an excited state in preference to emitting photon radiation. A number of condensable organic compounds are suitable quenching gases, with ethyl alcohol the most popular.

Since some of the organic vapor dissociates when quenching the discharge, self-quenching counters have a finite life. Usually 10^8–10^{10} pulses can be counted before operation becomes erratic. Tubes quenched with halogens such as Cl_2 have a longer life because the dissociated molecules recombine into their original form.

Most of the organic vapors used as quenching gases are readily condensable and consequently self-quenching tubes may be temperature sensitive. At low temperatures enough vapor may be condensed to prevent quenching action.

7.10 GAS-FLOW COUNTERS

Windows in the ordinary G-M counter must sustain a pressure differential of some 65 cm of mercury; this pressure requires an equivalent window thickness of at least 1 mg/cm^2. This window will stop all the beta particles from H^3 and a substantial fraction of those from the very useful isotopes C^{14} and S^{35}. The gas-flow counter operates at atmospheric pressure, or very slightly above, so that

samples can be introduced directly into the counting volume. This eliminates window absorption and also increases the fraction of the emitted particles entering the sensitive gas volume.

After a sample is introduced the counter chamber is rapidly flushed with a counting gas such as argon-isobutane or methane. A slow gas flow throughout the counting period provides a constant chamber environment.

A gas-flow counter may be operated either in the proportional region or as a G-M counter. Proportional counting has the advantage of providing some discrimination against unwanted counts, such as high-energy background events. Very well-regulated voltage supplies must be used in the proportional region, however, for here the sensitivity changes rapidly with voltage.

When beta particles are emitted from a sample the latter is left with a net positive charge. In general this charge presents no problem, since it leaks off to ground by devious paths. If the sample in a gas-flow counter is mounted on an insulator, charge leakage may be very slow, and the electric field in the counter may be badly distorted by the changing potential of the sample. This difficulty can be avoided by providing a conducting path from sample to ground.

As new materials have been developed it has been possible to make films of substantially less than 1 mg/cm^2 equivalent thickness, capable of withstanding differential pressures of a few cm of mercury. The use of these films in gas-flow counters represents a compromise between the stability of the thicker-window, sealed-off G-M tube and the low-energy sensitivity of the windowless gas-flow counter.

7.11 RESOLVING TIME

A finite time is required to collect the ions formed in a gas by absorbed radiation. During part of this time the counter is completely insensitive to a second ionizing event. This *dead time* is followed by a period of rapidly increasing sensitivity until the counter is again able to produce ionization pulses large enough to actuate the counting circuits. The time required to restore sensitivity is known as *resolving time*.

A typical G-M tube will have a resolving time of about 10^{-4} sec and so would respond correctly to 10^4 pulses per sec if they were evenly spaced. Since radiation pulses are random events there will

be a substantial loss of counts even when the average rate is well below 10^4 per sec.

Gas-flow counters may have a resolving time of only 10^{-6} sec so that these can be used at relatively high rates before corrections need to be applied for pulse losses. Methods of measuring resolving time and applying the corrections are described in Sec. 8.07.

7.12 SCINTILLATION COUNTERS

Photon radiation is detected with a low efficiency by the usual gas-filled counter, because of the small probability of an interaction. The chance of a photon-electron interaction in the gas itself is small because of the small mass involved, and most ionizations arise from electrons originating in the counter walls. A considerable improvement in photon-counting efficiency can be obtained by using scintillating crystals as the detector. A commonly used crystal, NaI, has a density of about 3.7 gms/cm^3 and, since it is composed of elements with $Z = 11$ and 53, photon absorption coefficients will be large. Anthracene or stilbene (diphenyl ethylene) crystals have some advantages for beta scintillators and silver-activated zinc sulphide is used for alpha counting.

All scintillator crystals have the property of emitting a flash of light following the absorption of energy from an ionizing particle. The amount of light emitted is, over a wide range, proportional to the energy expended by the particle in the crystal. Not all crystals are efficient scintillators; some absorb or *quench* their own emitted radiation so that little escapes for external detection.

Many early alpha-particle measurements were made by counting scintillations in a ZnS crystal, the observations being made with a microscope and a dark-adapted eye. Electronic scintillation counting has been made possible by the photo-multiplier tube, Fig. 7-9. Each photoelectron ejected by a light quantum originating in a scintillator, will be attracted to the first *dynode* element. Upon impact with the specially prepared surface of the dynode, each primary electron will eject several secondaries. This process is repeated at several dynode elements to give a current amplification of perhaps 10^9. Pulses from the photomultiplier are then further amplified and counted in the usual way.

Scintillators have resolving times of 10^{-7} sec or less and care

must be taken to insure that the associated circuits are as fast as the detector.

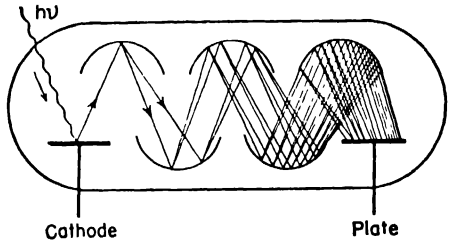


Fig. 7-9. Amplification by secondary electron emission in a photomultiplier.

7.13 GAMMA-RAY SPECTROMETER

The proportionality between ionization and pulse height permits the scintillator to be used as a *gamma-ray spectrometer.* By recording the number of pulses occurring in a series of pulse-height intervals an energy spectrum is obtained, which can be used for identification of the emitter.

The spectrum obtained from even a single monoenergetic gamma emitter is not simple. A prominent feature is the *photopeak,* which results from a photoelectric photon-electron conversion by the photoelectric effect. Monoenergetic electrons result from the conversion but statistical fluctuations in the crystal and at the photocathode produce a broadening in the recorded line, Fig. 7-10. Compton scattered photons have a good chance of absorption in the crystal; these will contribute a continuous spectrum ranging from the photopeak down to a limit associated with backscatter through 180°.

Simultaneous scintillations in the crystal will sum, adding to the complexity of the spectra, and also making them dependent upon crystal size. In a large crystal, for example, there is an increased chance of absorbing Compton scattered photons and hence an increased chance that these will interact and add to the light produced by the first Compton electron. This summation enhances the main photopeak.

Figure 7-10 shows the gamma-ray spectrum of the positron emitter Na^{22}. The broadened photopeak and continuous Compton spectrum are evident. Positron-electron annihilations produce the 0.51 Mev peak and some of these events sum with photopeak pulses

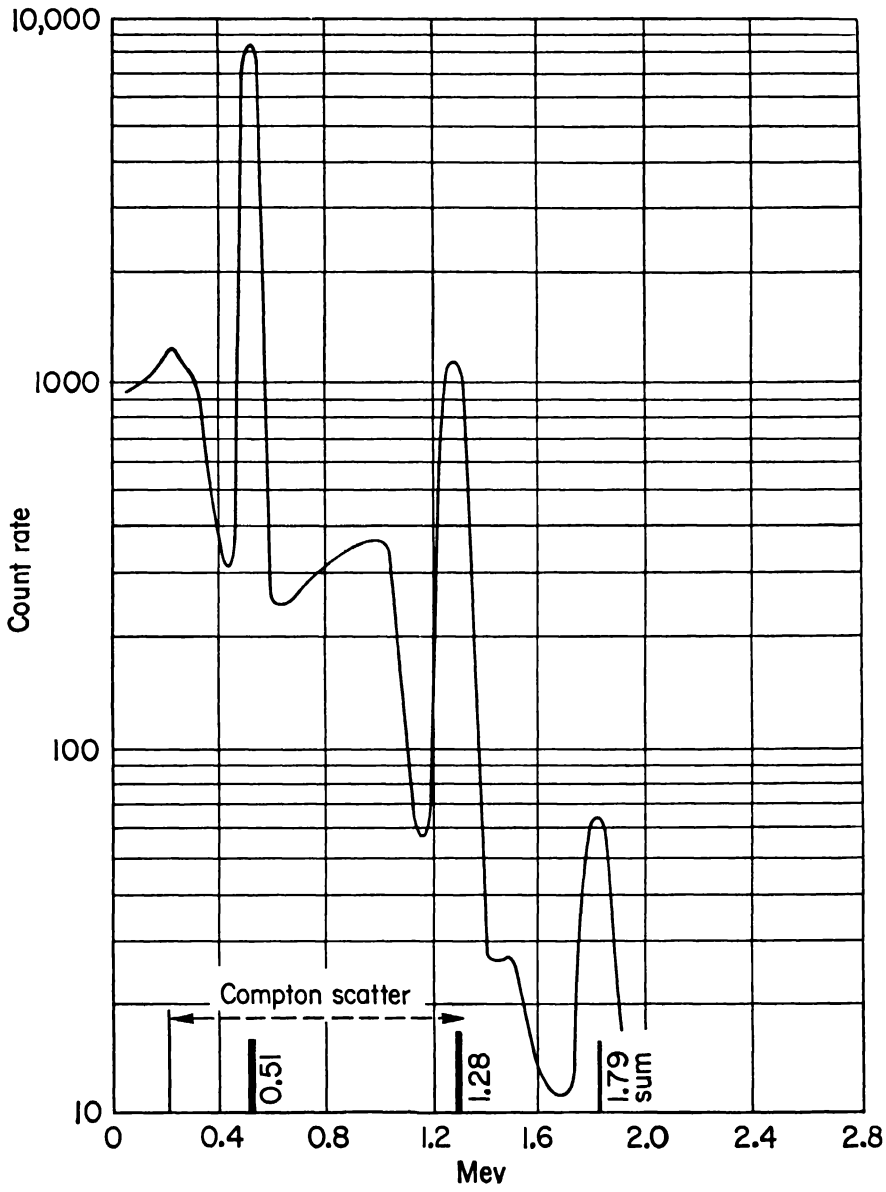


Fig. 7-10. Gamma-ray spectrum of Na^{22} from a scintillation spectrometer.

to give the 1.79 Mev line. Gamma-ray spectra can usually be identified by comparison with knowns but complex calculations are required to obtain a true emission-energy distribution from a recorded spectrum.

7.14 LIQUID SCINTILLATORS

It is sometimes desirable to have a photomultiplier "see" a scintillator solution in which the ionizing particles expend their energy. No known liquids are efficient scintillators, so the desired material must be put in a suitable solvent. Most good scintillators are linear arrangements of aromatic rings and require organic solvents such as toluene or xylene. The scintillator is present to only 1–5 gm per liter so the absorption characteristics are determined primarily by the solvent.

Most scintillators emit light of too short wavelength for efficient photomultiplier response so a third constituent, known as a *wave-shifter*, must be added. The wave-shifter absorbs the short wavelengths and emits longer wavelengths more suited to the photocathode. Frequently the samples to be assayed are soluble in water, but not in the organic liquids making up the scintillator solution. In these cases a fourth constituent, such as alcohol, must be added. Tritium, for example, can be counted as T_2O in a liquid scintillator containing alcohol.

The human whole-body counter may use as much as 150 gallons of liquid scintillator so arranged that the body is counted in nearly 4π geometry. A battery of photomultiplier tubes looks at the liquid and produces pulses which are ultimately fed into a pulse-height analyzer.

7.15 SCALING CIRCUITS

Mechanical registers fail to respond at counting rates much lower than those where resolving time becomes important, so *scaling circuits* must be introduced. The basic unit, or *binary scaler,* is a circuit having two stable states. Each incoming pulse shifts the circuit from one state to another, as A to B or B to A. A succeeding circuit will respond only to a shift from A to B, so it responds at a rate one-half that of the first circuit. Such a device is called a scale of 2, and by repetition one obtains scales of 4, 8, 16 . . . 64, ...

By special connections a scale of 16 can be converted to a scale of 10 and these units can be cascaded to obtain higher decimal scaling factors. A mechanical register will record the scaled number

of counts; to these are added the number of counts still held in the scaling units, and displayed by any of a variety of ways.

7.16 COINCIDENCE AND ANTI-COINCIDENCE

Special applications require the use of circuits which will record only when two or more counters receive a pulse within a very short time interval. In one application *coincidence counting* has been used to improve the localization of radioactive materials in brain tumors.*

Consider a positron emitter such as As^{74} localized at point *O*, Fig. 7-11. Each positron, at the end of its path, will combine with an electron to produce two oppositely directed gamma rays. A single scintillator at *A* will record these photons but will give little clue as to the point of origin. Two scintillators in coincidence will record at *A* and *B* only, but not at *A'B'* and *A"B"*. Thus the coincidence circuit achieves a considerable amount of localization.

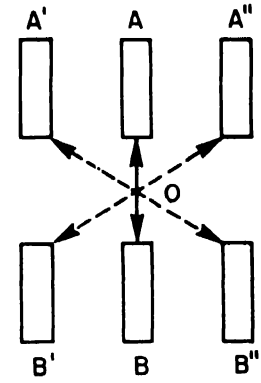


Fig. 7-11. Schematic for localization by coincidence counting.

Anti-coincident circuits can be used to reduce the background count due to penetrating cosmic radiation. The geometrical arrangement is shown in Fig. 7-12. Many of the penetrating cosmic-ray events will simultaneously trip both counters *A* and *B*, but in anti-coincidence these counts will not be registered. A count in detector *A* alone, produced by radiation from *O*, will be passed on to the scaling circuits. Low-level counters may use batteries of anti-coincidence counters † to "protect" a central volume in which the sample is placed.

PROBLEMS

7-1. An ionization chamber filled with air at atmospheric pressure is to be used to assay C^{14}. Assume a spherical chamber with the sample placed at the center and calculate the minimum radius needed to achieve maximum ionization. *Ans.* 23.2 cm.

* Brownell, G. L. *Acta Radiol.* **46**, 125, 1956.

† Miller, D. F., L. D. Marinelli, R. E. Rowland, and J. E. Rose *IRE Trans. Nuc. Sci.*, **NS-3**, 90, 1956.

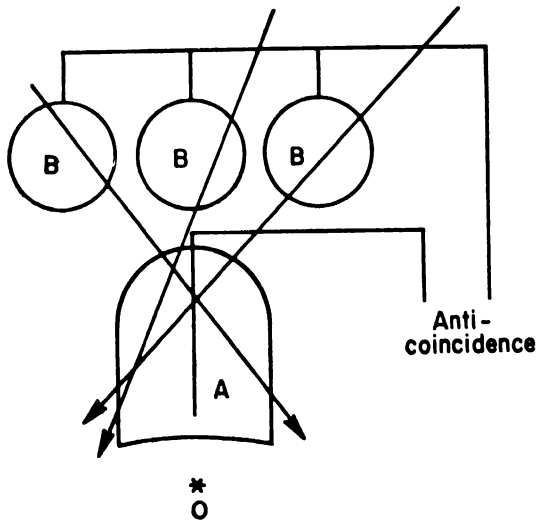


Fig. 7-12. Reduction of background by anti-coincidence counting.

7-2. Estimate the percentage loss of ionization in the chamber of Prob. 7-1 if C^{14} is assayed through a window of 5 mg/cm^2 equivalent thickness instead of being introduced into the chamber.

7-3. An ionization chamber-electrometer system has a capacitance of 40 μμfd. What will be the size of a voltage pulse produced by an alpha particle from Po^{210}? *Ans.* 6.23×10^{-4} volts.

7-4. What average current will be produced by 0.015 μc of Po^{210} placed in the chamber of Prob. 7-3 with 2π geometry? What will be the average current if 0.02 μc of H^3 is introduced into the chamber as H_2?

7-5. It is desired to obtain a signal of 0.5 volts from the chamber described in Prob. 7-4 with the Po^{210} sample. What value of series resistance must be used? *Ans.* 7.2×10^{10} ohms.

7-6. What is the time constant of the chamber electrometer system with the resistance as calculated in Prob. 7-5?

7-7. The allowable concentration of Sr^{89} ($\bar{E}_\beta = 0.56$ Mev) in drinking water is 7×10^{-5} μc per ml. To measure this, what size sample must be evaporated for measurement in 2π geometry in a chamber and electrometer set-up capable of detecting a current of 2×10^{-13} amp? *Ans.* 58.6 ml.

7-8. A G-M tube collects 10^9 electrons per pulse. What voltage pulse will be produced in a tube with a capacitance of 25 μμfd?

7-9. A G-M tube has a volume of 30 ml and is filled with 90 per cent argon and 10 per cent alcohol to a total pressure of 10 cm of mercury. Calculate the useful life of the tube if 10^9 alcohol molecules are dissociated at each pulse. *Ans.* Maximum life 10^{10} pulses.

7-10. The G-M tube of Prob. 7-9 is used in a survey meter and reads 40 counts per minute at a location where background radiation is 0.0018 mr/hour. Estimate the useful life of this tube in hours if it responds to an average intensity of 10 mr/hour.

7-11. Calculate the lower energy limit of the Compton scattered photons from Co^{60}, as recorded by a gamma-ray spectrometer. What summed peaks would be expected? *Ans.* 210 Kev, 2.50 Mev.

7-12. A scintillation counter has an over-all counting efficiency of 8 per cent in the 1.1–1.4 Mev range, and shows a count of 200 per minute on a 1500 ml, 24 hour urine sample from a worker who has accidentally ingested Co^{60}. Calculate the body burden of Co^{60} assuming an excretion rate of 2 per cent per day.

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8

RADIOACTIVE ASSAY

8.01 GENERAL CONSIDERATIONS

Measurements of radiation in its various forms have many aspects—only a few can be considered here. The assay of isotopes in tracer studies represents the most common application and will serve to illustrate the principles back of other types of measurement.

Radioactive tracing is simple in principle. If the fate of a particular molecular configuration is to be studied, a sample of the compound is synthesized with a fraction of a normal stable constituent replaced by a radioactive isotope. A portion of the *tagged* compound can be administered by any desired route and samples withdrawn later for radioactive assay. Each measurement can then be expressed as a fraction of the amount administered.

Tracing is relatively simple in a physical system which is in equilibrium or which tends toward equilibrium. For example, sup-

pose a closed compartment containing a fluid of unknown volume V. A volume v having a concentration of c_1, microcuries per ml is added and after mixing is complete a concentration c_2 is measured in a small aliquot. Then, obviously,

$$(V + v)c_2 = vc_1$$

and

$$V = \frac{v(c_1 - c_2)}{c_2} \tag{8-1}$$

A living system may exist in a steady state, but metabolic processes usually preclude the static equilibrium condition represented by Eq. (8-1). Thus, biological tracing data must be interpreted with a good bit of caution and results frequently require collateral information for a complete understanding.

8.02 BASIC REQUIREMENTS

Several requirements must be fulfilled if a radioactive isotope is to be successfully used as a tracer in a biological system. The first requirement is obviously that the radioactive isotope behave as nearly as possible like the stable isotope it replaces. If, for example, C^{14} is used as a tracer for naturally occurring carbon it is necessary to know that C^{14} will behave nearly like the stable nuclides C^{12} and C^{13}. The radioactive isotope will certainly enter into the desired chemical reactions, for chemical properties are determined by the number of orbital electrons, and hence by Z. Since C^{14} is a heavier nucleus, we might expect some differences in reaction *rates,* however, and this is indeed the case.

With elements of high atomic number the percentage mass difference between stable and radioactive nuclei is small and the rate differences may be negligible. The most serious situation arises with hydrogen, where H^3 has a mass about three times that of the most abundant stable hydrogen isotope. In the case of hydrogen, differences in reaction rates are sufficient to produce death * in mice when about 30 per cent of the light isotope is replaced by H^2. When

* Katz, J. J., H. L. Crespi, R. J. Hasterlich, J. F. Thomson, and A. J. Finkel. *J. N. Cancer Inst.* **18**, 641, 1957.

exact reaction rates are required collateral data may be needed to establish the isotopic mass effect.

A second requirement is that the amount of administered material be not so great as to alter the existing situation. This requirement puts a lower limit on the specific activity of the administered material. In general this is not a severe restriction, for high specific activity isotopes are usually available. In some cases, however, the dictates of specific activity may require the use of an elaborate, high-yield synthesis in place of a simpler process which results in a greater dilution. No rigid criteria can be given as to the amount of isotope tolerated without distorting normal conditions. Each case must be considered on its own merits and the validity of the tracing procedure must be established.

It is also necessary to insure that the amount of radiation produced by the administered isotope does not seriously alter normal events. Again rigid criteria are hard to establish since there is a wide difference in the radiation sensitivity of various normal functions. For most purposes it is probably safe to permit *in animals* one rad in 24 hours, 4 rad per week or 8 rad per month to any or all body tissues.

The use of radioactive isotopes in humans requires a different set of criteria, for here the effects of radiation on life span, carcinogenesis, and genetic inheritance must be considered. Special license is required from the Atomic Energy Commission for the use in humans of Commission-produced isotopes and a local committee must pass on each proposed human application.

8.03 ISOTOPIC EXCHANGE

A radioactive isotope must have reasonable values of half life and energy of emission if it is to be suitable for use as a tracer. Availability and cost will be weighed in terms of the importance of the anticipated results. In addition to these requirements it is essential that the tracer used have a negligible exchange with other isotopic atoms. This criterion may be difficult to establish but until it is the results of a tracer study will be uncertain.

Exchange is the free, reversible interchange of atoms of a given element between the labelled molecules and other unrelated compounds. Consider, as an example, the metabolic fats of glucose,

$C_6H_{12}O_6$. The short half life of O^{14}, O^{15}, and O^{19} precludes the use of oxygen as a tracer, but both H^3 and C^{14} are available and have reasonable characteristics. Hydrogen is, however, a very labile atom and H^3 put into glucose might reversibly exchange with the H^1 and H^2 present throughout the body. Preliminary experiments would be needed to establish which, if any, of the positions could be used for H^3 labelling. If all proved unsatisfactory a C^{14} label would be required.

8.04 THE PROBLEM OF SYNTHESIS

A wide variety of compounds with radioactive labels is now available commercially and consequently the problems of synthesis do not arise frequently. It is occasionally necessary, though, to start with an isotope as produced by accelerator or reactor, and use it in the synthesis of the desired compound.

Except in unusual circumstances a compound cannot be labelled by direct exposure to neutrons or charged particles. An n, γ reaction will produce a radioactive isotope of the original element, but when the gamma ray is emitted, recoil of the nucleus is almost certain to break molecular bonds and thus destroy the original structure.

Careful planning is required when a complex molecule must be synthesized from the inorganic compounds usually supplied from the reactor. The quantity of radioactive material is small and if precipitations are involved it may be necessary to add carrier to insure that the solubility product is exceeded. Usually carrier must be added with discretion to avoid undue loss of specific activity. Convenience must frequently be subordinated to yield and unusual reactions must be used to prevent loss of material.

Many products of biological importance cannot be synthesized; they must be labelled by natural production methods. *Biosynthesis* with C^{14} labelling can be achieved by growing plants in an atmosphere of $C^{14}O_2$ using C^{14} labelled synthetic nutrients.* Foxglove, snapdragon, opium poppy, Hevea, and many other plants have been successfully cultivated in this manner.

Biosynthesis will not place the radioactive isotope in a particular position; the resulting compounds are *uniformly labelled.* Some radiation injury to the plant is inevitable during biosynthesis, so

* Scully, N. J., et al. *Proc. Geneva Conf.* **12**, 377, 1956.

that a compromise must be made between injury and high specific activity.

In some cases chemical exchange can be used to obtain a desired product. Thus a given material, kept in an atmosphere of H^3, may acquire an equilibrium concentration of the active isotope. The labelled material can be used wherever exchange processes are not important or can be minimized.

8.05 COUNTING STATISTICS

Each nuclear disintegration is an independent event uninfluenced by other similar events, or by external conditions. As a consequence of this random origin, the disintegration rate will fluctuate above and below an average rate, which can be determined in principle by obtaining the total number of disintegrations in an infinitely long time. Any type of properly operating assay equipment, operated for relatively short periods, should reflect fluctuations in the disintegration rate.

In the following discussion the minute will be taken as the unit of time. Each counting time is assumed to be so short that decreases in rate due to decay can be neglected. In general this condition is easily met. If it is not, corrections can be made to the measured values.

Probability theory states that in a random process the probability that exactly N events will occur in time t is given by

$$P_N = \frac{(\overline{R}\, t)^N e^{-\overline{R}t}}{N!} \tag{8-2}$$

where $\overline{R}$ = average rate of occurrence
$N!$ = N factorial = $1 \times 2 \times 3 \ldots N$

Equation (8-2) is an expression of the *Poisson* distribution. The product $\overline{R}\, t$ is the number of events expected on the average during interval t.

$\overline{R}$ is the value desired from a radioactive assay. The assay must be so carried out that $\overline{R}$ can be inferred, within specified limits, from measured values of N and t. The most important statistical quantity associated with a measurement of N is the *standard deviation*

$\sigma_N = \sqrt{N}$. Since there is no fluctuation in t we have, in terms of rates, since $R = N/t$

$$\sigma_R = \frac{\sqrt{N}}{t} \tag{8-3}$$

What is really needed is the standard deviation of $\overline{R}$. Since R is only an estimate of $\overline{R}$, σ_R is only an estimate of $\sigma_{\overline{R}}$.

From Eq. (8-2) it can be shown that a single determination of $R = N/t$ has a 68 per cent chance of falling within $\pm\sigma_R$ of the true rate $\overline{R}$, 95.3 per cent within $\pm 2\ \sigma_R$, and 99.7 per cent within $\pm 3\ \sigma_R$. Standard deviation may also be expressed as a fraction of the quantity being measured. This is known as *variation.*

$$V_N = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}} \tag{8-4}$$

A properly operating counter should give a series of values of R which obey the Poisson distribution about $\overline{R}$. If the variations are either greater or less than expected some malfunction is probable.

Illustrative Example

A series of two-minute counts was made on a Co^{60} sample to check the behavior of a G-M counter:

No.	Counts	CPM(R)	Deviation from the mean
1	6978	3489	+ 2
2	7024	3512	+ 25
3	7047	3523	+ 38
4	6808	3404	− 83
5	6916	3458	− 29
6	6884	3442	− 45
7	7012	3506	+ 19
8	7200	3600	+113
9	6912	3456	− 31
10	6968	3489	− 3
Total	69749	34874	
Mean		3487	

Estimated $\sigma_R = \sqrt{3487} = 59$ cpm $\qquad V_R = 1/59 = 0.017$

Two of these values are more than σ_R from the mean. Three would be expected but in this short series agreement with theory is satisfactory.

8.06 EFFECT OF BACKGROUND

When a sample is being assayed the detector is responding to background radiation as well as to events originating in the sample. An independent determination of background is made and the net counts obtained by subtraction. Statistical theory gives the standard deviation of the rate due to the sample alone as

$$\sigma_S = \sqrt{\sigma_T^2 + \sigma_B^2} \tag{8-5}$$

where the subscripts S, T, and B refer to sample, sample plus background, and background, respectively. From Eq. (8-3) this becomes, for the rates

$$\sigma_S = \sqrt{\frac{N_T}{t_T^2} + \frac{N_B}{t_B^2}} = \sqrt{\frac{R_T}{t_T} + \frac{R_B}{t_B}} \tag{8-6}$$

The corresponding fractional deviation or *variation* V_S is

$$V_S = \frac{1}{R_T - R_B}\sigma_S = \frac{\sigma_S}{R_S} \tag{8-7}$$

The particular requirements of an assay fix a desirable value of V_S and hence σ_S. Note that in general V_S must be made smaller than the desired precision of the measurement. Suppose, for example, that a given net counting rate is desired to a percentage of 2 per cent. V_S can be set equal to 0.02 and appropriate values of t_T and t_B determined. An assay made under these conditions has however only a 68 per cent chance of being within 2 per cent of the correct value. If counting times are determined from $V_S = 0.01$ the chance of being correct to 0.02 rises to 95 per cent.

8.07 ASSAY TIME

Equation (8-6) permits an evaluation of a counter in terms of the time required to obtain an assay with a given V_S. As written, Eq. (8-6) can be satisfied by a variety of combinations of t_T and t_B. It is possible to obtain an expression for the combination that will minimize the total counting time. Here we will consider only the special case of making all counts to a predetermined time; $t_T = t_B$.

With this restriction Eqs. (8-6) and (8-7) lead to

$$t_T = \frac{R_T + R_B}{V_S^2 R_S^2} = \frac{R_S + 2R_B}{V_S^2 R_S^2} \tag{8-8}$$

If approximate values of R_S and R_B are known Eq. (8-8) can be used to obtain an estimate of the counting times and the numbers of counts required to obtain a desired value of the variation, V_S.

Illustrative Example

Calculate the counting times and the numbers of counts required to obtain a variation of 0.02 for a sample known to give about 250 cpm in a counter where $R_B = 40$ cpm. By Eq. (8-8)

$$t_T = \frac{250 + (2 \times 40)}{(0.02)^2 \times (250)^2} = \frac{330}{25} = 13.2 \text{ min}$$

Total counting time $2 \times 13.2 = 26.4$ min.
Total background count $40 \times 13.2 = 528$.
Total counts with sample $290 \times 13.2 = 3828$.

Equation (8-8) permits a comparison of two assay systems in terms of the time required to attain a given value of V_S. Consider two systems that may have quite different values of R_T and R_B for a given radiation source. Then

$$\mathrm{M} = \frac{(t_T)_1}{(t_T)_2} = \frac{(R_S + 2R_B)_1}{(R_S + 2R_B)_2} \cdot \frac{(R_S^2)_2}{(R_S^2)_1} \tag{8-9}$$

For high values of sample activity R_B becomes negligible and then

$$\mathrm{M} = \frac{(R_S)_2}{(R_S)_1} \tag{8-10}$$

As would be expected, the lower assay time is obtained with the system having the greater response to the sample.

For very weak samples $R_B > R_S$ and we have

$$M = \frac{(R_S^2)_2}{(R_S^2)_1} \cdot \frac{(R_B)_1}{(R_B)_2} \tag{8-11}$$

In some detectors changes designed to increase R_S will produce an almost proportional increase in R_B. As Eq. (8-11) shows, however, there will still be an advantage in favor of the higher counting rates. This advantage will be greatly increased if a differential increase in R_S relative to R_B can be made. This increase is frequently possible in gamma-ray spectrometers.

The above analysis has been carried out in terms of $t_T = t_B$. Iden-

tical results are obtained if we set $N_T = N_B$. This is the condition that obtains if all assays are made to a predetermined total count.

8.08 RESOLVING TIME CORRECTIONS

When strong sources are being assayed, care must be taken to insure that the equipment is operating properly. Ionization-chamber systems must be operated at saturation at the highest intensities if response is to be proportional to activity. Saturation conditions can be readily checked by increasing the chamber voltage during a measurement. If ionization current increases with voltage, saturation is not being maintained.

The problem is different with pulse counters which have a resolving time during which the system will not produce a countable pulse. If the tube has a resolving time τ minutes it will just respond correctly to $1/\tau$ evenly spaced pulses per minute. Radioactive decays are not evenly spaced, however, so a pulse counter will miss some pulses even when the average rate is quite low.

Let a true counting rate be R per unit time, with a detector of resolving time τ responding at a rate of only r per unit time. Then in unit time the total insensitive time is $r\tau$ and there will be $Rr\tau$ counts missed. The number of counts missed is also $R - r$ and so

$$R - r = Rr\tau$$

and

$$R = \frac{r}{1 - r\tau} \tag{8-12}$$

Self-quenching G-M tubes have a relatively long resolving time ($\sim 10^{-4}$ sec) and appreciable losses occur at rather low rates. Corrections are needed with proportional or scintillation counters only at very fast rates. In any case arrangements should be made to count at a lower rate if the losses amount to perhaps 15 per cent of the actual count.

Resolving time is usually determined experimentally from four measurements involving two sources of sufficient strength to cause appreciable counting loss. With one source in position a rate is determined. A second source is introduced and a new rate determined.

The first source is removed for a third measurement, and finally the background count is obtained. The observation may be tabulated

Observed	Expected
r_1	R_1
r_{12}	$R_1 + R_2 - R_B$
r_2	R_2
R_B	R_B

These data give three equations of the type of Eq. (8-12) connecting the unknowns R_1, R_2 and τ. The solution for τ is

$$\tau = \frac{r_1 + r_2 - r_{12} - R_B}{r_{12}^2 - r_1^2 - r_2^2} \tag{8-13}$$

In making resolving-time corrections care must be taken to use the same units of time in τ and in all of the *rs*.

8.09 SELF-ABSORPTION

When beta assays are made on solid samples some of the beta particles may be absorbed within the sample itself. Corrections for loss due to *self-absorption* must be made if samples of different size are to be assayed, or if absolute activity values are required. Corrections for self-absorption are usually made from a series of counts taken on a series of weighed samples covering a range of thicknesses.

When self-absorption is appreciable a plot of specific activity (cpm/mg) as a function of sample size will appear as in Fig. 8-1. The smooth curve can be readily extrapolated back to zero sample weight, to give a value of specific activity without self-absorption. If a series of samples of reasonably constant density are being assayed a plot similar to Fig. 8-1 can be used as a working curve to correct all measurements to a constant self-absorption.

Figure 8-1 shows clearly the reduced contributions from thick samples because of absorption of betas emitted by underlying material. Eventually an *infinite thickness* will be reached, where all emissions from the lower layers are absorbed. Beyond infinite thickness count rate will remain constant, and measured specific activity will decrease proportionately to the sample size. Specific activity at infinite thickness can be used for relative measurements but will not give absolute values.

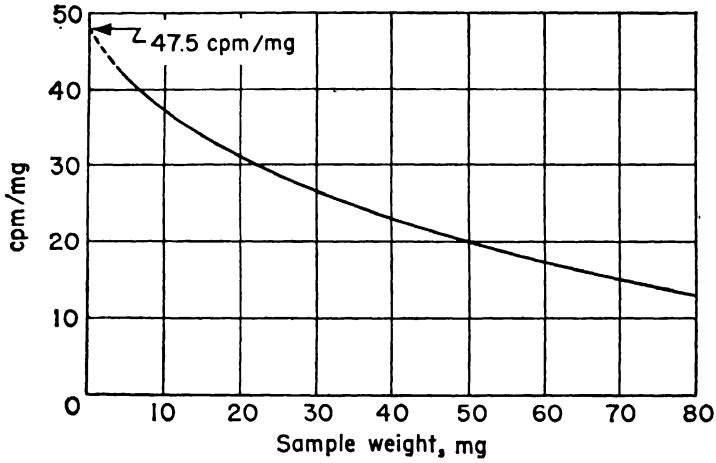


Fig. 8-1. Specific activity as a function of sample weight.

Self-absorption data may also be plotted as in Fig. 8-2. In this plot the specific activity without absorption is determined from the initial slope and the infinite thickness value from the height of the plateau.

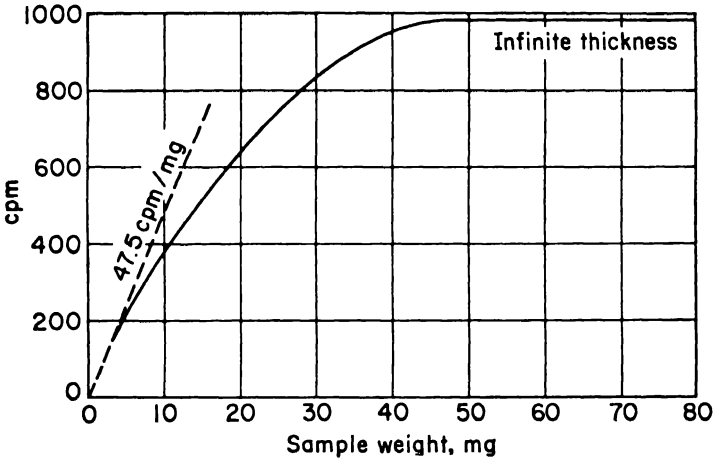


Fig. 8-2. Total sample activity as a function of sample weight.

8.10 COUNTER GEOMETRY

It is possible to make a radioactive sample very thin and mount it on a very thin support in the center of the sensitive counting

volume in 4π geometry. Usually, however, only a fraction of the emitted particles can enter the detector. The fraction entering does not depend upon Euclidian geometry alone; scatter from sample supports and shielding structures can increase the fraction, and window absorption can reduce it.

The fraction of particles counted out of those emitted is known as the *geometry* or efficiency of the system. Geometry is seldom calculable and in many cases need not be known. In the usual tracing experiment an assay of the administered material is made at some convenient efficiency. If all samples are assayed with the same geometry all results can be expressed as a fraction of the amount administered without knowing absolute values.

In a few cases counter efficiency can be calculated. This is the case for photon detection with a sodium-iodide scintillator if the geometrical arrangement is properly arranged. Figure 8-3, calculated

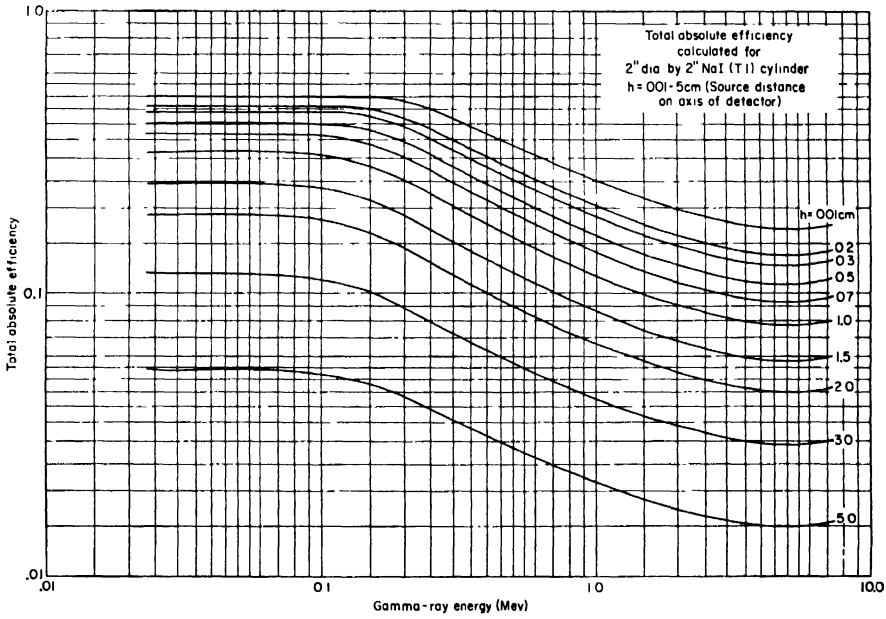


Fig. 8-3. Photon efficiencies of a sodium iodide crystal. From "Scintillation Spectrometry Gamma Ray Catalogue." AEC Research and Development Report IDO–16108.

from the known absorption coefficients of sodium iodine, is typical of scintillator efficiencies.

A good many isotopes are now available as standardized samples

from the National Bureau of Standards and some commercial sources. Counter efficiency can be determined with these standards but for absolute counting all samples must be mounted in identical fashion.

If the decay scheme of a nuclide is accurately known counter efficiency can sometimes be established by coincidence counting. Coincidences may be of several different kinds but for simplicity consider a β,γ coincidence from a nuclide emitting $a\gamma$ rays for each β. The counting arrangement will be as in Fig. 8-4.

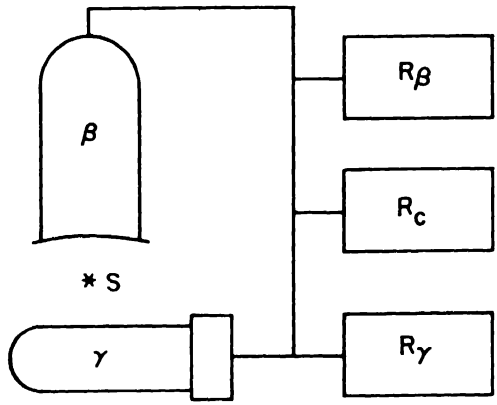


Fig. 8-4. Schematic counter arrangement for coincidence counting.

Let the source have a disintegration rate R. Then the beta-count rate will be

$$R_\beta = R\varepsilon_\beta + R_{B\beta} \tag{8-14}$$

where ε_β = efficiency of the beta counter
$R_{B\beta}$ = background rate of beta counter

Similarly for the gamma count

$$R_\gamma = aR\varepsilon_\gamma + R_B\gamma \tag{8-15}$$

When the two counters are connected to give a count only on coincidence there will be a small rate R_B due to cosmic rays and other background radiation. This background can be minimized but not eliminated. There will also be a chance coincidence due to the simultaneous arrival of a beta from one disintegration and a gamma from another. This statistical coincidence can be shown to have a rate

$$R_s = 2R_\beta R_\gamma \tau \tag{8-16}$$

where τ is the time during which the circuit will accept coincidence.

When the coincidence count is made a rate

$$r_C = R_C + R_B + R_s \tag{8-17}$$

will be observed. The two chance coincidence factors can be subtracted to give R_c. This true coincidence is

$$R_C = aR\varepsilon_\beta\varepsilon_\gamma \tag{8-18}$$

We now have three equations, Eqs. (8-14), (8-15), and (8-18), in three unknowns and these can be solved for ε_β, ε_γ, and R.

8.11 CARBON-14 ASSAYS

Radioactive carbon, usually as C^{14}, is one of the most important radioactive nuclides. Its relatively soft beta emission makes assays difficult, but many good methods have been developed. The large bulk of biological samples must be reduced if C^{14} assays are to be made without excessive self-absorption.

C^{14} is usually counted in the solid state as barium carbonate. All the carbon in the sample can be burned to CO_2 and the gas bubbled through a barium hydroxide solution. A fine-grained precipitate of barium carbonate will be formed, which can be dried on a planchet for assay.

Carbon activities of the order of 10^{-6} μc/gram have been assayed * in a screen-wall counter. The screen-wall counter permits the use of as much as 10 grams of sample spread over a large area. The counter has a large background but heavy shielding and anticoincidence methods reduce it by a factor of about 100.

Carbon can be assayed in the gas phase by taking advantage of the readily attainable freezing temperature of CO_2. The gross sample can be burned to CO_2 as before or CO_2 can be liberated from a barium carbonate precipitate by a strong acid. Water vapor can be absorbed by a suitable agent such as P_2O_5. A trap cooled with liquid nitrogen will freeze out all the CO_2 and then all noncondensed gases can be pumped off. The cold trap is then warmed and the CO_2 is moved into the counting chamber.

* Anderson, E. C., J. R. Arnold, and W. F. Libby. *Rev. Sci. Instr.* 22, 225, 1951.

If an ionization chamber-electrometer system is used, the chamber pressure must be brought up to a standard value with non-radioactive CO_2. CO_2 cannot be used in a pulse counter because of its tendency to form negative ions. These ions arrive late at the central wire to produce spurious pulses, which make counter action erratic.

Water-soluble C^{14}-containing compounds can be assayed in liquid scintillator solutions containing alcohol as a solvent. This method can be used with coincidence circuits to reduce background, and the whole detector system is sometimes maintained at a low temperature to reduce spurious fluctuations in the photomultiplier tubes.

8.12 ASSAY OF TRITIUM

Tritium assay poses some very difficult problems because of the very soft, 18 Kev beta-particle emission. Solid samples have been measured as stearates in a gas-flow counter but only small samples can be used since an equivalent thickness of 1 mg/cm^2 will absorb the H^3 betas. It appears that liquid or gas phase assays are to be preferred to solid-state measurements.

All the hydrogen in a sample can be burned to water and the latter can be added to a liquid scintillator,* miscibility being achieved with alcohol, as usual. Dioxane does not require the addition of alcohol but it is an inferior scintillator solvent and is not generally used.

Hydrogen is an acceptable counting gas; samples can be admitted directly into pulse counters and high geometrical efficiencies can be obtained. Unfortunately, tritium in the sample exchanges readily with any hydrogen adsorbed on counter surfaces or occluded in the walls and thus counters become quickly contaminated.

Tritium has been assayed in the gas phase by converting it to methane, a very satisfactory gas for pulse counters. Methane cannot be condensed at liquid-nitrogen temperature, making the quantitative transfer more difficult than in the case of CO_2. Gas-phase tritium assays can be done with ionization chambers and electrometers; † by applying some correction factors absolute measurements can be made.

* Hayes, F. N., and R. S. Gould. *Science* **117**, 480, 1953.

† Reich, H. G., I. T. Myers, and R. F. Palmer. *Rad. Res.* **4**, 451, 1956.

Tritium has also been counted as n-butane † produced from water by a Grignard reaction. Normal butane can be condensed by liquid nitrogen for efficient transfer, but it is not a good quenching gas, so this must be added. N-butane does not, however, interfere with the operation of pulse counters by negative ion formation.

Tritium can be counted as water in a liquid scintillator, taking all the usual precautions to reduce background and spurious fluctuations. The energy-pulse height proportionality of scintillators permits double labelling ** with H^3 and C^{14} and separate counting in a two-channel pulse-height analyzer.

8.13. PHOTOGRAPHIC EMULSIONS

Photographic materials are used in three different ways for measuring radiation. In a suitable holder to make the emulsion response more tissue-equivalent, photographic films are used to measure the exposure dose of external radiation. This most important application will be discussed in detail in connection with radiation safety practices.

Autoradiographs are produced when a photographic emulsion is brought into contact with or in close juxtaposition to a tissue slice bearing a beta-emitting radioactive nuclide. After a suitable exposure time processing will reveal blackened areas corresponding to the areas of isotope deposition. The techniques of autoradiography are legion; only general principles can be mentioned here. Special sources must be consulted before doing serious work in the field.

Autoradiography is a powerful technique because of its high ultimate sensitivity. Electrical circuits can integrate only over a limited time but emulsion can be exposed for weeks or months, until the accumulated effect of even weak emissions has produced a measurable photographic effect. Emulsions are available covering a wide range of sensitivities with the common materials requiring perhaps 10^5 beta particles per square millimeter to produce a measurable optical density.

Thin tissue sections must be used if good spatial resolution is required, in order to locate accurately the source of the beta emis-

† Glascock, R. F. *Proc. Geneva Conf.* **12**, 397, 1956

** Okita, G. T., J. J. Kalata, F. Richardson, and G. V. LeRoy. *Nucleonics* **15**, 111, 1957.

sions. Beta particles originating within a thick specimen will suffer multiple scattering before striking the photographic emulsion, and so will broaden the image. Tritium betas have such a short range that they can only emerge from a thin outer layer, and high-resolution autoradiographs can be produced from thick sections, Fig. 8-5.

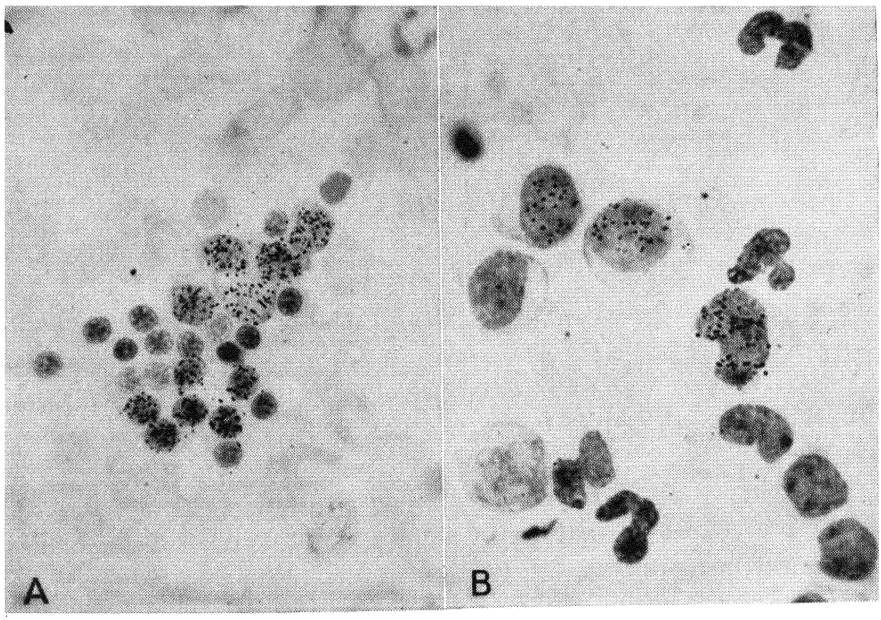


Fig. 8-5. Autoradiographs of erthythropoietic cells labelled with H^3 after one-hour incubation in vitro with tritiated thymidine. (A) Normal human bone marrow cells. (B) Peripheral blood cell of patient with chronic myelocytic leukemia. Courtesy of V. P. Bond, T. M. Fliedner, and E. P. Cronkite.

Nuclear track emulsions are used to detect and identify the tracks of individual ionizing particles. Alpha particles, protons produced most usually as a recoil from a fast neutron collision, and electrons have quite different values of LET and consequently can be readily identified by the track of ionization left in suitable emulsions. Emulsions have been invaluable in studying the properties of some of the newly discovered particles such as mesons and hyperons.

Nuclear-track emulsions are usually 50–100 microns thick instead of the more usual 8–10 microns; therefore special processing methods are needed for the thick materials. With carefully controlled pro-

cedures nuclear track emulsions can be used to measure exposure to fast neutrons. Quantitation requires the careful and tedious counting of proton tracks at high magnification. Here again technique approaches an art, so that work in an established laboratory is the best prelude to successful application.

8.14 REACTION KINETICS AND TRACERS

It has already been pointed out that most biological systems are dynamic and metabolizing, so that the results of many tracer studies must be interpreted in terms of reaction kinetics instead of as volumes of static compartments. A considerable mathematical background has been developed but the general treatment is too formidable for treatment here. A few special cases will suffice to illustrate the principles involved.

It is assumed that the tagged compound is administered into a single body system or *compartment,* using this word in a broad sense. Thus, "compartment" might refer to the blood stream, all body water, or a cell, set apart by its boundary membrane. The following symbols will be used:

P = amount of labelled compound in compartment A at time t.
p = concentration of labelled compound in compartment A at time t.
v_a = volume of compartment A.
k_{ab} = transfer coefficient from compartment A to B.
Q = amount of labelled compound in compartment B at time t.
q = concentration of labelled compound in compartment B at time t.
v_b = volume of compartment B.
k_{ba} = transfer coefficient from compartment B to A.
k_{bo} = irreversible transfer from B to outside.

Tracing experiments will provide values of p and q as a function of time. From these data it is desired to characterize the combined system in terms of the various transfer coefficients. In the cases to be considered the instantaneous flow of a given tagged species is considered equal to the product of the transfer coefficient and the amount of material in the source compartment. It is assumed that the labelled species is uniformly distributed throughout the compartment, a condition not always fulfilled in practice.

8.15 SPECIFIC EXAMPLES

Consider a constant concentration in compartment A with an irreversible flow into B ($k_{ba} = 0$) and an irreversible flow out of compartment B. Then in a short time Δt

$$\Delta Q = (k_{ab}P - k_{b0}Q)\Delta t \tag{8-19}$$

which integrates to give

$$Q = P_0 \frac{k_{ab}}{k_{b0}}(1 - e^{-k_{b0}t}) \tag{8-20}$$

where P_0 = quantity of label in A at $t = 0$. Eq. (8-20) has the exact form of Eq. (3-27) if the ks are identified with the λs, and this similarity is to be expected, since Eq. (3-27) was derived for the formation of a radioactive daughter from an essentially constant source. The reaction case is of limited application because it is not easy to maintain a constant concentration in compartment A. The ultimate quantity in B will be

$$Q_\infty = \frac{k_{ab}}{k_{b0}} P_0 \tag{8-21}$$

For the second example consider an isolated two-compartment system ($k_{b_0} = 0$). Assume $P = P_0$ and $Q_0 = 0$ at $t = 0$

$$\Delta P = (-k_{ab}P + k_{ba}Q)\Delta t \tag{8-22}$$

$$\Delta Q = (-k_{ba}Q + k_{ab}P)\Delta t \tag{8-23}$$

$$\text{from which } Q = \frac{k_{ab}P_0}{k_{ab} + k_{ba}}(1 - e^{-(k_{ab} + k_{ba})t}) \tag{8-24}$$

$$\text{at equilibrium } Q = \frac{k_{ab}P_0}{k_{ab} + k_{ba}} \tag{8-25}$$

It is evident from the simple examples given above that the mathematics becomes rather cumbersome for multi-compartment systems. The exponential equations obtained are analogous to those obtained when electrical condensers are charged and discharged through resistors. This parallelism permits the use of electrical analogue computers* to obtain the k values. For complex systems the

* Brownell, G. L., R. V. Cavicchi, and K. E. Perry. *Rev. Sci. Insts.* **24**, 704, 1953; Macdonald, J. R., E. G. Perry, L. L. Madison, and D. W. Seldin. *Rad. Res.* **6**, 585, 1957.

analogue computer is probably the only reasonable way of obtaining the *ks*.

PROBLEMS

8-1. An ionization chamber for the assay of Na^{24} is used with an electrometer capable of measuring a current of 10^{-15} amperes. Blood samples of 3 ml are to be measured in 2π geometry. How much Na^{24} must be given a 75 kg man if blood samples are to be analyzed 60 hours later? Assume uniform distribution and a biological half life of 55 hours and neglect gamma-ray ionization. *Ans.* 18.5 μc.

8-2. Estimate the tissue dose of radiation received in the first hour after the Na^{24} in Prob. 8-1 was administered.

8-3. An ionization chamber has a volume of 800 cm^3 and operates at atmospheric pressure. This chamber is used to count C^{14} as CO_2 in 4π geometry. How large a tissue biopsy can be used with this chamber if the tissue contains 13 per cent carbon by weight?
Ans. 3.3 grams.

8-4. A compound containing 2μc of C^{14} is given to a 70 kg man. What maximum ionization current can be expected in the ion chamber of Prob. 8-3? Assume uniform distribution and negligible excretion.

8-5. A G-M counter has a background rate of 30 cpm and is used to count a sample having a net count rate of twice background. Calculate the counting schedule needed to obtain a relative standard deviation of 0.01. *Ans.* Sample 500 min, background 167 min.

8-6. Repeat the calculation of Prob. 8-5 for a net sample-count rate equal to background. Repeat for a net sample-count rate of one-half background.

8-7. A G-M counter tube has a resolving time of 3×10^{-4} sec. Calculate the counting rate in cpm for which the loss will be 1 per cent.
Ans. 1,980 cpm.

8-8. A G-M counter tube has a resolving time of 1.6×10^{-4} sec. What is the true counting rate when the tube responds to 3300 cpm from a radioactive source?

8-9. The following data were obtained from a beta-gamma coincidence count on Co^{60}, which is known to emit 2 gamma rays for each beta particle.

$R_\beta = 3{,}266$, $R_\gamma = 1{,}643$, $R_{\beta B} = 26$, $R_{\gamma B} = 23$, $R_B = 1$, $r_C = 249$, cpm, $\tau = 5 \times 10^{-6}$ min.

Calculate the counter efficiencies and the activity of the sample.

Ans. 2.7×10^4 dpm, $\varepsilon_\beta = 0.12$, $\varepsilon_\gamma = 0.03$.

8-10. Calculate the dead time of a G-M counter from the following data:

Background 35 cpm
Source 1 in position 6,650 cpm
Both sources in position 13,300 cpm
Source 2 in position 7,250 cpm.

8-11. A sample known to contain about 0.01μc of H^3 can be assayed at 97 per cent geometry in an ionization-chamber electroscope system. How much time will be required to obtain an assay by rate of charge if the chamber has a capacitance of 25μμfd and the electroscope can detect a potential difference of 0.12 volts? *Ans.* 4 min 47 sec.

8-12. The tritium sample in Prob. 8-11 can be assayed in a liquid-scintillator pulse counter at 1.5 per cent efficiency. Anti-coincidence counters and heavy shielding have reduced background to 45 cpm. Calculate the time required to obtain an assay with a relative deviation of 0.01.

8-13. A 20 gram mouse is given a compound containing 0.7 μc of C^{14}. After equilibrium the animal is killed and sections taken for autoradiography. Estimate the exposure time required for a section 20 microns thick if the photographic material requires at least 5×10^5 particles/mm^2 to produce a satisfactory image.

8-14. The following data were obtained by measuring a series of weighed samples of a pure sample.

weight (mg)	2	4	6	8	10	15	20	25	30	35
cpm (net)	85	160	235	305	335	360	380	398	408	415

Plot a self-absorption curve and determine the specific activity of the sample with no absorption.

8-15. The transport of K^{42} from plasma into red cells can be used as an example of an isolated two-compartment system. Assume $k_{ab} = 0.07$/hour and $k_{ba} = 0.50$/hour and calculate the time course of buildup in the red cells. Assume a blood volume of 6.6×10^3 ml and a hematocrit of 0.35. Estimate the amount of K^{42} that would be needed in a 72 kg man to obtain a count of 200 cpm from a 2 ml blood sample 30 minutes after K^{42} administration.

9

ENERGY LOSS BY CHARGED PARTICLES

9.01 ENERGY-LOSS MECHANISMS

Frequent reference has been made to ionizations and excitations resulting from charged-particle collisions without considering in detail the nature of the interactions. These are not collisions in the ordinary macroscopic sense. Each moving charged particle has an associated electric field which moves along with the particle and interacts with the fields of other charges near which it passes. The distortion of the stationary field may be sufficient to release an orbital electron from control of its nucleus, or to raise it to an excited state. The forces of reaction on the moving charge will slow it and deflect it from its previous course. A heavy particle like a proton will show little deflection in an encounter; a moving electron will deviate sharply from its original path.

The interaction just described is an *inelastic collision,* and results in a loss of energy by the moving charge. We have already seen

that electromagnetic waves are radiated whenever a moving charge is accelerated (bremsstrahlung production) and hence there will be an additional energy loss known as *radiative energy loss*. Radiative energy loss is removed from the moving charge at the point of the acceleration but this energy may not be deposited in the medium near this point because of the relatively long mean free path of the photon. From previous discussion it would be expected that radiative energy loss would become more important at high particle velocities and in high atomic number media.

At low velocities the field of the moving charge will be almost spherically symmetrical, with an intensity which decreases as the inverse square of the distance. Under these conditions interactions with the fixed charges in a ponderable medium have a high probability. At higher, but still non-relativistic velocities, interaction probabilities will decrease because of the decreased times of interaction. At high relativistic velocities the moving field is distorted, shortening in the direction of motion and expanding in the transverse direction. This effectively increases the area swept out by the moving field and therefore increases the interaction probability. Thus there is an energy of *minimum ionization* or lowest energy loss per unit-path length.

Electric field strengths will fall off as the inverse square of distance only in a rarefied medium such as a gas. In a condensed medium such as a liquid the field will distort, or *polarize* close-lying atoms in such a direction as to effectively decrease the field at greater distances. Thus in condensed media collision energy loss will be reduced because of polarization.

9.02 COLLISION-ENERGY LOSS

Loss of energy through particle-particle interactions can be expressed in a variety of ways. *Collision-energy loss* dE/dx, is the amount of energy lost by the initiating particle per unit path length. Common units for dE/dx are ergs/cm, Mev/cm, or ev/μ. If dE/dx and W, the average energy required to form an ion pair are known, *specific ionization* can be determined. Primary specific ionization includes only those ions formed by the incident particle and total specific ionization includes the contributions from all secondary processes.

Linear energy transfer, LET, is a useful parameter first proposed by Zirkle.* It is defined as the energy deposition per unit path length of the original particle. LET is equal to collision energy loss less any radiative energy loss not locally deposited.

One readily observable component of some collision situations is known as *Cerenkov* radiation. Each moving charge has an associated electromagnetic field which is propagated at the electromagnetic velocity for the particular medium involved. In empty space this is $c = 3 \times 10^{10}$ cm/sec but in a dielectric medium such as glass or plastic the electromagnetic velocity may be substantially less than c.

A charged particle may readily be given a velocity nearly equal to c so that in a dielectric the field cannot keep pace with the particle. Under these circumstances the particle will decelerate to a velocity compatible with field propagation and Cerenkov radiation will be emitted.

Most of the Cerenkov radiation lies in the visible and ultraviolet and is readily observed. This radiation is just one form of collision energy loss and separate account need not be taken of it. At usually encountered energies Cerenkov radiation is only a small fraction of the total collision energy loss.

9.03 CLUSTER IONIZATION

Specific ionization, on a macroscopic scale, is a smoothly varying function of particle energy. On a microscopic scale primary ionization will occur with irregular spacings because of the chance nature of the individual encounters. Large variations from average values result from the formation of *ion clusters.*

In a primary ionizing event there is a reasonable probability that the orbital electron will be ejected with sufficient energy to produce ionization on its own account. The kinetic energy of the electron will not be large, its range will be correspondingly short, and any secondary ionizations will therefore take place very close to the original event. Because of this, ionizations tend to form in clusters instead of being uniformly distributed.

The formation of ion clusters plays an important role in some

* Zirkle, R. E. *J. Cell. Comp. Physiol.* **39**, Suppl. 75, 1952.

biological systems. For example, in a system which can be injured or inactivated by a single ionization, cluster formation represents a distinct loss of effectiveness. Conversely, a single hit may be ineffective, with injury production requiring more than one ionizing event closely contiguous in space and time. In this case a cluster may be effective where innumerable single events are without effect.

Ion-cluster formation can be studied with a *cloud chamber.* A cloud chamber consists of a cylinder with a viewing window at one end and closed at the other end with a tight-fitting piston. A small amount of water or other suitable liquid is put in the cylinder, which then becomes saturated with vapor. When the piston is suddenly withdrawn the expanding gases cool and become saturated. If suitable nuclei such as ions are present the supersaturated vapor will coalesce into visible droplets around each ion, and thus the path of an ionizing particle can be visualized.

Table 9-1 lists the distribution of cluster sizes as calculated from the data of C. T. R. Wilson.*

Table 9-1 DISTRIBUTION OF ION-CLUSTER SIZES

Ion pairs per cluster	1	2	3	4	more than 1
Fraction of clusters	0.45	0.22	0.11	0.10	0.12

9.04 SPECIFIC IONIZATION—EXPERIMENTAL

Measurements of specific ionization have been made with very thin ionization chambers. Characteristically, specific ionization produced by a single particle is nearly constant until it nears the end of its range. The particle then begins to lose energy at a more rapid rate until it is finally no longer able to ionize, Fig. 9-1.

Specific ionization is proportional to the square of the charge on the particle but otherwise is almost independent of the type of particle. The important parameter appears to be particle velocity; at equal velocities an alpha particle will produce a specific ionization almost exactly four times that of a proton.

When specific ionization is measured with a collimated particle beam, a *Bragg ionization curve,* Fig. 9-1, is obtained. This is quite

* Wilson, C. T. R. *Proc. Roy. Soc. London.* **A**, 104, 192, 1923.

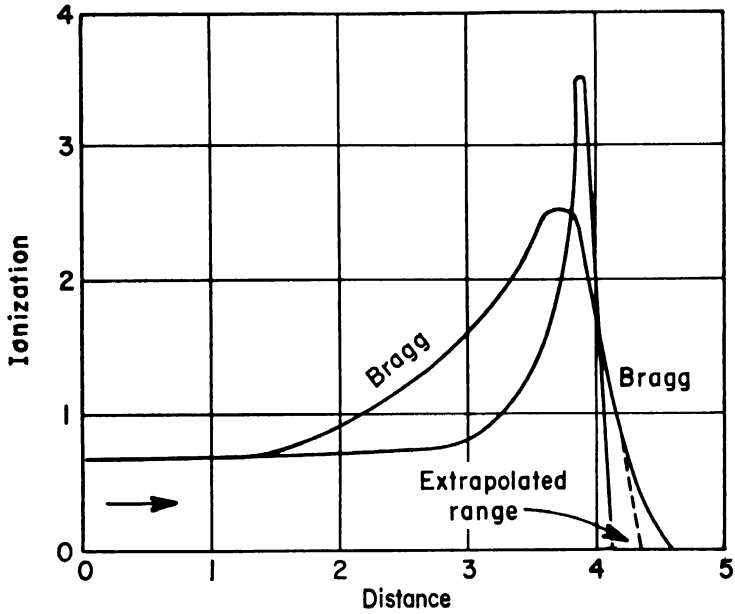


Fig. 9-1. Schematic ionization of a single particle and a Bragg curve for a large number of particles, originally monoenergetic.

similar to the corresponding curve for a single particle but even with a monoenergetic beam the region of maximum ionization is broader and the ultimate range portion does not cut the axis sharply but has a definite tail.

The broadening and *straggling* result from the chance nature of the collision. Straggling makes the determination of ranges difficult. The descending portion of the Bragg curve can be extrapolated to the axis as shown, to give the *extrapolated* range, and this can be related to the mean range by empirical equations.

9.05 RANGE OF BETA PARTICLES

Frequently a simple *aluminum absorption curve,* Fig. 9-2, can be used to establish the identity of a beta emitter by direct comparison with absorption data from knowns taken under identical counting conditions. It is not possible to determine the maximum range of

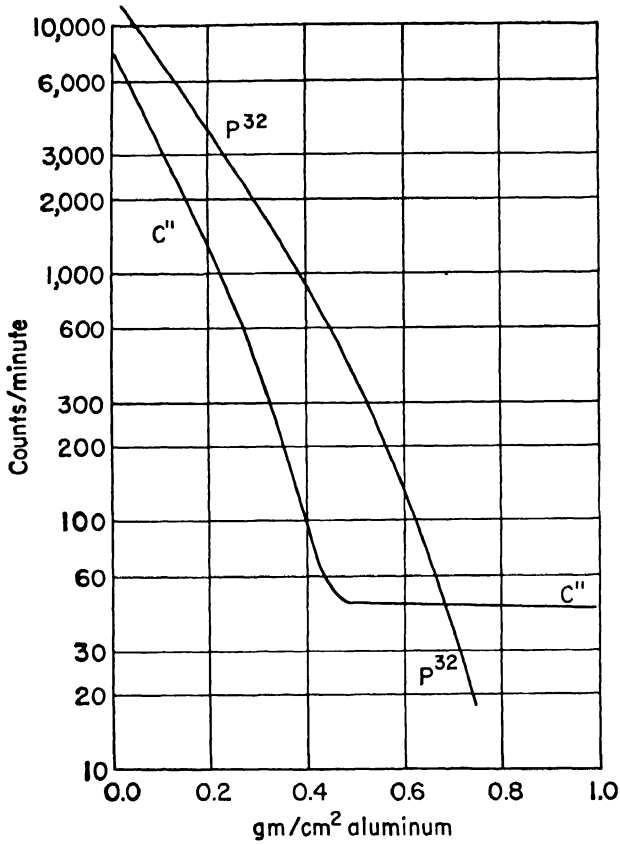


Fig. 9-2. Aluminum absorption curves for P^{32} and C^{11}. The P^{32} is typical of a pure beta emitter; C^{11} shows the tailing off due to annihilation radiation.

beta particles by an extrapolation similar to that of the Bragg curve. With a continuous-energy spectrum there is considerable difficulty in identifying the true end point so that range must be determined from a complex extrapolation process.

Feather based his method on the known range of 480 mg per cm^2 for the beta particles from Bi^{210} but other nuclides of known range can be used. Whatever the standard, two aluminum absorption curves are obtained under identical counting conditions. After all corrections for background, coincidence, and so on have been made, the two sets of data are normalized at the zero absorber point, and log (activity) plotted against absorber thickness, Fig. 9-3.

The abscissa is now divided into fractions of the standard range,

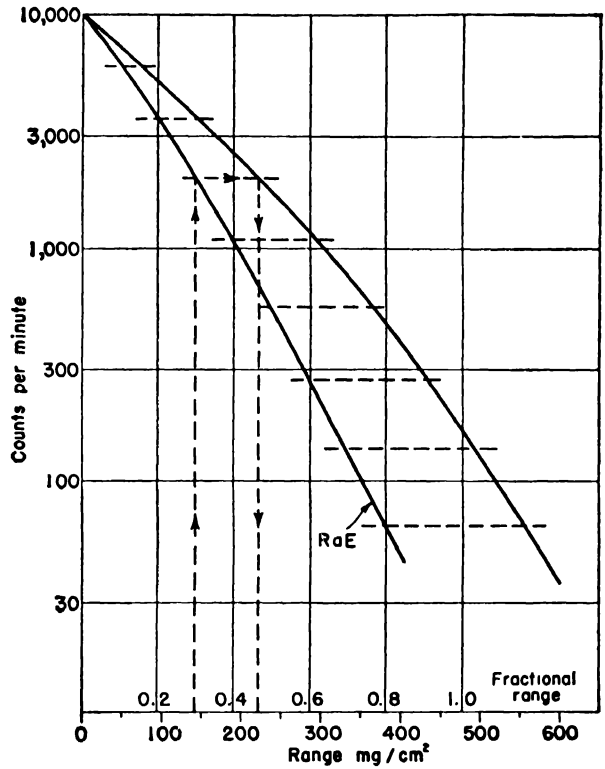


Fig. 9-3. Plot of absorption data for a Feather analysis.

tenths being a convenient subdivision. At each subdivision a vertical is erected to the standard curve, a horizontal is drawn to the unknown, and a second vertical dropped to the abscissa. Each of these verticals intersects the abscissa at a fractional range. When this fractional range is divided by the range fraction (221/0.3 = 737 in Fig. 9-3) an estimate of total range is obtained.

A plot of estimated total range as a function of range fraction, Fig. 9-4, will give a smooth curve which can be extrapolated quite accurately to the maximum range.

9.06 QUANTITATIVE RELATIONS—ELECTRONS

At low energies, when the velocity of the moving electron approaches that of the orbitals, capture is highly probable, and theo-

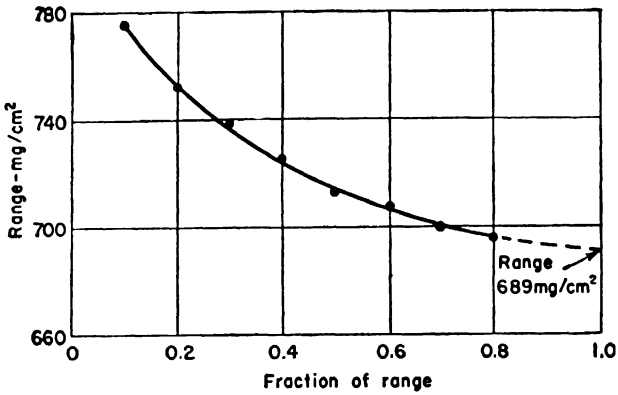


Fig. 9-4. Extrapolation of estimated ranges in Feather analysis.

retical calculations become extremely difficult. As a result, there is some uncertainty as to the exact situation at the end of electron tracks. At higher energies theory can account quite well for the observed ionizations.

An expression for collision energy loss at high energies has been given by Bethe and Ashkin.*

$$-\left(\frac{dE}{dx}\right)_c = \frac{2\pi e^4 NZ}{m_0 v^2}\left[\ln\frac{m_0 v^2 E}{2I^2(1-\beta^2)} - \ln 2(2\sqrt{1-\beta^2} - 1 + \beta^2) + (1-\beta^2) + \frac{1}{8}(1-\sqrt{1-\beta^2})^2\right] \tag{9-1}$$

where N = number of absorbing atoms per cm³
Z = atomic number of absorbing medium
v = velocity of moving electron
E = energy of moving electron, ergs
I = average ionization energy of absorber atoms, ergs
e = electron charge in esu.

Since collision energy loss is the result of interactions with orbital electrons it would be expected that it would be proportional to the electron density NZ and this term appears in Eq. (9-1). State of aggregation or chemical combination are without effect except as they alter NZ. Collision energy loss is a complex function of electron velocity, as can be seen from the numerous appearances of v and β in Eq. (9-1).

* Bethe, H. A., and J. A. Ashkin. *Experimental Nuclear Physics,* E. Segre, Ed., Vol. I. Wiley, New York, 1953.

Average ionization energy, I, is an important term in the collision energy loss function; considerable effort has gone into determining the proper values for it. Bakker and Segre * measured the first four values listed in Table 9-2. The other values were determined by interpolation.

Table 9-2 AVERAGE IONIZATION ENERGY

Substance	Z	I (ev)
H	1	15.6
C	6	76 5
Al	13	150
Air	—	80.5
N	7	88
O	8	98
Water	—	68

Since I appears in Eq. (9-1) as the natural logarithm, and since simple additivity seems to prevail, values for compounds can be calculated from the logarithmic average.

$$\ln \bar{I} = \frac{N_1 Z_1 \ln I_1 + N_2 Z_2 \ln I_2 + \cdots}{N_1 Z_1 + N_2 Z_2 + \cdots} \tag{9-2}$$

An expression for radiative-energy loss due to decelerations has also been given by Bethe and Ashkin. For materials of biological interest ($Z \leq 8$) this is

$$-\left(\frac{dE}{dx}\right)_r = \frac{NEZ(Z+1)e^4}{137 m_0^2 c^4}\left(4 \ln \frac{2E}{m_0 c^2} - \frac{4}{3}\right) \tag{9-3}$$

From Eq. (9-3) the rate of energy loss is about proportional to electron energy E and to Z^2. The total path length will be inversely proportional to Z and so the total radiative energy loss (or bremsstrahlung production) will be proportional to E^2Z. This is in accord with the empirical result given in Eq. (2-5).

Sternheimer † has developed expressions to be applied to $(dE/dx)_c$ to account for the polarization effect in condensed media. The corrections are about proportional to electron density NZ, and increase with particle energy. In water the correction to $(dE/dx)_c$ is about 10 per cent at 10 Mev. Figure 9-5 gives values of $(dE/dx)_c$ and $(dE/dx)_c + (dE/dx)_r$ the values for water being corrected for polarization.

* Bakker, C. J. and E. Segre. *Phys. Rev.* **811**, 189, 1951.

† Sternheimer, R. M. *Phys. Rev.* **88**, 851, 1952.

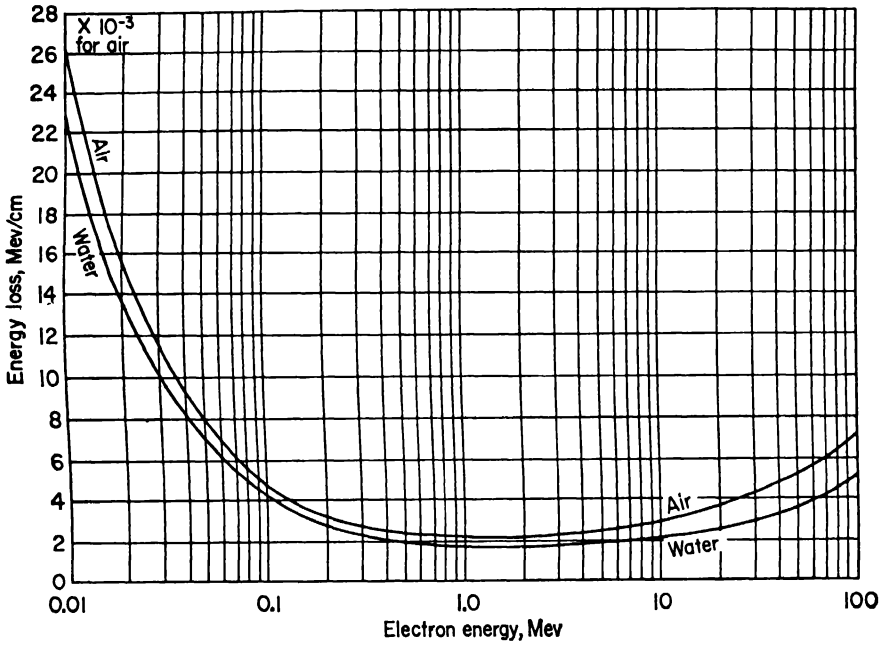


Fig. 9-5. Specific energy loss in air and water of an electron.

9.07 ENERGY LOSS BY HEAVY CHARGED PARTICLES

The remarkable development of high-energy accelerators has made available penetrating beams of protons, alpha particles, and even heavier atoms which have been stripped of one or more electrons and given very high kinetic energies. Prior to the advent of these high-energy machines the only heavy particle beams came from the alpha particles emitted by naturally radioactive nuclides. With only a few Mev available these particles had a range of less than a millimeter in tissue, and were of biological importance only when the alpha emitter had gained entrance into the body. Heavy particles can now be given energies of several Bev; the increased penetration permits the use of these particles as external sources of radiation.

The deceleration of a heavy particle at collision is much less than that of an electron in a similar interaction. Consequently, radiative energy losses are negligible. Another consequence of a large mass is a greatly reduced reaction on the trajectory of the particle.

Heavy particles will move along almost linear paths in sharp contrast to the tortuous tracks of electrons. It is this property which makes protons and other heavy particles useful for delivering energy to sharply defined volumes.

Theory is adequate to explain collision-energy loss of heavy particles at high energy, but at low energies a detailed analysis is not possible. As the high-speed particle slows there is an increasing probability of electron capture, either to reduce the net charge or to form a neutral atom. However, as long as the particle has a kinetic energy of more than a few ev there is a possibility of re-ionization by mechanical collision. A particle may gain and lose electrons several times before it is finally reduced to the average energy of thermal motion. Because of this complexity analytical relations are restricted to high velocities where changes in ionization state are unlikely.

Bethe * gives the following expression for the collision-energy loss of a heavy charged particle.

$$-\left(\frac{dE}{dx}\right)_c = \frac{4\pi z^2 e^4 NZ}{m_0 v^2}\left[\ln\frac{2m_0 v^2}{I} - \ln(1-\beta^2) - \beta^2\right] \qquad \textbf{(9-4)}$$

where z = net number of charges on the moving particle
m_0 = rest mass of the electron.

As expected, dE/dx is independent of particle mass. Because of uncertainties in electron capture Eq. (9-4) should not be used for protons below 0.100 Mev, and for alpha particles below 1 Mev. Very high values of dE/dx are possible because of the presence of z^2 in the numerator of Eq. (9-4) and the fact that for a given energy a heavy particle moves relatively slowly.

At high altitudes the cosmic radiation contains an appreciable number of high-energy heavy nuclei stripped of all, or nearly all, their electrons. As these enter an absorbing medium and are slowed they progressively acquire orbital electrons until they come to rest as neutral atoms. As the net charge is reduced there is a corresponding reduction in specific ionization and the track in a nuclear emulsion has a characteristic taper. These are known as *thindowns.*

The biological effects of these massive ionizations are unknown. Much of the intense ionization is probably wasted on already damaged tissue, so there may be a loss of effectiveness due to overhitting. On the other hand a properly placed heavy-ion track might disrupt

* Bethe, H. A. *Loc. cit.*

a vital structure, say in the central nervous system, not seriously damaged by a less-intense ionization.

9.08 RADIATION DOSE FROM INTERNAL SOURCES

Equation (9-1), with corrections for radiation and polarization, can be used to determine the LET and specific ionization of an electron. For many purposes this detailed information is not needed, and it is sufficient to calculate the total energy deposited in a tissue by a given radiation source. Perhaps the most common problem is that of determining the absorbed dose following administration of a radioactive isotope.

In tracer studies with animals such dosage calculations are required to make sure that the results are not invalidated by the effects of excessive radiation. When radioactive nuclides are given to humans either for study, diagnosis, or therapy, a calculation of tissue dose is essential to insure that the radiation level will be adequate, but not excessive.

In general, only approximate calculations can be made because of the complex distribution of the administered nuclide in both position and time. Each material entering a living organism will be metabolized in its own characteristic fashion. It is usually necessary to make assumptions as to the tissue concentrations. In spite of unavoidable uncertainties, estimates of tissue dose can usually be made with sufficient accuracy.

In a living system excretion acts to lower the tissue concentration of any non-replenished substance such as an administered radioactive nuclide. Excretion may be a complex function of concentration and time but in many cases can be taken to be a constant fraction of the concentration. This is exactly analogous to the situation for radioactive decay and leads to an exponential decrease in concentration characterized by a *biological decay constant* λ_B.

With both physical decay (λ_p) and biological excretion operating tissue concentration will decrease according to two exponential functions.

$$C = C_0 e^{-\lambda_p t} e^{-\lambda_B t} = C_0 e^{-\lambda_e t} \tag{9-5}$$

From the properties of exponential functions the *effective* decay con-

$$\lambda_e = \lambda_p + \lambda_B \tag{9-6}$$

Tables of radioactive constants are usually given in terms of half lives so Eq. (9-6) is converted to

$$\frac{0.693}{T_e} = \frac{0.693}{T_p} + \frac{0.693}{T_B}$$

and this leads to

$$T_e = \frac{T_p \times T_B}{T_p + T_B} \tag{9-7}$$

In actively excreting systems T_e must be used in place of the physical half life. Values of T_p and T_B will be found in various tables * but some of the excretion constants are based on rather meager data and are subject to future change.

9.09 TISSUE DOSE FROM BETA PARTICLES

Beta particles from radioactive isotopes have energies ranging from zero to a few Mev, and in tissue deposit their energy within a few millimeters of the point of emission. In an organ or tissue of reasonable size, energy deposition from beta particles can therefore be considered equal to the energy carried off by the beta particles emitted in that organ or tissue.

Consider a tissue having, at zero time, a concentration C_0 microcuries per gram of an isotope characterized by decay constants λ_p, λ_B, and λ_e sec^{-1}. Let the maximum beta-particle energy be E_β Mev and the mean energy be $\bar{E}_\beta$ Mev. At $t = 0$ the rate of energy deposition in the tissue will be $3.7 \times 10^4\ C_0\ \bar{E}_\beta$ Mev per sec per gram. At any later time t the rate of energy deposition will be

$$\frac{dE}{dt} = 3.7 \times 10^4\ C_0 \bar{E}_\beta e^{-\lambda_e t} \quad \text{Mev/sec/gram} \tag{9-8}$$

The total energy delivered from time 0 to t is obtained by integrating the dose-rate equation between these limits. This gives

$$E = 3.7 \times 10^4 \frac{C_0 \bar{E}_\beta}{\lambda_e}(1 - e^{-\lambda_e t}) \quad \text{Mev/gram} \tag{9-9}$$

* *National Bureau of Standards Handbook* H 52, "Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water," 1953.

Equation (9-9) can be readily converted to units of ergs per gram and since 100 ergs per gram is 1 rad

$$D_\beta = 5.92 \times 10^{-4} \frac{C_0 \bar{E}_\beta}{\lambda_e} (1 - e^{-\lambda_e t}) \quad \text{rad} \tag{9-10}$$

The factor $C_0 (1 - e^{-\lambda_e t})$ gives the number of microcuries per gram decaying during the time under consideration. Dose can, therefore, be expressed in terms of the quantity destroyed, as in the case of radon. Complete decay will give a tissue dose of

$$D_{\beta\infty} = 5.92 \times 10^{-4} \frac{C_0 \bar{E}_\beta}{\lambda_e} \quad \text{rad} \tag{9-11}$$

These expressions are valid as long as the assumptions made in deriving them are not violated. Values of λ_B are particularly suspect, for biological half life may change drastically during a long time interval, and thus require a series of approximate calculations. Radium, for example, is excreted rapidly for a short time after ingestion, but the residual deposits in bone and once this is accomplished excretion rate becomes very low.

It is sometimes convenient to have the dosage equations in terms of half lives and to use the day as the unit of time. With these changes we have

$$D_\beta = 73.8 C_0 \bar{E}_\beta T_e (1 - e^{-\frac{0.693t}{T_e}}) \quad \text{rad} \tag{9-12}$$

$$D_{\beta\infty} = 73.8 C_0 \bar{E}_\beta T_e \quad \text{rad} \tag{9-13}$$

9.10 PHOTON-EMITTING NUCLIDES

In most cases tissue dose due to the gamma rays associated with beta-particle emission is relatively unimportant. The reason for this unimportance is that the beta particles deposit all of their energy locally, whereas energetic photons carry a considerable fraction away from the tissues bearing the radioactive material. In some cases, however, the photon dose governs, so calculations must be made to determine the relative contributions of all radiations present.

A case in point is a nuclide which decays by K capture or one which has a large K/β branching ratio. In K capture the emissions will consist of the characteristic X-ray spectrum of the daughter element. These emission lines may have relatively low energies, since the K lines of even the highest Z elements lie below 100 Kev. For

elements of low or moderate Z the characteristic photons are so soft that they are strongly absorbed. In this case they can be treated like beta particles in making calculations of tissue dosage. These calculations are readily made with the equations developed above by replacing C_0 with the corresponding number of photon emissions and $\overline{E}_\beta$ by the proper photon energy.

When a beta emission is accompanied by hard gamma rays, photon-dosage calculations must be made in terms of the absorption coefficients corresponding to the photon energies. These calculations are complicated by the fact that local dose now depends upon the size and shape of the body containing the isotope as well as upon the distribution of the isotope within the body. Exact calculations depend upon the evaluation of integrals over complex shapes. Fortunately the accuracy required can usually be obtained from estimates using approximate configurations, so that detailed calculations are usually avoided.

9.11 TISSUE DOSE FROM INTERNAL GAMMA EMITTERS

Consider a tissue volume of arbitrary shape, Fig. 9-6, containing a uniform concentration of C μc per gram of a nuclide having a

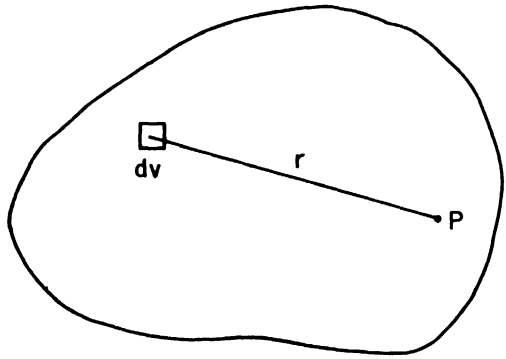


Fig. 9-6. Tissue containing a uniform concentration of a gamma emitter.

gamma-emission constant of Γ rhm. The emission constant gives the dose rate from a point source; the dose rate at any arbitrary point

in the medium P must be obtained by integrating the dose from all the differential volumes with due regard for inverse-square falloff, and absorption by intervening tissues.

The dose rate at P due to the small volume dv is

$$dr = 10^{-2}\frac{C\varrho\Gamma}{r^2}e^{-\mu_r r}dv \tag{9-14}$$

where ϱ = tissue density in gms per cm^3 and μ_r is the linear coefficient for true absorption. If several photons of different energies are emitted μ_r must be an effective, or mean value. A factor of 10^{-2} appears in Eq. (9-14) to make the units of C, r, and Γ consistent. The total dose rate at P will be

$$r_p = 10^{-2}C\varrho\Gamma\int_v \frac{e^{-\mu_r r}}{r^2}dv \quad \text{r/hour} \tag{9-15}$$

where the integration is to be taken over the entire emitting volume v.

In general the integration in Eq. (9-15) is extremely difficult to do except for a few special points in some relatively simple geometrical shapes. So-called g values of this integral are available for a few simple configurations. In general a detailed knowledge of r_p is not needed and an average value will suffice. Then the g value can be replaced by a $\bar{g}$ value obtained by a double integration over v. Figures 9-8 and 9-9 show $\bar{g}$ values for tissue-equivalent cylinders and the human body, plotted from calculations made by Bush.*

Using $\bar{g}$ values, the dose-rate equation becomes

$$\bar{r} = 10^{-2}C\varrho\Gamma\bar{g} \quad \text{r/hour} \tag{9-16}$$

It is usually necessary to calculate the total dose delivered over some time interval, which can readily be done with the usual decay law. With the hour as the unit of time

$$\begin{aligned}\bar{D}_\gamma &= 10^{-2}C_0\varrho\Gamma\bar{g}\int_0^t e^{-\lambda_e t}dt \\ &= \frac{10^{-2}C_0\varrho\Gamma\bar{g}}{\lambda_e}(1 - e^{-\lambda_e t})\end{aligned} \tag{9-17}$$

In terms of days and half-life

$$D_\gamma = 0.346C_0\varrho\Gamma\bar{g}T_e\left(1 - e^{-\frac{0.693t}{T_e}}\right) \tag{9-18}$$

* Bush, F. *Brit. J. Radiol.* **19**, 11, 1946; Bush, F. *Brit. J. Radiol.* **22**, 96, 1949.

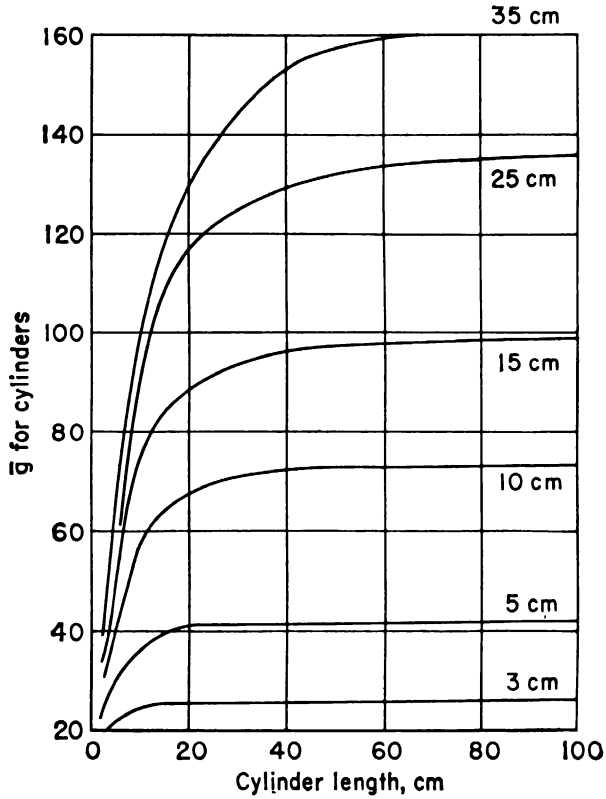


Fig. 9-8. $\bar{g}$ values for cylinders. From calculations by Bush, F. *Brit. J. Radiol.* **22**, 96, 1949.

Bush based his calculations on the gamma radiation from equilibrium radium; since the $\bar{g}$ values contain a μ_t factor the plotted values of $\bar{g}$ will be in error for nuclides whose gamma energies are different from those of radium. Fortunately the absorption coefficients in biological materials do not vary greatly over the usual gamma-energy range until low energies are reached. Then it may be more nearly correct to treat the gammas as betas of equivalent energy.

9.12 REP, RAD, REM, R, AND RBE

We have seen that the roentgen unit can, because of the relative constancy of W, be considered to be essentially equivalent to the

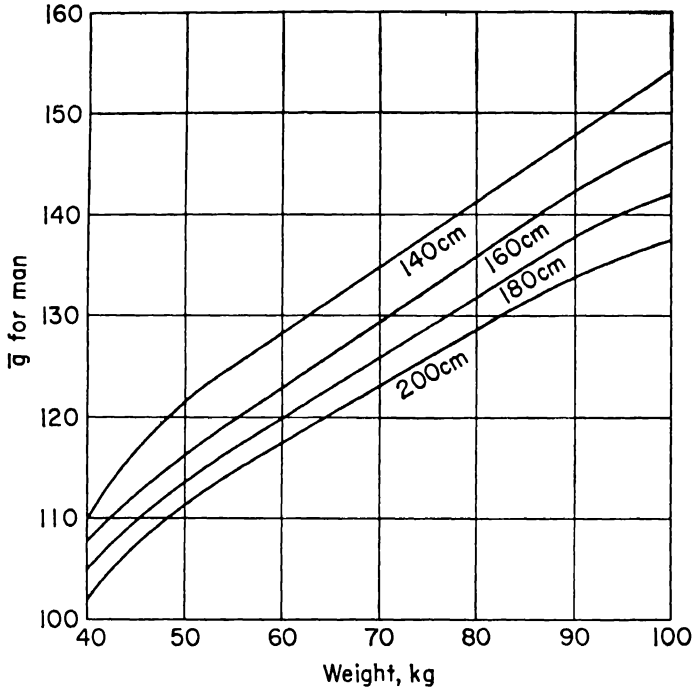


Fig. 9-9. $\bar{g}$ values for humans. From calculations by Bush, F. *Brit. J. Radiol.* **22**, 96, 1949.

absorption of 87.6 ergs per gram. When particulate radiation came into common use it was natural to attempt to extend the definition and the rep (roentgen equivalent physical) was intended to accomplish this extension. Unfortunately a variety of definitions became associated with the rep and it is now no longer used.

The rad has, however, been defined in unambiguous fashion, and takes the place of the obsolete rep. There is no assurance that radiation effects, particularly in biological systems, will be a function of ionization or of energy absorption only, so another unit is needed to take into account effectiveness as well as quantity. The rem, or *roentgen equivalent man*, is that amount of any type of radiation producing the same biological effect as is obtained from an absorbed dose of 1 rad of 200 KVP X-rays. Unlike the r and the rad, the rem can not be measured directly with a physical instrument. Some biological effect must be observed and this correlated with a measurement of dose by physical methods.

Rem and rad are related through the relative biological effectiveness, RBE. From the definition

$$\text{rem} = \text{rad} \times \text{RBE} \tag{9-18}$$

Values of RBE depend upon the biological effect under consideration as well as upon the kind of radiation producing it. For example, fast neutrons are particularly effective in producing lens opacities with an RBE of perhaps 20; but for other effects, such as mammalian mortality, the RBE may be more nearly 1 for fast neutrons. Extreme care must be taken in designing experiments intended to measure RBE, for this factor may depend upon many variables, some of which are very difficult to control.

PROBLEMS

9-1. A 250 KVP X-ray machine delivers 55 r/min at a TSD of 1 meter. Calculate the tissue-dose rate in rad/min at 1 meter TSD assuming true absorption coefficients of 0.019 cm^2/gram (air) and 0.025 cm^2/gram (water). *Ans.* 63.4 rad/min.

9-2. Calculate the absorbed dose rate in an aluminum foil, true absorption coefficient 0.039 cm^2/gram, placed in the beam described in Prob. 9-1, at 1 meter TSD.

9-3. An exposure dose of 350 r of 250 KVP X-rays is just enough to produce epilation on a small area of skin. The same degree of epilation is observed with an absorbed dose of 315 rad of 2 Mev electrons. Calculate the epilating dose in rem and the RBE of the electron beam for epilation. *Ans.* 306 rem, 0.972.

9-4. It is desired to just produce epilation with an X-ray beam of 80 KVP (effective energy 40 Kev). Assume an RBE for epilation of 1.4 and calculate the exposure dose in roentgens needed to achieve the desired result.

9-5. Calculate the linear energy transfer in Mev/cm for a 100 Kev electron and a 1 Mev electron moving through water.
Ans. 4.2 Mev/cm, 1.9 Mev/cm.

9-6. Repeat the calculations of Prob. 9-5 for electrons moving in air.

9-7. Assume tissue fat to have a composition given by $(CH_2)_n$ and calculate the average ionization potential. *Ans.* 52 ev.

9-8. Compare the LET of a 400 Kev electron in water and in fat of density 0.95 grams/cm^3.

9-9. Radioactive sodium, Na^{24}, distributes uniformly throughout the body when given as NaCl and is then eliminated with a biological half-life of 30 days. Calculate the absorbed dose due to beta particles in the first 24 hours after the administration of 18 μc of Na^{24} to a 78 kg man. What will be the beta dose from the complete disintegration of the radioactive nuclide? *Ans.* 1.96 mrad, 5.7 mrad.

9-10. Calculate the absorbed beta dose for the first 24 hours following the administration of 8.5 μc of I^{131}. Uptake in a 22 gram thyroid estimated as 45 per cent of the dose, biological half life 7.3 days.

9-11. The decay scheme of Na^{24} shows a 1.380 Mev and a 2.758 Mev gamma ray following each beta decay. Assume the man in Prob. 9-9 to have a height of 180 cm and estimate the gamma-ray doses corresponding to the two beta doses. *Ans.* 4.0 mr, 11.7 mr.

9-12. Estimate the 24 hour gamma-ray dose to the thyroid of the patient in Prob. 9-11. $\bar{g}$ for a sphere $= 3\pi r$ (cm).

9-13. To determine the effective half life of S^{35} in the skin a tracer dose of $Na_2S^{35}O_4$ was given and serial biopsies taken for assay. From the following data determine the effective half life and the biological half life of S^{35} in the skin. All counts corrected for background and other variables.

counts/min/gm	564	459	387	312	260	212	168	117	76	56
time, days	0	5	10	15	20	25	30	40	50	60

9-14. Plutonium-239, a bone-seeking element, is excreted at a rate of 0.01 per cent per day. What is the effective half life and the biological half life of Pu^{239}?

9-15. The following data, corrected for background and all other variables, were obtained for Feather analysis of unknowns *A* and *B*, using P^{32} with a range of 828 mg/cm² as a standard. Determine the beta-particle ranges from a Feather analysis.

absorber, mg/cm²	0	100	200	300	400	500	600	700	900	1,100
cpm, P	4,700	2,950	1,710	1,010	573	297	131	187		
cpm, A	6,100	3,220	1,610	768	306	85.8				
cpm, B	7,900	5,550	3,860	2,690	1,830	1,230	803	495	158	35

Ans. A. 630 mg/cm².

9-16. There is some reason to believe that the RBE depends upon the LET of the radiation. Estimate the photon energies necessary to insure substantial changes in LET so that this hypothesis can be tested.

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10

NEUTRONS AND THEIR REACTIONS

10.01 DISCOVERY OF THE NEUTRON

Among the many achievements of Lord Rutherford was the prediction, in 1920, of a particle of unit mass and zero charge. It must have given him real satisfaction when Chadwick demonstrated in 1932 the existence of this particle and called it the *neutron*. In Germany, Bothe and Becker, and in France Joliot and Curie had observed a very penetrating, non-ionizing radiation produced when light elements were bombarded with alpha particles. Both of these groups assumed this radiation to be penetrating gamma rays of about 50 Mev.

From cloud-chamber photographs Chadwick showed that the new radiation was a neutral particle with a mass about as great as that of the proton. Later work showed the neutron to be an unstable particle which decays with a half life of 13 minutes according to

$$_0n_1 \longrightarrow \beta^- + {}_1p^1 + Q \qquad (10\text{-}1)$$

The neutron is heavier than the proton by the equivalent of 1.292 Mev and the observed maximum energy of the beta spectrum, 0.782 Mev, has exactly the required value, so the energetics of Eq. (10-1) appear to be well established.

Although neutron decay follows Eq. (10-1) it must not be inferred that electrons as such exist inside the neutron prior to emission. The emission process includes the creation of an electron-neutrino pair so the emitted particles have only a virtual existence prior to emission. This virtual existence applies to the electrons emitted in any beta decay, for there is not room inside any nucleus to contain a free electron.

In identifying the neutron Chadwick used the $Be^9(\alpha,n)C^{12}$ and later the $B^{11}(\alpha,n)N^{14}$ reaction to establish the mass of the neutron from known atomic-mass values. The nuclear potential barrier is a formidable hurdle for doubly charged ions and the alpha particles from naturally radioactive nuclides can effectively penetrate only low Z structures.

Discovery of the neutron provided a strong stimulus to the development of high-energy positive-ion accelerators so that more effective penetration of the potential barrier could be achieved, and nuclear reactions could be studied in elements of high atomic number.

10.02 POSITIVE-ION ACCELERATORS

Cockcroft and Walton in 1929 developed the voltage-multiplying circuit now named for them, and with it produced the first nuclear disintegrations with man-accelerated proton beams. Voltages of perhaps one million can be attained, and because of this rather modest limit, Cockcroft-Walton installations have been rather neglected for more spectacular methods. Interest in the Cockcroft-Walton circuit is reviving because of its large current capabilities.

The Van de Graaff principle can be used to accelerate positive charges by merely reversing the polarity sprayed on the belt. Pressure-insulated machines up to about 8.5 Mev have been built and currents of 5 ma have been attained, but these values may be close to the limits of practical design for a single acceleration. The voltage

limit has been essentially doubled by starting with negative ions and then stripping off electrons after one acceleration. The resulting positive ions can receive a second acceleration by the same potential source, so they return with about twice the energy developed by the machine.

In 1931, Lawrence and Livingston built the first magnetic-resonance accelerator or *cyclotron,* where the final energy is attained by the repeated application of small increments. In the cyclotron, ions forced into circular paths by a magnetic field receive about 50 Kev each half-revolution, and travel with increasing radii until allowed to strike a suitable target. Cyclotron sizes are given in terms of the diameter of the magnet, a 60 inch machine producing about 20 Mev protons.

Above 20 Mev relativistic increases in particle mass limit the cyclotron, but this limit can be substantially raised in the frequency-modulated cyclotron or *synchrocyclotron.* The epitome of this design is reached in the 184 inch, 400 Mev machine at Berkeley, California.

At the higher energies the magnet required by a cyclotron type of machine assumes heroic proportions, so that the ring type of magnet of the proton synchroton represents a real saving. Machines using this principle are in operation at 6 Bev and a 25 Bev machine is under construction.

Linear proton accelerators have been constructed for use up to about 30 Mev and are capable of delivering relatively large currents.

10.03 ENERGETICS OF NEUTRON PRODUCTION

Neutrons, being uncharged particles, cannot be accelerated directly by electrical or magnetic fields. As produced by a nuclear reaction, a neutron derives its energy from the reaction itself and from the kinetic energy of the initiating particle.

Illustrative Example

Calculate the energy available from the $Be^9(\alpha,n)C^{12}$ reaction. From tables of atomic-mass values we find

Be^9	9.015043	C^{12}	12.003842
He^4	4.003873	n^1	1.008982
	13.018916		13.012824

mass difference 0.006092 amu

$Q = 0.006092 \times 931 = 5.66$ Mev

Note that the atomic mass of He^4 was used in the calculation even though the actual bombarding particle is doubly ionized. This compensates for the two orbital electrons required by C^{12} over the four associated with Be^9.

The energy of the incoming particle must be added to that obtained from changes in binding energy as calculated in the example. The total available energy will divide between the neutron and the recoiling nucleus in a manner determined by the angle at which the neutron is ejected.

Table 10-1 REACTION ENERGIES FOR NEUTRON PRODUCTION

Reaction	Energy, Mev
$H^3(d,n)He^4$	17.6
$Be^9(\alpha,n)C^{12}$	5.6
$Be^9(d,n)B^{10}$	4.1
$H^2(d,n)H^3$	3.3
$H^3(p,n)He^3$	−0.76
$Li^7(p,n)Be^7$	−1.65

From Table 10-1 it is evident that a wide range of neutron energies is made available by the proper choice of targets and bombarding energy.

10.04 NEUTRON SOURCES

The most intense neutron fluxes are produced by nuclear reactors, or piles, which will be considered separately. Next come neutrons produced by various accelerator-induced nuclear reactions. Cyclotrons can produce intense beams of high-energy particles but these have a considerable energy spread, and are accompanied by strong gamma radiation. Thus cyclotron neutrons are far from monoenergetic and are contaminated with gamma rays.

Neutrons can also be produced by the *photodisintegration* of the

nucleus, and at high photon energies, >10 Mev, the cross section for these (γ,n) reactions is large enough to produce intense neutron sources. Energy thresholds for (γ,n) reactions are quite sharp, and this fact provides some useful calibration points in the Mev region. Useful thresholds are $Be^9(\gamma,n)Be^8$ at 1.66 Mev and $H^2(\gamma,n)H^1$ at 2.22 Mev.

The usual photoneutron source utilizing the bremsstrahlung as produced by an accelerator will be far from monoenergetic. The neutrons will be accompanied by an intense photon radiation, although some separation can be achieved since forward bremsstrahlung production will predominate, whereas neutron emission is essentially isotropic.

Monoenergetic neutrons are probably best produced by a positive ion reaction using a Van de Graaff generator for acceleration. This source will also be relatively free of gamma radiation.

Low-intensity sources suitable for many purposes are made by mixing a radioactive nuclide with a suitable target material. Low Z elements, usually beryllium, are favored targets since they have a low potential barrier.

Ra^{226}-Be, Po^{210}-Be, and Pu^{239}-Be sources all depend upon an (α,n) reaction for neutron production. To most fully utilize the short-range alpha particles, finely powdered beryllium must be intimately mixed with the active material. Compressed discs may have a yield of 1 neutron for each 2500 alpha particles.

A Po-Be source has the advantage of a low gamma-ray contamination, but decays with the relatively short half life of Po^{210}. A Ra-Be source is relatively constant, but has a strong gamma emission. Pu-Be sources combine the best features of the previous two but are limited in output by the low specific activity of Pu^{239}.

10.05 REACTION CROSS SECTION

A neutron passing through any medium may interact by elastic collision, inelastic collision, fission, or radiative capture. The relative probabilities can be thought of as target sizes or cross sections.

Consider a beam of monoenergetic neutrons incident upon a slab of absorber, Fig. 10-1. Let there be n neutrons with velocity v in each cm^3 of the incident beam, and for simplicity consider a cross-sectional area of 1 cm^2 at any point in the beam. In one second all

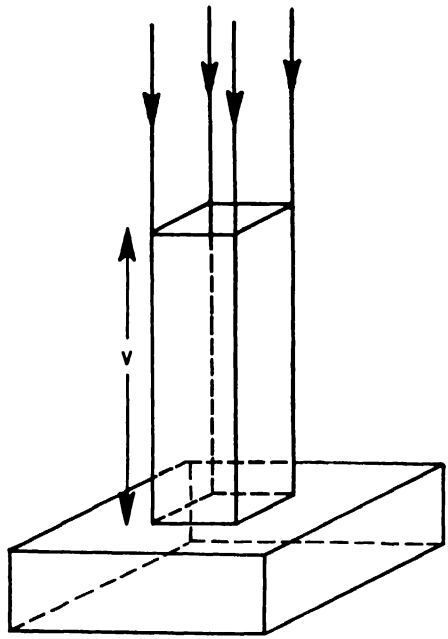


Fig. 10-1. Monoenergetic neutrons of velocity v incident on an absorber.

the neutrons contained in a volume v cm long will cross the unit area. This number, which is obviously nv, is called the *neutron flux*, F.

In passing through a thin slab of absorber the beam will lose a fraction of the incident flux through a variety of interaction processes involving the neutrons and the atoms in the absorber. If the absorber has an atomic weight M and a density ϱ there will be $\varrho N/M$ atoms per cm^3 of absorber, N being Avogadro's number. In a thin layer of absorber Δx there will be $\varrho N \Delta x/M$ targets in each unit area. With a loss in neutron flux proportional to the incident flux, the number of targets, and the cross section of each target

$$-\Delta F = \sigma_t F \frac{\varrho N}{M} \Delta x \tag{10-2}$$

The constant of proportionality, σ_t, is the *total cross section* for a variety of neutron interaction processes. Thus

$$\sigma_t = \sigma_{el} + \sigma_{inel.} + \sigma_{abs.} \tag{10-3}$$

where the subscripts refer to elastic, inelastic, and absorptive processes

respectively. The absorption cross section σ_{abs} is made up of several components such as a fission cross-section, σ_f, and an activation cross-section σ_{act}, to be discussed in detail later.

Equation (10-2) is in a form previously encountered, and can be readily integrated to give

$$F = F_0 e^{-\frac{\sigma_t \varrho N_x}{M}} \tag{10-4}$$

where F_0 is the incident flux and F the flux at depth x. Equation (10-1) will not be valid, in general, for large values of x, since σ_t is not constant, but is a complicated function of neutron velocity, and velocity degradation as well as absorption is taking place.

Neither σ_t nor its component cross sections bears any simple relation to the geometrical cross section of the target atoms. Most cross sections are of the order of atomic areas, however, and it is customary to express cross sections in *barns* where 1 barn $= 10^{-24}$ cm^2. Determinations of σ_t and its components are difficult and our knowledge of cross sections is far from complete. Some values will be found in tables of nuclear constants. In using tabular values care must be taken to note whether they apply to a particular nuclide or to the element as found in natural isotopic abundance.

10.06 NEUTRON CLASSIFICATIONS

Neutrons cannot be accelerated like charged particles, but a beam of high-energy neutrons can be degraded by collision processes to very low energies. Neutrons can be classified into various energy ranges whose boundaries are rather indistinct.

High-energy neutrons are usually considered to have energies greater than 10 Mev. *Fast* neutrons will range from 10 Kev to 10 Mev. *Intermediates* range from 100 ev to 10 Kev and *slows* go down to 0.030 ev. Neutrons just above 1 ev are sometimes called *epithermals.*

When neutrons lose energy by collision without absorption they will slow until their mean kinetic energy is equal to the mean thermal energy of the surrounding atoms. The neutrons are then said to be *thermal* and by kinetic theory have an energy

$$E = \frac{1}{2} kT \tag{10-5}$$

where k = Boltzmann constant 1.8×10^{-16} ergs/°C
T = absolute temperature.

An application of Eq. (10-5) shows that at 20° C the thermal energy is 0.025 ev. Slower neutrons cannot be obtained unless they are brought into equilibrium with matter at a lower temperature.

Another energy classification depends upon the unique absorptive properties of the element Cadmium. Cadmium absorbs strongly all neutrons having energies below 1 ev and is almost transparent to faster neutrons. This 1 ev energy is called the *Cadmium cut-off* and the transmitted components are called *cadmium neutrons.*

10.07 FAST NEUTRON REACTIONS

Neutrons moving through matter behave quite differently from charged particles and their behavior depends strongly upon their energy. When the neutron has an energy of 20 Mev or more it is capable of disrupting a struck nucleus with the ejection of a number of particles. This process of *spallation* is said to produce *stars* because of the pattern seen in cloud-chamber photographs. Star formation, leading to a collection of nuclear debris, is infrequently encountered in biological applications at sea level. Star formation may become biologically important in space travel, however, because at high altitudes there will be a substantial number of these high-energy interactions, with massive ionization.

Fast neutrons lose their energy primarily through *elastic collisions.* The struck nucleus receives a substantial fraction of the kinetic energy of the neutron, and is scattered. The energy relations in an elastic collision are

$$E = \frac{4\,m\,M}{(m + M)^2} \cos^2\theta \qquad \textbf{(10-6)}$$

where E = fraction of original neutron energy transferred
m = mass of neutron
M = mass of target nucleus
θ = angle of recoil measured from original neutron direction.

A study of Eq. (10-6) shows that the most effective energy transfer occurs when $M = m$, that is, when the neutron collides with something of its own mass. Energy transfer to electrons and to heavy nuclei will be relatively small, but a hydrogen atom will receive a

large fraction of the original kinetic energy. This fact has important biological implications, for all living tissue has a high hydrogen content. About 90 per cent of the energy transfer from a fast neutron beam to tissue takes place through elastic collisions. When neutrons interact with nuclei substantially heavier than hydrogen a relatively greater amount of energy will be transferred by competitive processes.

a. *Inelastic scattering.* The incident neutron may enter a nucleus which then emits a lower-energy neutron. The residual nucleus will be left in an excited state which will subsequently be relieved by the emission of gamma radiation. This can be thought of as an (n,n) process. Above about 10 Mev more than one neutron may be emitted and we then have $(n,2n)$ processes. At still higher energies $(n,3n)$ reactions are possible.

b. *Charged-particle emission.* Fast neutrons may enter a nucleus and transfer to a charged particle enough energy to permit it to escape over the potential barrier. Thus we have (n,p) or (n,d) reactions and, less probably, (n,α). Charged-particle reactions are important because there is a change in atomic number, and hence the product atoms can be chemically separated from the target.

The importance of the $N^{14}(n,p)C^{14}$ reaction for the production of tracer material has already been mentioned. This reaction is also of importance when neutrons are absorbed by living tissue, since the recoiling protons will contribute about 10 per cent of the total ionization. A smaller contribution will come from the beta particles emitted by the C^{14}.

c. *Fission.* A fast neutron may enter a nucleus and cause it to fission, a process to be described in detail later.

10.08 SLOW NEUTRON INTERACTIONS

Intermediate-energy neutrons enter into reactions characteristic of both fast and slows, but experimental work in this energy region is difficult and detailed information is lacking.

The overwhelming slow-neutron reaction is radiative capture (n,γ). Many nuclei undergo radiative capture with a probability which is inversely proportional to the neutron velocity; the so-called $1/v$ law. With a $1/v$ or $1/\sqrt{E}$ capture probability radiative capture

becomes most likely at thermal energies, and quite unlikely for fast neutrons. Because of the prominence of radiative capture even a pure neutron beam will become contaminated with gamma radiation in passing through absorptive material.

In many elements the $1/v$ absorption has superposed on it a series of resonance absorptions due to energy resonances between the incoming neutrons and nuclear-energy levels. Because of these resonances cross sections for neutron absorption are usually complex functions of neutron energy.

10.09 NUCLEAR FISSION

A few heavy nuclides have a large cross section for *fission*, the process of splitting a compound nucleus into two approximately equal fragments, following entry of a neutron. This is the process characterized by σ_f, one of the components of σ_t in Eq. (10-3). The outstanding example of a readily fissionable natural nuclide is U^{235}, and Pu^{239} is the most common man-made nuclide with a high cross section for fission.

A detailed study of nuclear binding energy relations will show that *excitation energy*, which is the energy required to induce fission, is relatively low in nuclides with an even neutron number N. The compound nucleus U^{236} formed by $U^{235} + n$ has an even N, and fissions readily with thermal neutrons. The most common isotope of uranium, U^{238}, forms a compound nucleus of odd N, and here a neutron must have a kinetic energy in excess of 1 Mev to induce fission.

Asymmetric fission, leading to one heavy and one light component, is most probable, as shown by Eq. (3-8). A second example is

$$_{92}U^{235} + {}_0n^1 \longrightarrow {}_{54}Xe^{140} + {}_{38}Sr^{94} + 2n + Q \qquad (10\text{-}7)$$

Fission reactions are highly exothermic, Q in Eq. (10-7) being over 200 Mev. Most of this energy appears as kinetic energy of the fission fragments with small contributions from the beta particles and the gamma radiation.

The number of free neutrons released in fission varies with the exact details of each fission process. The average number released is greater than two and in this fact lies the possibility of a self-

sustaining *chain reaction*. To accomplish this reaction it is only necessary to so arrange things that at least one fission-produced neutron can initiate a second fission. When a configuration is designed to utilize as many fission neutrons as possible to initiate succeeding fissions an enormous energy release takes place in a matter of microseconds, and we have a nuclear detonation. Extraordinary temperatures and pressures are produced in the fissioning mass and these are propagated outward to produce the well-known destruction by blast and fire.

10.10 NUCLEAR REACTORS

A *nuclear reactor* or *pile* contains both readily fissionable U^{235} and the more abundant isotope, U^{238}. *Slugs* of the uranium fuel elements are separated by a *moderator*, usually pure carbon in the form of graphite stringers, or deuterium, as heavy water. The function of the moderator is to slow down, or *thermalize*, without capture, the fast neutrons produced by U^{235} fission.

Because of the $1/v$ law thermal neutrons in a reactor have a good chance of capture by U^{238} according to

$$U^{238} + n \longrightarrow U^{239} + \gamma \qquad (10\text{-}8)$$

Radiative capture is followed by two spontaneous beta emissions

$$U^{239} \xrightarrow[23\ M]{} Np^{239} + \beta \qquad (10\text{-}9)$$

$$Np^{239} \xrightarrow[2\,30\ D]{} Pu^{239} + \beta \qquad (10\text{-}10)$$

Plutonium-239 has a cross section for fission comparable to that of U^{235}. Plutonium can be separated from the unfissioned uranium by chemical methods instead of requiring the elaborate physical methods needed to separate U^{235} from U^{238}. Since Pu^{239} has a half life of 25,000 years it can be stockpiled for use as a source of energy or as material for fission weapons.

A nuclear reactor, like a fission bomb, is an essentially unstable device. Fortunately a small fraction of the neutrons emitted are *delayed* sufficiently to permit the introduction of mechanically operated control devices. These *control rods* consist of an element such as cadmium or boron with a high cross section for thermal neutron capture. In normal reactor operation these control rods are ad-

justed so that exactly one neutron per fission will be available to initiate another fission.

A variety of reactor designs is available for special applications. For biomedical purposes a reactor may have a large *thermal column*, a relatively large volume consisting only of graphite moderator. Any neutrons entering this volume will be thermalized before reaching the center of it. Animals or other test objects can then be introduced into the center of the thermal column, where they will be exposed to the thermal-neutron flux and gamma radiation produced by the fission process and the decay of the fission products.

Large quantities of heat are generated by the fission process; it is usually removed by air or water cooling. In a power reactor, steam may be generated and delivered to turbines or other prime movers. The efficiency of heat engines goes up with the operating temperature and reactor cooling water may be replaced by a liquid metal. Even at the best efficiency attained, however, nuclear energy cannot at present compete economically with fossil fuels in the United States.

10.11 ARTIFICIAL RADIOISOTOPE PRODUCTION

The high-neutron fluxes available in nuclear reactors permit the large-scale production of radioactive isotopes. Stable elements placed in the thermal column may absorb neutrons with favorable cross sections, because of the $1/v$ law. The usual reaction is radiative capture (n,γ) and in most cases the product nuclide is radioactive.

Consider a reactor with a thermal-neutron flux F in which a sample of N atoms with activation cross section σ_{act} is to be irradiated. The use of σ_{act} assumes that the irradiation will lead to a radioactive product, characterized by a decay constant λ. At any time t let the number of activated nuclei be N.* Then in a short interval of time dt there will be $F\sigma_{act}Ndt$ nuclei activated and $\lambda N^* dt$ will decay. From these relations we get by integration

$$N^* = \frac{F\sigma_{act}N}{\lambda}(1 - e^{-\lambda t}) \qquad \textbf{(10-11)}$$

The number of nuclei decaying per unit time will be

$$N^*\lambda = F\sigma_{act}N(1 - e^{-\lambda t}) \qquad \textbf{(10-12)}$$

From these relations one can calculate the activity obtained from a given irradiation.

Illustrative Example

A 1 gram sample of Na^{23} is irradiated in a thermal neutron flux of 10^{12}/cm²/sec. With thermal neutrons σ_{act} for Na^{23} $(n,\gamma)Na^{24}$ is 0.49 barns and Na^{24} has a half life of 14.9 hours. Calculate the activity of the sample after 24 hours of irradiation.

$$N = \frac{6.02 \times 10^{23}}{23} = 2.62 \times 10^{22} \text{ target nuclei}$$

$$\lambda = \frac{0.693}{T_{1/2}} = \frac{0.693}{14.9 \times 3600} = 1.29 \times 10^{-5}/\text{sec}$$

$$t = 24 \times 3600 = 8.64 \times 10^{4} \text{ sec}$$

$$N^* = \frac{10^{12} \times 0.49 \times 10^{-24} \times 2.62 \times 10^{22}}{1.29 \times 10^{-5}}(1 - e^{-(1.29 \times 10^{-5} \times 8.64 \times 10^{4})})$$
$$= 6.7 \times 10^{14} \text{ nuclei}$$

$$N^*\lambda = 6.7 \times 10^{14} \times 1.29 \times 10^{-5} = 7.6 \times 10^{9} \text{ dps}$$
$$= \frac{7.6 \times 10^{9}}{3.7 \times 10^{7}} = 234 \text{ mc.}$$

Equations (10-11) and (10-12) apply only during the time of irradiation when radioactive nuclei are being produced by a constant neutron flux F. Production will cease when the sample is removed from the reactor and the maximum activity will decay with its characteristic half life. After removal

$$N^* = \frac{F\sigma_{act}N}{\lambda}(1 - e^{-\lambda t})e^{-\lambda t'} \qquad (10\text{-}13)$$

$$N^*\lambda = F\sigma_{act}N(1 - e^{-\lambda t})e^{-\lambda t'} \qquad (10\text{-}14)$$

where t' is the time of decay taken from the instant the sample was removed from the reactor.

10.12 SPECIFIC ACTIVITY AND ISOTOPE PRODUCTION

The high-neutron fluxes available in reactors, readily maintained for long periods of time, permit the large-scale production of radioactive isotopes. However, the most common reaction is radiative capture, and here the radioactive nuclide is an isotope of the stable starting material. Since the two isotopes cannot be separated by chemical means the active material will be diluted by a large quantity

of the stable isotope. If the activation cross section or the flux is low the resulting product may be too dilute for some applications.

Illustrative Example

An animal experiment requires the administration of 1 mc/kg of Na^{24} and to maintain normal physiological conditions it is deemed inadvisable to administer more than 15 mg/kg total sodium. Can a sample prepared as in the illustrative example of sec. 10.11 be used for this purpose 24 hours after removal from the reactor?

From the previous example the specific activity upon removal from the reactor was 234 mc/gm. Twenty-four hours later the activity will be

$$234 \times e^{-\frac{0.693 \times 24}{14.9}} = 76.4 \text{ mc}$$

Specific activity will be 0.076 mc/mg, a 15 mg aliquot will contain 1.14 mc and the sample is suitable.

Many of the chemical separation procedures depend upon differential solubilities of target and product and sometimes there is not enough of the product to come out of solution. It is then necessary to add a small amount of a stable isotope of the product element, to serve as a *carrier*. If no material need be added the separated produce is said to be *carrier-free* and has the highest specific activity compatible with its half life.

In a few cases the *Szilard-Chalmers* reaction can be used to obtain high specific activities from radiative capture reactions. The classic example of this is the production of I^{128} by the neutron bombardment of an organic compound such as ethyl iodide. The basic reaction is

$$I^{127} + n \longrightarrow I^{128} + \gamma \qquad \textbf{(10-15)}$$

When the gamma ray is emitted by the excited I^{128} nucleus the recoil ruptures the chemical bonds and free iodine is liberated.

$$C_2H_5I^* \longrightarrow C_2H_5 + I^* \qquad \textbf{(10-16)}$$

The free iodine can be readily separated by chemical methods.

10.13 ACTIVATION ANALYSIS

Radioactivity induced by either neutron or charged-particle bombardment provides a very powerful and only partially exploited method of chemical analysis. An unknown sample is irradiated and

the resulting radioactive nuclides identified by appropriate counting techniques. Each radioactive nuclide has an unalterable half life and energy of emission; a determination of either one of these provides presumptive identification. A determination of both factors definitely identifies the radioactive nuclide, and hence the element from which it was produced.

Half-life determinations are made from a series of radioactive assays. Energies may be determined from a series of assays made with absorbing material placed between source and counter, or by gamma-ray spectrometry. Identification may not be possible in some complex mixtures, but in favorable circumstances less-than-microgram quantities can be detected. Quantitative analyses can be made by simultaneously irradiating a sample containing known quantities of the pertinent elements and measuring the relative activities in the standard and the unknown.

Because of the usually favorable cross sections for (n,γ) reactions, activation analyses are most frequently done with neutrons. Bombardment with charged particles permits activation analyses of shallow volumes close to the surface, or of sharply circumscribed areas. Occasionally a charged-particle activation will confirm an analysis not entirely proven by neutron activation.*

Samples prepared for neutron activation are usually sealed in quartz containers. Common glasses contain appreciable amounts of boron and B^{10} has a very large capture cross section for thermal neutrons. The presence of boron puts an unnecessary load on the neutron source, greatly reducing the neutron flux reaching the sample.

10.14 NEUTRON THERAPY

As the physical properties of neutrons became known it was natural to hope that their unique properties would be of value in radiation therapy. Dr. R. S. Stone† was the first to use cyclotron neutrons in a group of cancer patients. Methods of accurate dosage determination were lacking so Dr. Stone used a Victoreen 100 thimble chamber and called its readings "*n* units" instead of roent-

* Atchinson, G. J., and W. H. Beamer. "Neutron Activation Analyses with the Van de Graaff Accelerator." *Anal. Chem.* **28**, 237, 1956.

† Stone, R. S., and J. C. Larkin, Jr. *Radiology* **39**, 608, 1942.

gens. The results of animal experiments and theoretical considerations suggested that 1 *n* unit was equivalent to 2.5 r and treatment was given accordingly. The neoplastic tissue responded to neutrons as to other forms of penetrating radiation, but delayed, untoward reactions ensued and the overall results were not encouraging.

Technical advances in the techniques of neutron measurement continued, and in 1952 a detailed analysis of the problem was reported.* Unfortunately, the RBE of neutrons depends upon the size of the animal being irradiated, as well as upon the characteristics of the neutron beam and the effect being measured. Because of this complication, extrapolation of values from small animals to man is uncertain. It should be pointed out that pure neutron irradiations cannot be achieved. Radiative capture reactions are inevitable in any tissue, so any neutron flux will be accompanied by an appreciable γ ray component.

Table 10-2 shows some RBE values for neutrons as given by Harris:

Table 10-2 RBE of Reactor Thermal-Column Radiations

Effect	Slow neutron flux/roentgen	RBE
Lethality in mice	1.35	1.51
Spleen weight loss in mice	1.32	1.55
Thymus weight loss in mice	1.18	1.73
Iron uptake in rats	1.19	1.11
Lens opacity in mice	0.20	10.20
Testicular atrophy in mice	0.28	2.49

Some unfortunate human overexposures have emphasized the outstanding ability of neutrons to produce lens opacities.

A new approach † to the therapeutic use of neutrons is yet to be evaluated. In this technique an element with a high capture cross section is administered in a form expected to concentrate in malignant tissue. A subsequent slow neutron irradiation should release charged particles to produce localized tissue destruction. As an example the reaction

$$B^{10} + n \longrightarrow Li^{7} + \alpha \qquad \textbf{(10-17)}$$

* Brennan, J. T., P. S. Harris, R. E. Carter, and W. H. Langham. *L. A* 1100, 1952; Harris, P. S., and J. T. Brennan. *L. A.* 1110, 1952; Harris, P. S., *Rad. Research* 1, 34, 1954.

† Farr, L. E., J. S. Robertson, E. E. Stickley, H. J. Bognall, O. D. Easterday, and W. Kahle. *Recent Advances in Neutron Capture Therapy* Second U. N. International Conference on the Peaceful Uses of Atomic Energy. A/conf. 15/P/883.

has a cross section of 2.3 barns and massive destruction would be expected along the path of the alpha particle. The differential concentrations of boron so far attained are disappointing, but better results may eventually be attained.

10.15 NEUTRON DOSIMETRY

Neutron dosimetry is complicated by the variety of interactions involved, by the large changes in cross section with energy, and by the variations of RBE associated with the charged particles. On the average the kinetic energy of a neutron after n collisions, $\overline{E}_n$, is related to the original energy by

$$\overline{E}_n = E_0 e^{-n\xi} \tag{10-18}$$

where

$$\xi = 1 - \frac{(A-1)^2}{2A} \ln \frac{A+1}{A-1} \tag{10-19}$$

From the form of Eq. (10-18) it is evident that the greatest transfer of energy from a fast neutron will occur on the first collision. Detailed calculations of *first-collision dose* can be made * as a function of neutron energy. The results of such a calculation are shown in Fig. 10-2.

More detailed calculations can be made by the *Monte-Carlo* method in which the complete life history of a large number of neutrons is followed in detail. The nature of each interaction is determined by random choice, hence the name of the method. Monte-Carlo calculations are tedious, even when done with computers, but give the energy absorption in some detail.

The results of Monte-Carlo calculations of neutron absorption are shown in Figs. 10-3 and 10-4. The curves giving the absorbed energy in rad come directly from the Monte-Carlo calculations.† The rem values in Fig. 10-4 were obtained by assuming that the RBE of the charged particles produced by the neutron interactions were functions of LET only. Each particle was then weighted ac-

* Hurst, G. S. *Brit. J. Radiol.* **27**, 353, 1951.

† Snyder, W. S., and J. Neufeld. *Brit. J. Radiol.* **28**, 342, 1955.
Snyder, W. S., and J. Neufeld. *Rad. Research* **6**, 67, 1957.

cording to the assumed RBE. Different assumptions of RBE values will lead to somewhat different rem values.

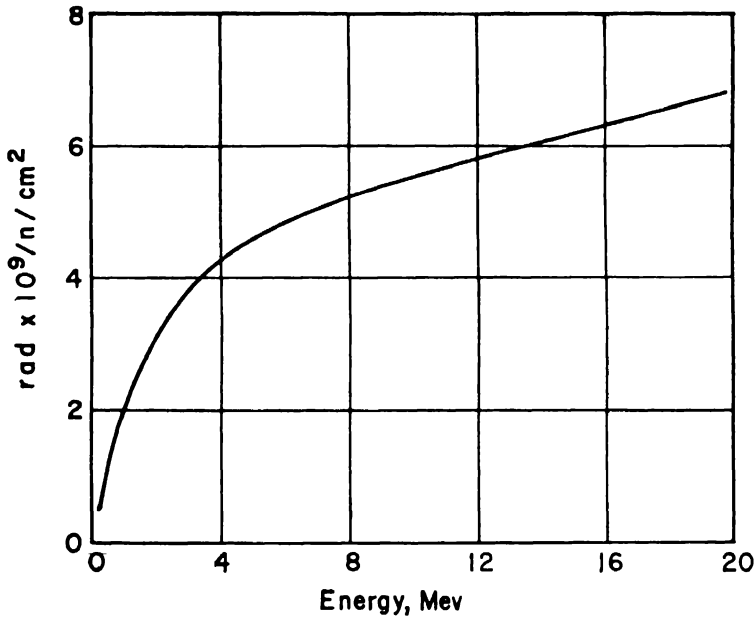


Fig. 10-2. First collision dose in tissue as a function of neutron energy. Data from Hurst, G. S. *Brit. J. Radiol,* **27,** 353, 1954.

10.16 FISSION PRODUCTS AND FALLOUT

In a large-scale fission in either a reactor or a detonation there will be 40 or more reactions analogous to Eq. (10-7) and each initial product will become the head of a fission chain having several radioactive members. A fission-product mixture consists, therefore, of well over 100 radioactive constituents, each decaying with its own characteristic half life. The composition of a fission-product mixture will not be constant, for as decay proceeds, short-lived components disappear and long-lived products become more prominent. For several months after formation the radioactivity of a fission-product mixture is given by

$$A = \frac{A_1}{t^{1.2}} \qquad \textbf{(10-20)}$$

$(A - \alpha)(1 - e^{-\beta t}) + \alpha\gamma t$

A_1 = activity at unit time.

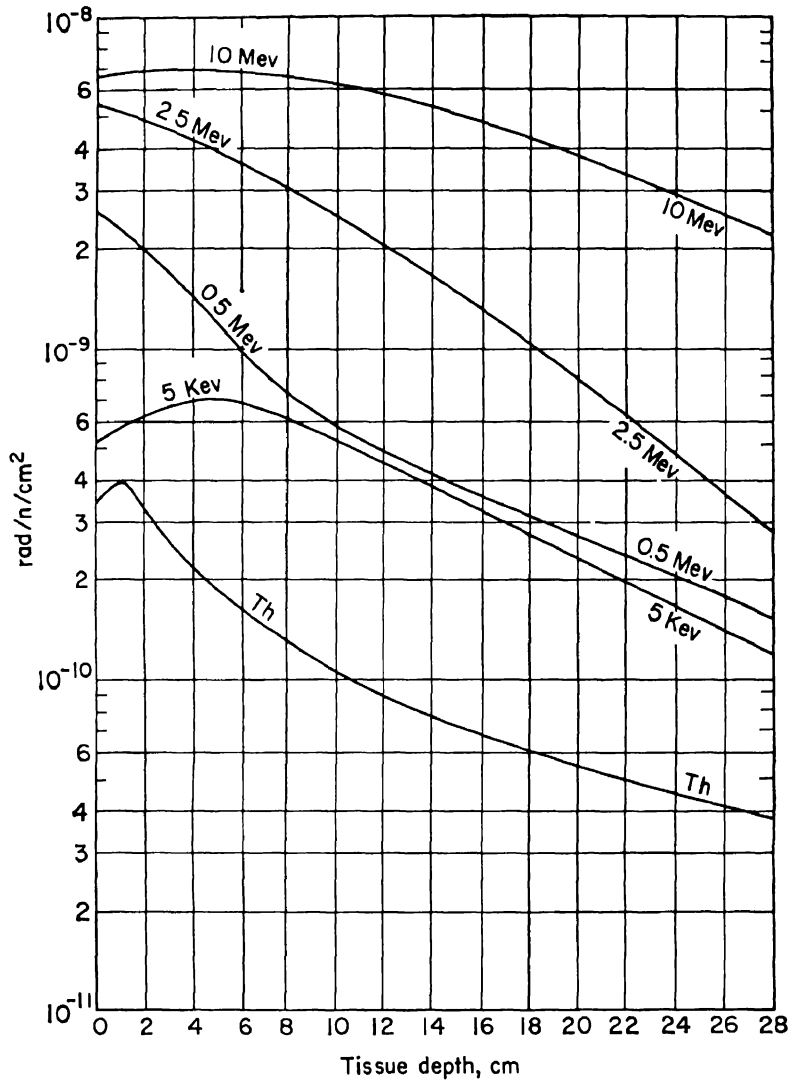


Fig. 10-3. Energy deposition in tissue from neutron beams. Data from Monte Carlo calculations of Snyder, W. S. and J. Neufeld. *Brit. J. Radiol.* **28**, 342, 1955.

Equation (10-18) is an empirical relation which has been found to express fairly well the combined decay of the large number of individual decays, each following an exponential law. Integration of Eq. (10-20) from t to ∞ gives an approximate expression for the total dose received from fission products from time t. This is

$$D = 5\,At \qquad \textbf{(10-21)}$$

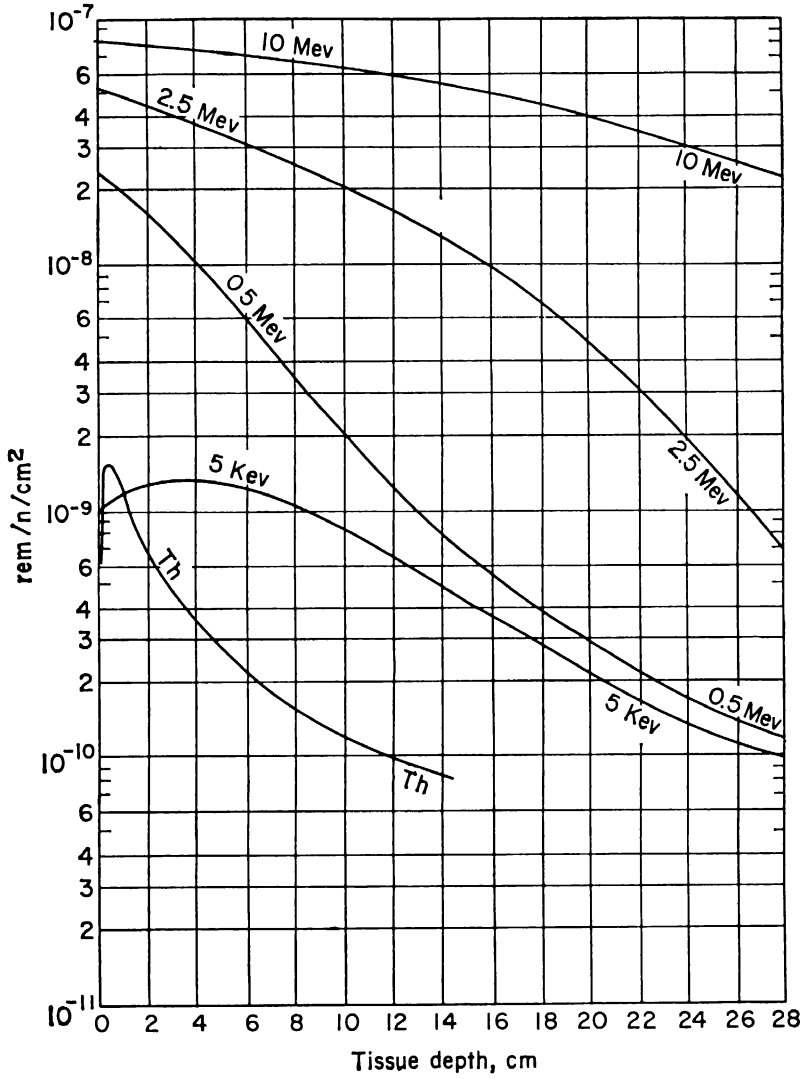


Fig. 10-4. Absorbed dose in rem from neutron beams. Adapted from calculations of Snyder, W. S. and J. Neufeld. *Brit. J. Radiol.* **28**, 312, 1955.

where A and t must be in self-consistent units. For example, if $A =$ 200 mr per hour at 3 hours after detonation the infinity dose at that point would be $5 \times 0.2 \times 3 = 3$ roentgens.

Reactor fission products are normally contained in the fuel elements, which are fabricated in a variety of forms. After an appropriate fraction of the nuclear material has fissioned the fuel elements

will be removed for recovery of the plutonium. At this time the fission products will be extracted as wastes, to be disposed of in some safe manner.

A fuel element may rupture in an air-cooled reactor or failure of control devices may result in a reactor runaway or a meltdown. In either of these cases fission products may be released into the atmosphere to constitute a potential hazard downwind from the release point. Large quantities of fission products will be released to the atmosphere in a nuclear detonation and when they return to earth they are called *fallout.*

Two distinct types of fallout are recognized. In a very high-altitude burst the fission products will be released high above the earth's surface and will rise, usually well above the tropopause. Since these products are in a finely divided form they will remain in suspension for many months or years and will return to earth only after considerable radioactive decay has taken place. Long-lived products such as Sr^{90} will predominate in this delayed fallout.

In a low-altitude detonation there will be an intimate mixing of fission products at a high temperature with particles of sand or debris from the earth's surface. Many of the fission products will condense out on the sand particles as the mixture cools. Fallout will now take place much earlier because the rate of fall will be that characteristic of much larger particles. Radiation intensities may be high enough to deliver lethal doses over a wide area downwind.

PROBLEMS

10-1. Calculate the mass of the neutron from tabulated values of atomic masses and the Q of the $H^3(d,n)He^4$ reaction.

Ans. 1.008958 amu.

10-2. Calculate the atomic mass of B^{10} and velocity of the neutron produced by $Be^9(d,n)B^{10}$ using tabular values of atomic masses.

10-3. A neutron source is to be constructed using 1 curie of Ra^{226} in equilibrium with its daughters, and an optimum amount of Be. Estimate the neutron flux from this source at a distance of 1 meter. What is the gamma-ray intensity from this source at a distance of 1 meter? *Ans.* 590 n/cm/sec, 840 mr/hour.

10-4. A Van de Graaff generator operates at 5 Mev with a beam current of 30 microamperes of deuterons. The yield of the

$Be^{9}(d,n)B^{10}$ reaction at 5 Mev is 1.8×10^{10} neutrons/sec/microampere. How many curies of Po^{210} in a Po-Be mixture would be required to produce the same neutron flux?

10-5. Calculate the maximum energy of the neutrons produced by the two methods considered in Prob. 10-4.
Ans. From $Be^{9}(d,n)B^{10}$ 9.4 Mev, from Po^{210} and $Be^{9}(\alpha,n)C^{12}$ 10.9 Mev.

10-6. Lead is a relatively ineffective neutron shield, although it is an excellent photon absorber. Calculate the energy of a neutron originally having an energy of 10 Mev, after a maximum-energy transfer collision with a lead nucleus. Compare this with the energy after a similar collision with a carbon nucleus.

10-7. How many collisions with carbon will be required to thermalize a 3 Mev neutron? What fraction of the total energy is transferred at the first collision? *Ans.* 113 collisions, 15.2 per cent.

10-8. Calculate the velocity of a thermal neutron. What would be the energy in ev and the velocity of neutrons in equilibrium with liquid nitrogen at a temperature of $-195°$ C? What is the equivalent temperature of a 14 Mev neutron?

10-9. A 1 gram sample of natural silver (51.3 per cent Ag^{107} and 48.7 per cent Ag^{109}) is bombarded for 28 days in a nuclear reactor at a thermal neutron flux of 5×10^{12} n/sec/cm^2. Assume $\sigma_{\text{act th}}$ for $Ag^{109}(n,\gamma)Ag^{110}$ to be 1.4 barns for the natural element and calculate the number of millicuries of 270 day Ag^{110} formed. What is the specific activity of the sample? *Ans.* 73.4 mc, 73.4 mc/gm of Ag.

10-10. A tracing experiment using 26.5 day Cr^{51} requires the use of 150 microcuries and a specific activity of at least 100 mc/gram. The cross section for $Cr^{50}(n,\gamma)Cr^{51}$ was 11 barns for thermal neutrons. If natural chromium (4.31 per cent Cr^{50}) is irradiated in a flux of 3×10^{12} n/sec/cm^2 calculate the bombardment time required and the amount of sample that must be bombarded.

10-11. Calculate the specific activity of a sample of natural cobalt (100 per cent Co^{59}) irradiated in a reactor for 1 year at 6×10^{11} n/sec/cm^2. $\sigma_{\text{act. th.}}$ for 5.28 year Co^{60} according to $Co^{59}(n,\gamma)Co^{60}$ is 19 barns. What is the maximum specific activity of Co^{60} obtainable at this neutron flux? *Ans.* 387 mc/gram, 3.14 c/gram.

10-12. Repeat the calculations of Prob. 10-11 for Co^{60} produced by a Ni^{60} $(n,p)Co^{60}$ reaction if the cross section for this reaction for fast neutrons is 0.02 barns, and the fast-neutron flux is 8×10^{11} n/sec/cm^2.

10-13. Fallout particles arriving 3.5 hours after a nuclear detonation produce a radiation field of 360 mr/hour. What dose will be delivered in an infinite time by this source? What dose will be received in the first 21 hours after fallout? *Ans.* 6.3 r, 2.1 r.

10-14. Assume that on the average 200 Mev per fission is available for power production, and calculate the mass of U^{235} that must be fissioned to produce 50,000,000 kilowatt hours of energy. 1 kilowatt hour = 3.6×10^{13} ergs.

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11

CHEMICAL EFFECTS OF RADIATION

11.01 THE TIME SCALE

Although the chemical effects of radiation are imperfectly understood even today their existence has been known since about 1901. Early observations showed that hydrogen and oxygen were continuously evolved from solutions of radioactive salts, and that hydrogen was in excess over the proportions found in water. Later studies demonstrated the presence of hydrogen peroxide in the proper concentration to balance the excess hydrogen.

Some simple approximate calculations show that the initial events involved in the absorption of radiation take place with considerable rapidity. A 1 Mev electron moves with a velocity of 2.8×10^{10} cm/sec and hence passes through an atomic diameter in about 10^{-18} sec. An electron with only 1 ev energy has a velocity of 1.8×10^{7} cm/sec and traverses an atom in about 10^{-15} sec.

If a molecule receives energy at a single point this excess energy

will be distributed throughout the structure by inter-atomic vibrations. Since most molecules have vibrational absorption bands in the infra-red ($\lambda \cong 10{,}000$ A) the time of one vibration will be about 10^{-14} sec. By about 10^{-13} sec, therefore, the energy will be distributed throughout the molecule and prompt dissociation, if it is to occur, will have taken place. In some cases dissociation may be delayed to 10^{-7} sec, but this probably represents an upper limit. More sophisticated considerations lead to the conclusion that all the original processes associated with radiation absorption will be complete in less than 10^{-4} sec. One of the mysterious but intriguing aspects of radiation action is the fact that a primary process, complete in 10^{-4} sec, may lead to the death of an animal 15 days later, or the production of a radiogenic cancer in 10–20 years.

11.02 IONIZATION AND CHEMICAL YIELD

Ionization by radiation is a relatively straightforward process, although the ultimate fate of the ions may be quite complex. In gases the ions can be collected at electrodes with a negligible loss due to recombination, and can be measured as an electrical charge or an electrical current. From a knowledge of the energy absorbed and the number of ion pairs produced it is possible to determine W, the energy required to form one ion pair. The values obtained are almost independent of the gas used, and lie well above the ionization potentials. Obviously some other, non-ionizing process is utilizing a substantial fraction of the absorbed energy.

Chemical effects in liquids and solids are of more interest to the biologist, and here it is not possible to collect and measure the ions produced. In condensed systems there are many more collisions than in a gas; practically all ions will be lost by recombination before they can be collected at electrodes. There is some reason to believe that W has about the same value (32–35 ev/ion pair) in all media. If this is the case N, the number of ion pairs formed by a known exposure dose can be determined from known absorption coefficients. The number of molecules M_i of a particular chemical species formed by the radiation can be determined by analytical methods. The ratio M_i/N can then be used to indicate the yield, or sensitivity of the reaction leading to product i. There may of course be a different value of M_i for each reaction product.

Because of uncertainties in values of W the use of M_i/N as a measure of yield has practically been abandoned. It is now customary to use *G values*, or the yield of each product expressed in molecules formed per 100 ev of energy absorbed. Approximate *G values* can be found by multiplying M_i/N ratios by 3. Each reaction product will have its characteristic G value, the individual values in any complex reaction being related by the stochiometry of the reaction mechanisms involved.

11.03 MOLECULAR EXCITATION

Although the energy that goes into excitation cannot be directly measured it does not follow that excitation is ineffective in producing chemical change. According to the Franck-Condon principle the situation in a diatomic molecule will be about as shown in Fig. 11-1.

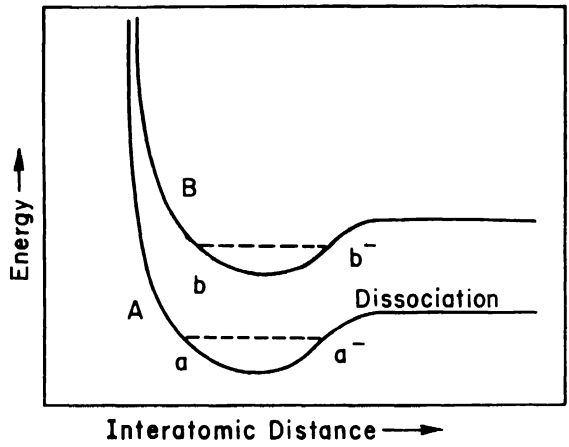


Fig. 11-1. Energy-distance relationships between two atoms in the ground state and a higher state of electronic excitation.

In the ground state the molecule will have an energy level a and an interatomic spacing corresponding to the values on potential energy curve A. When the molecule receives energy by electronic excitation the potential energy curve may change to B, with points a and a' changing to b and b'. The interatomic spacing cannot change instantaneously, however, and thus the molecule may dissociate, since bb' lies well above the energy needed for infinite separation.

In a more complex molecule, energy of excitation not leading to dissociation according to the Franck-Condon principle will be spread throughout the molecule by vibrations. If the excess energy so distributed exceeds any bond strength, dissociation will result. Bond strengths can be estimated from spectroscopic measurements. As an example, infra-red absorption measurements give a C–C bond strength of 3.6 ev and a C–H strength of 3.5 ev. Chemical reaction energetics are more often given in kilocalories per mole, obtained from bond strengths measured in ev by a simple conversion of units. This conversion gives a dissociation energy for the C–C bond of about 83 kilocalories per mole.

In a complex molecule with many bonds the excitation energy, when spread over all bonds, may be insufficient for dissociation of even the weakest. The molecule then remains in an excited state until a statistical fluctuation in energy raises one bond above the dissociation energy, or until the energy of excitation is removed by inter-molecular collisions. This delayed dissociation may take place as much as 10^{-7} sec after the energy is received. In liquid systems the frequency of inter-molecular collisions is much greater than in a gas, and one would expect an increase in de-excitation collisions and a decrease in chemical yields. This prediction is in general borne out by experiment.

An excited molecule need not dissociate at all. Excess energy may be transferred to another molecule by collision, and the second molecule may or may not dissociate, depending upon the energies involved. An excited molecule may emit one or more photons of visible or ultra-violet light, thus returning to the ground state without dissociation. Many details of excitation energy transfer are not understood but it is certain that many of the possible results of excitation can lead to changes of molecular configuration of biological significance. Excitation phenomena have been neglected in radiobiology, not because they are unimportant, but because of the great experimental difficulties involved in studying them.

11.04 DIRECT AND INDIRECT ACTION

In a pure material, irradiated as a solid, radiation effects can only result from a *direct action* whereby the molecules gain energy of excitation or ionization by direct interaction with the charged

particles. Direct action can, and does, take place in solutions, but in general this accounts for only a small fraction of the total effect. Energy transfer from charged ionizing particles is a non-specific effect and therefore will be proportional to the amount of any constituent present. Considerations of concentration alone, therefore, show that direct solute action in solutions will be less important than in solids.

In *indirect action* the primary energy transfer takes place at the solvent molecules to produce chemical radiation products. These intermediates then react with solute molecules to form products which are only indirectly the result of irradiation. Indirect action is obviously of great importance in biological systems because of the large water content of most living tissues. The radiolysis of water will be considered in detail in the next section.

It is frequently desirable to determine whether a given reaction is predominantly direct or indirect—a few simple tests furnish presumptive, if not conclusive, evidence. One of the most satisfactory tests involves a study of the chemical yield of various solute concentrations, at constant absorbed energy.

In direct action the total amount of reaction product formed will be directly proportional to the amount of solute present, over a wide concentration range. This is equivalent to saying that a given radiation dose will cause the reaction of a constant *fraction* of the solute, independent of concentration. For example, direct action would be inferred if a given radiation dose produced a constant percentage inactivation of an enzyme system or a bacterial culture, regardless of concentration.

At a constant radiation dose the number of intermediate products formed from solvent molecules will be practically independent of solute concentration. The *total amount* of solute affected by indirect action will be independent of concentration except at extreme dilutions where recombination may occur before an intermediate-solute collision. Figure 11-2, (A) and (B), shows schematically yield-concentration relations for the two kinds of action.

11.05 RADIOLYSIS OF WATER

Much effort has been expended in studying the actions of radiation on water—the principal products are well known. Detailed

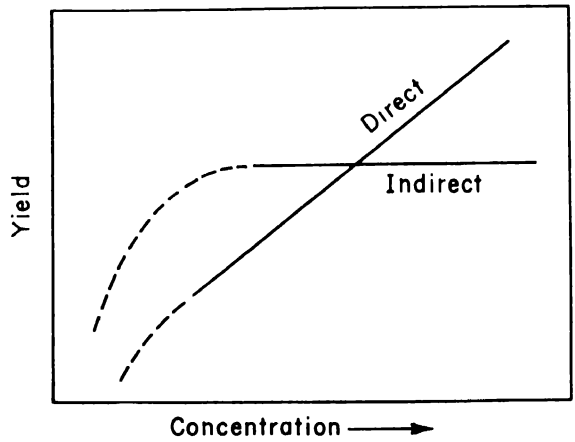


Fig. 11-2. Idealized yield-concentration relationships at constant radiation dose for direct and indirect action.

mechanisms, however, are still not entirely understood. Schematically we may write

$$H_2O \longrightarrow aH + bOH + cH_2 + dH_2O_2 \qquad (11\text{-}1)$$

where *a, b, c,* and *d* are yield coefficients which will vary with the LET of the radiation and the kind and amount of gas dissolved in the water.

Products H and OH each contain an odd number of electrons and hence at least one electron is unpaired or not associated with another. Any chemical structure containing an unpaired electron is called a *free radical* and is known to be relatively reactive. Thus H and OH are much more reactive than their ionic counterparts H^+ and OH^-, which exist in all electrolytic solutions.

When radiation impinges upon a water molecule the first act is the ejection of an electron

$$H_2O \longrightarrow H_2O^+ + e^- \qquad (11\text{-}2)$$

The positive ion dissociates

$$H_2O^+ \longrightarrow H^+ + OH \qquad (11\text{-}3)$$

and the electron attaches itself to a neutral water molecule, which in turn promptly dissociates

$$e^- + H_2O \longrightarrow H_2O^- \qquad (11\text{-}4)$$

$$H_2O^- \longrightarrow H + OH \qquad (11\text{-}5)$$

Ions H^+ and OH^- play no role in subsequent actions. Before the radiation absorption there was a substantial concentration of these ions, and so as radiation products they add nothing new.

Subsequent events depend strongly upon the LET of the ionizing particle. Consider first the case of an α particle which will move in an essentially linear path producing about 400 ion pairs per micron. The initial events, Eqs. (11-2) and (11-3) will take place along the path of the particle so there will be a central core of closely spaced OH radicals.

The electron in Eq. (11-2) will fly out from the central core and initiate reactions (11-4) and (11-5) at an appreciable distance from it. At the end of reaction (11-5) the situation will be about as shown in Fig. 11-3A. Diffusion will immediately set in and there will be some recombination or *back reaction*

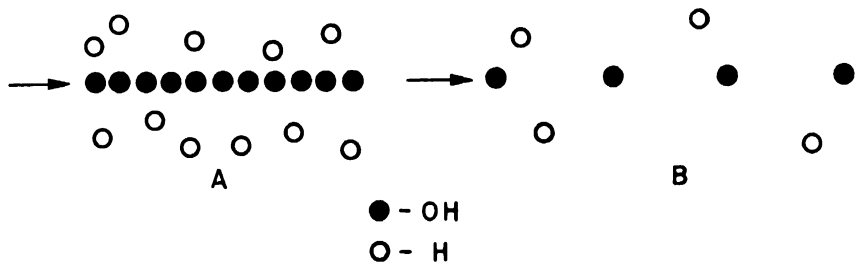


Fig. 11-3. Spatial distribution of primary reaction products before diffusion, recombination, or reaction. (A) High LET. (B) Low LET.

$$H + OH \longrightarrow H_2O \qquad (11\text{-}6)$$

With a high value of LET adjacent OH radicals are more closely spaced than are H and OH radicals so in this case the favored reactions are

$$H + H \longrightarrow H_2 \qquad (11\text{-}7)$$

$$OH + OH \longrightarrow H_2O_2 \qquad (11\text{-}8)$$

Thus it would be expected that irradiation with alpha particles would produce hydrogen gas and hydrogen peroxide. The latter product is an oxidizing agent which may persist in solution for some time, as contrasted to the relatively transient existence of free radicals. If dissolved oxygen is present we may also have

$$H + O_2 \longrightarrow HO_2 \qquad (11\text{-}9)$$

where HO_2 is a free radical that is somewhat less reactive than the original radicals.

The situation will be somewhat different if the original ionizing particle is an electron having a linear ion density of say, 10 ion pairs per micron. In this case reactions (11-7) and (11-8) are not favored because of the large spacing between ionizing events. Back reaction (11-6) is still probable, but the H and OH radicals will have a greater chance of existing until they meet solute molecules. Thus a particle with a high LET is said to favor molecular products whereas a low LET particle tends to produce free radicals.

Product yield is also affected by LET through the *cage effect.* In a sparsely ionizing situation an isolated radiation product may be prevented from diffusing by the surrounding solvent molecules, which form a restraint, or cage. In attempting to escape, excess energy may be lost by collisions and the chance of recombination is good. When the ionizing particle has a high linear-ion density the reaction products may be so closely spaced that each cage is incomplete and escape is more probable.

11.06 RADICAL PRODUCTION BY EXCITATION

The mechanism presented in section 11.05 was developed primarily by Lea * who made use of a diffusion theory of Jaffe.† The Lea mechanism requires that the electron ejected in the first act, Eq. (11-2) travel away from its point of origin so that it eventually interacts with a second water molecule according to Eq. (11-4). Calculations made by Dale, Gray and Meredith ** show that the electron may travel as much as 150 A on the average and this is a sufficient distance to remove it from the Coulomb field of the associated H_2O^+ ion.

As previously mentioned, the behavior of very low-energy charged particles is not uniquely calculable and Samuel and Magee †† arrive

* Lea, D. E. *Actions of Radiations on Living Cells.* Cambridge Univ. Press, Cambridge, 1917.

† Jaffe, G. "Zur Theorie der Ionisation in Kolonnen." *Ann. der Physik* **42,** 303, 1913.

** Dale, W. M., L. H. Gray, and W. J. Meredith. *Phil. Trans. Roy. Soc.* **A 242,** 33, 1949.

†† Samuel, A. H., and J. L. Magee. "Theory of Radiation Chemistry II, Track Effects in Radiolysis of Water." *J. Chem. Physics* **21,** 1080, 1953.

at a value of only 20 A for the movement of the initial electron. If this value is correct, the electron is not capable of moving away from the parent atom. The electron would then return to form an excited water molecule and this would immediately dissociate. The reactions would be

$$H_2O \longrightarrow H_2O^+ + e^- \qquad (11\text{-}10)$$

$$H_2O^+ + e^- \longrightarrow H_2O^* \qquad (11\text{-}11)$$

$$H_2O^* \longrightarrow H + OH \qquad (11\text{-}12)$$

This process would be repeated along the path of the primary ionizing particle according to its characteristic LET. Back reaction to H_2O and combination to H_2 and H_2O_2 then take place between adjacent products.

The end products of this mechanism are the same as those from the Lea mechanism, but the spatial distribution of the product will be quite different. The distinction is of some importance in estimating the efficiency of radiation in producing various biological effects. It appears that in some cases single events suffice, whereas in others two closely spaced events are needed. At the present time experimental evidence is not sufficiently clear-cut to distinguish between the two mechanisms. It should be pointed out, however, that detailed calculations by Platzman and Froelich * suggest that the initial electron may have a path length even greater than 150 A.

11.07 OXIDATION OF FERROUS IRON

Fricke † showed in 1927 that ferrous ions are oxidized to ferric by radiation, and suggested this system as a practical dosimeter. After being virtually neglected for many years this reaction has been intensively studied, and is now recognized as one of the most generally useful chemical dosimeters. The exact mechanisms are not understood, but this has not prevented practical applications; ferrous sulphate is now almost universally used as a dosimeter in chemical studies.

* Platzman, R. H., and H. Froelich. *Phys. Rev.* **92**, 1152, 1953.

† Fricke, H., and S. Morse. *Am. J. Roentgenol. Rad. Therapy* **18**, 430, 1927

As ordinarily used the dosimeter consists of a 10^{-3} to 10^{-4} molar solution of ferrous ammonium sulphate, $Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$ in 0.8 N H_2SO_4. An acid solution is required to prevent hydrolysis and Fricke and Morse * pointed out that at 0.8 N H_2SO_4 the photon-absorption coefficients approximate those for soft tissue. In the concentration range specified the action is essentially indirect and the yield is independent of solute concentration. Below 10^{-5} *M* there is some loss of ferric iron because of radical recombination.

Response of the ferrous sulphate system can be determined by any analytical method for either Fe^{2+} or Fe^{3+} ions. For small radiation doses, analyses for Fe^{3+} are to be preferred since there will be an essentially zero blank from the unirradiated solution.

Fe^{2+} has been determined by forming a complex with o-phenanthroline in acetate buffer † at pH 4–5. The complex has an absorption band at 5100 A with a molar-extinction coefficient of 11,100.** It is more common to determine Fe^{3+} directly from the absorption band at 3050 A, which has a molar-extinction coefficient of 2,166.††

Oxygen is consumed in the ferrous oxidation and therefore both sensitivity and useful range are determined by the amount of oxygen dissolved in the solution. For convenience most work is done with solutions in equilibrium with room air—little trouble is encountered in obtaining reproducible sensitivity. Water for the solutions must be of high purity but ultimate precautions are not necessary. Reproducibility is improved by making the ferrous-sulphate solution 10^{-3} to 10^{-4} *M* in NaCl. These ions act as scavengers for residual organic impurities, which would otherwise compete for the primary radicals formed by the radiation.

11.08 FERROUS SULPHATE AS A DOSIMETER

Several features combine to make ferrous-sulphate oxidation a useful dosimeter. The *G* value for the reaction is almost independent of LET over a wide range, so the system is energy-independent down to low energies.

* Fricke, H., and S. Morse *Phil. Mag* **7**, 129, 1930.

† Fortune, W. B., and M. G. Mellon. *Ind. Eng. Chem.* (Anal. Ed) **10**, 60, 1938.

** Brandt, W. W., and G. F. Smith. *Anal. Chem.* **21**, 1313, 1949.

†† Hardwick, T. J. *Can. J. Chem.* **30**, 17, 1952.

Table 11-1 G VALUES FOR FERROUS SULPHATE OXIDATION *

Radiation	$G(Fe^{3+})$
1 Mev gamma rays	15.6
$H^3\beta s(\overline{E} = 5.69$ Kev)	12.9
Po^{210} αs 5.3 Mev	6.2
Recoil particles from $Li^6(n,\alpha)H^3$	5.2
Recoil particles from $B^{10}(n,\alpha)Li^7$	4.2

* From McDonell, W. R., and E. J. Hart. *J. Am. Chem. Soc.* **76**, 2121, 1954.

From the H^3 β particle results it appears that the dosimeter responds uniformly to energies down to perhaps 20 Kev. The reduced yields at higher LET undoubtedly result from radical recombination.

The *G* value is also independent of dose rate from the lowest values studied up to at least 10^{10} rad/sec, the high rates being obtained by direct electron bombardment.

With a stable *G* value and readily reproducible solutions, ferrous sulphate can be used for dosage determinations without calibration. If a spectrophotometric assay is used, absorbed dose can be determined from the measured optical density and the extinction coefficient, which can be determined independently.

If a light intensity I_0 is incident on an absorption cell having an effective length of l cm the transmitted light intensity I is given by

$$\log_{10}(I_0/I) = \varepsilon c l \tag{11-13}$$

where ε = molar-extinction coefficient
c = concentration, moles per liter
$100\ I/I_0$ = per cent transmission
$\log_{10}(I_0/I)$ = optical density, *OD*.

Illustrative Example

A ferrous-sulphate solution after irradiation has an optical density of 0.364 measured at 3050 A in a 1 cm cell. Calculate the absorbed dose in rad.

$$\log_{10}(I_0/I) = 0.364 = 2{,}166 \times c \times 1$$
$$c = 1.59 \times 10^{-4} \text{ mol/liter}$$
$$6.02 \times 10^{23} \times 1.59 \times 10^{-7} = 9.60 \times 10^{16}\ Fe^{3+} \text{ ion/gram}$$
$$\frac{9.60 \times 10^{16}}{0.156} = 6.14 \times 10^{17} \text{ ev/gram}$$
$$6.14 \times 10^{17} \times 1.6 \times 10^{-12} = 9.8 \times 10^{5} \text{ erg/gram} = 9{,}800 \text{ rad}$$

Oxygen depletion sets a useful upper limit of about 50,000 rad to the ferrous sulphate dosimeter. The reaction is essentially indirect, so a reduced effect cannot be obtained without a drastic reduction in solute concentration. At this point solute depletion sets an upper limit of usefulness.

11.09 REDUCTION OF CERIC SULPHATE

It is frequently necessary to measure doses well beyond the upper range of the ferrous sulphate dosimeter. In this region the ceric sulphate system can be used to advantage. Solutions in 0.8 N H_2SO_4 from 10^{-5} to 0.4 molar in ceric sulphate have been used, the highest concentration being used for absorbed doses up to 10^8 rad.*

Assay is most conveniently done by absorption spectroscopy at 3200 A, where the molar-extinction coefficient of Ce^{4+} is 5,800. At high solute concentrations the pre-irradiation OD is inconveniently large and must be determined by dilution with 0.8 N H_2SO_4. In most concentration ranges response is linear with dose up to about 80 per cent solute depletion. Oxygen is produced by the reaction so the upper range limit can be raised by increasing the original solute concentration.

Unfortunately the G value depends upon solute concentration and to some extent upon LET so each solution must be calibrated against some standard such as ferrous sulphate. At 10^{-3} M the G value for 1 Mev photons is about 2.50.

The ceric system is very sensitive to impurities; no stabilizer similar to the NaCl scavenger is known. The utmost care must be used in preparing the water and only the cleanest of glass vessels can be used for the irradiations.

Dose-rate independence is satisfactory and the ceric system seems to be the method of choice for extremely high-dose determinations, in spite of the care that must be taken to insure meaningful results.

11.10 RADIOLYSIS OF CHLORINE-CONTAINING COMPOUNDS

It has been known for many years that many chlorine-containing compounds are unusually sensitive to radiation. Free HCl is pro-

* Harlan, J. T., and E. J. Hart. *Nucleonics* **17**, 102, 1959, Taimuty, S. I., L. H. Towle, and D. L. Peterson. *Nucleonics* **17**, 103, 1959.

duced by radiation from chlorinated hydrocarbons such as carbon tetrachloride or chloroform, with G values reaching 1000 or even more. Yields of this magnitude require the formation of 10 product molecules for each ev expended, and this requires the presence of some chain reaction. It is very difficult to use these high yields in practice, because chain reactions are extremely sensitive to many variables which may be difficult or impossible to control.

Taplin * has shown that these high-yield reactions can be stabilized by adding chain inhibitors such as resorcinol. With this stabilization G values may be reduced to 100 or less but radiation doses of the order of 100 rad can still be measured. A direct single-phase system can be made by incorporating a suitable pH indicator in a stabilized chlorinated hydrocarbon.

Additional sensitivity can be achieved with a two-phase system consisting of a stabilized, chlorinated hydrocarbon and an aqueous solution of an indicator such as Bromcresol purple. HCl will be liberated in the hydrocarbon and, upon shaking, it will be preferentially picked by the aqueous phase. By a proper choice of relative volumes a ten-fold sensitivity increase can be realized.

The sensitive dosimeters described necessarily have a high Cl content and consequently are energy-dependent. The high response to low-energy photons can be reduced by enclosing the solutions in a suitable lead filter which will permit measurement with reasonable accuracy from 80 Kev to 1.2 Mev.

Chloral hydrate, $CCl_3CH(OH)_2$ is an organic halogen that has been used as a dosimeter. In aqueous solution HCl is formed and measurement can be made by indicators, pH, or electrical-conductivity determination. G values of up to 250 have been observed with all the usual drawbacks of chain reactions. Since reasonable sensitivity can be achieved in solutions only 10^{-3} M in chloral hydrate the system is essentially energy-independent and with proper temperature control reproducible results can be obtained.

Chloral hydrate has been adapted to depth-dose measurement in phantoms † by incorporating it in an agar gel. By adding an indicator to the gel, radiation fields can be visualized or measurements made by absorption spectroscopy. Alternatively, micro-pH or conductivity electrodes can be pushed through the gel to obtain continuous records of absorbed energy. The gel system has a density of about 1.04 and is nearly tissue-equivalent down to energies of 10

* Taplin, G. V. UNESCO/NS/RIC/3.

† Andrews, H. L., R. E. Murphy, and E. J. LeBrun. *Rev. Sci. Instr.* **28**, 329, 1957.

Kev. The response is not linear with dose, but a linear recording system can be devised.

11.11 RADIATION EFFECTS IN LARGE MOLECULES

Biological interest centers on larger molecules than those previously discussed, but here information is incomplete and mechanisms are almost completely unknown. Enzyme inactivation has been extensively studied. Barron * has pointed out the sensitivity of SH groups toward oxidation by radiation. Table 11-2, taken from Barron's paper, shows the wide range of G values found in enzyme studies.

Table 11-2 G VALUES OF ENZYME SYSTEMS

Enzyme	G (Inactivation)
Yeast alcohol dehydrogenase	3.1
Phosphoglyceraldehyde dehydrogenase	2.9
Carboxypeptidase	0.55
D-amino acid oxidase	0.31
Ribonuclease	0.09
Trypsin	0.077
Lysozyme	0.03
Catalase	0.009

Maxwell † and his collaborators have identified all the important radiation products of glycine, and have proposed a mechanism for their production. G values are not constant with dose, because primary reaction products tend to compete for some of the radicals and alter the course of the reaction.

From the complex mechanisms involved in the radiolysis of simple molecules, it might appear that an understanding of radiation action on macromolecules would be out of the question. In fact considerable insight into reaction mechanisms is being gained. From the low inactivation yields it appears that many parts of a macromolecule can react without changing the biological activity. Another possibility is the repair of radiation-produced damage so that the initial configuration is restored. As an example many enzymes, inactivated by radiation, can be reactivated by the addition of gluta-

* Barron, E. S. G. *Rad. Res.* **1**, 109, 1954.

† Maxwell, C. R., D. C. Peterson, and N. E. Sharpless. *Rad. Res.* **1**, 530, 1954.

thione. Presumably this reduces the S–S group back to the original sulfhydryl, S–H. Again, a long chain, broken near its center by radical action, may be repaired before the relatively massive fragments can move apart sufficiently to achieve permanent separation.

The biologically important DNA (desoxyribonucleic acid) molecule is ruptured by radiation, as evidenced by a reduction in viscosity, and the effect continues after irradiation has ended.* The most probable point of attack is the bond between the sugar and the purine or pyrimidine base but this is not known with certainty. In other large molecules radiation favors the formation of cross-linkage and a more rigid structure results. Much of the polyethylene commercially available has been irradiated to improve its high-temperature viscosity by the formation of cross links.

PROBLEMS

11-1. Assume that an electron is ejected from a water molecule with an initial energy of 150 electron volts. Estimate the time required for this electron to travel the 20 A suggested by the calculations of Magee et al. *Ans.* 5.5×10^{-16} sec.

11-2. Calculate the attractive force between the electron and the H_2O^+ ion when separated by 20 A as in Probl. 11-1.

11-3. An energy of 5 ev is required to dissociate H_2O into OH and H. Express this in kilocalories per mole. *Ans.* 116 kilocal/mol.

11-4. A solution of 10^{-3} *M* chloral hydrate received 5,000 rad and an analysis showed the concentration of HCl to be 0.3 μ mole/ml. Calculate the *G* value of the reaction.

11-5. In radiation chemistry absorbed energy is frequently expressed in ev/ml. Calculate the rad delivered to an aqueous solution when the energy absorption was 2×10^{18} ev/gm. *Ans.* 3.2×10^4 rad.

11-6. A ferrous sulphate dosimeter is to be measured at 3050 A in absorption cell having a path length of 10 cm. Calculate the radiation dose that will produce an optical density of 0.100.

11-7. A ferrous sulphate dosimeter is 10^{-3} M in Fe^{2+} in 0.8 N H_2SO_4. Calculate the radiation dose required to deplete the Fe^{2+} to 6×10^{-4} M. *Ans.* 2.5×10^4 rad.

* Taylor, B., J. P. Greenstein, and A. E. Hollaender. *Arch. Biochem. and Biophy* **16,** 19, 1948.

11-8. The response of the ceric-sulphate dosimeter is nearly linear until all the cerium is reduced. Calculate the maximum dose of 1.2 Mev X-rays which can be measured by a ceric-sulphate solution 10^{-4} M in Ce^{4+} for 80 per cent depletion. What is the *OD* of the original solution at 3200 A in an 0.5 cm absorption cell?

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12

DOSE-RESPONSE RELATIONS IN MACROMOLECULES

12.01 THE BASIC PROBLEM

Ideally, one would like to describe the end effects of radiation absorption by living matter in terms of the primary physical and chemical changes. At the present time this Utopian goal appears to be far from fulfillment in spite of intense research at each end of the gap separating radiation chemistry and radiation biology.

In the absence of a complete description of radiation-initiated processes we must consider the gross actions of radiation and attempt to obtain some understanding of mechanisms by which the observed results may be obtained. Conversely, reasonable mechanisms of radiation action must be considered, and the implications tested against carefully obtained experimental data.

One of the early suggestions for radiation action was the *point-heat* theory of Dessauer. According to the point-heat theory absorption of energy by a relatively small structure such as a single molecule

results in a high local temperature. This high local temperature is assumed to initiate a destructive action at the site of absorption. The absorption of only a few electron volts of energy can indeed produce a relatively high temperature if we assume macroscopic properties to transfer to the microscopic scale.

Illustrative Example

Assume 100 ev absorbed by a molecule of molecular weight 15,000 and estimate the temperature attained by the molecule.

$$\frac{100 \times 1.6 \times 10^{-12} \times 10^{-7}}{4.18} = 3.8 \times 10^{-18} \text{ calorie absorbed}$$

$$1.5 \times 10^{4} \times 1.66 \times 10^{-24} = 2.5 \times 10^{-20} \text{ gm to be heated}$$

If such a single molecule can be considered to have a specific heat of unity

$$\text{Temperature rise} = \frac{3.8 \times 10^{-18}}{2.5 \times 10^{-20}} = 150°\text{C}$$

The apparent temperature rise is substantial but radiation effects are probably better interpreted in terms of ionization, excitation and dissociation.

12.02 ELEMENTARY TARGET THEORY

It is generally agreed that the primary act of radiation absorption takes place in a very localized volume, and it is reasonable to ask the size of the *target* presented by an organism when a given biological result is obtained. This *target size* is analogous to the cross sections discussed in connection with neutron interactions. In the present case one would expect the target sizes to be closely identified with some biological structure which might be considered a *sensitive volume.*

Target-size determinations have meaning only when the action is known to be predominantly direct. In solutions the diffusion of free radicals from the point of formation to a point of attack on a solution constituent prevents any significant size determinations. Even in a discrete unit such as a cell, calculations of target sizes are fraught with uncertainty. Because of this restriction target size determinations can be made in only a limited number of materials.

Dry viruses, enzymes, and hormones are among the materials which can be studied in this way.

In principle the experimental determination of dose-effect relationships is simple, but in practice great care must be taken to insure meaningful results. For example, one might expose a series of cultures of a spore-forming bacterium to a series of radiation doses and count the number of viable colonies after a suitable period of incubation. If these data are to be interpreted in terms of target sizes, the irradiated material must be as homogeneous as possible. For example, differences in clumping can alter the number of hits needed to prevent colony formation, and this can lead to completely erroneous conclusions. Implicit in target-size calculations is the assumption that each of the entities exposed is equally susceptible to radiation injury. In other words, target theory requires that any hit (or a given number of hits) within the sensitive volume is effective, and that hits outside this volume are ineffective.

12.03 IRRADIATION AT HIGH LET

Several early investigators recognized the possibility of using bombarding particles of different ionizing properties to obtain information on sensitive areas and volumes. Using modern radiation sources, E. C. Pollard and his collaborators have exploited these techniques and applied them to a variety of studies. The treatment given here follows closely that given by Pollard.*

Consider a molecule such as a protein to be bombarded by a heavily ionizing particle such as a deuteron or an alpha particle of moderate energy. For an order-of-magnitude calculation assume a spherical molecule of molecular weight one million. Such a molecule will have a radius of about 67 A, on the assumption of a density of 1.3 gm/cm^3. The probability is overwhelming that the heavily ionizing particle will produce at least one ionization in traversing a distance of 67 A. In such a system, therefore, the probability of a hit depends upon target area and not upon target volume, since the probability of a hit along the path of the particle is unity.

Let the target contain N molecules per cm^2 and let there be n

* Pollard, E. C. "Primary Ionization as a Test of Molecular Organization" *Advances in Biol. and Med. Physics* **3**, 153, 1953.

bombarding particles per cm^2. Then for a small number of bombarding particles dn the number of hits will be dN, where

$$dN = -SNdr \tag{12-1}$$

and S is a constant of proportionality. Equation (12-1) expresses the fact that the number of hits will be proportional to the number of available targets and the number of bombarding particles. Equation (12-1) is a very familiar form of differential equation whose solution is

$$N = N_0 e^{-Sn} \tag{12-2}$$

or

$$\ln \frac{N}{N_0} = -Sn$$

Since n has the dimensions of a reciprocal area (cm^{-2}) S is in the nature of an area (cm^2), because the product must be a pure number. There will be a particular value of $n = n_{37}$ for which

$$Sn_{37} = 1 \tag{12-3}$$

and this leads to

$$N = 0.37\ N_0 \tag{12-4}$$

From Eqs. (12-3) and (12-4) the target cross section S is equal to the reciprocal of the number of bombarding particles per cm^2 required to produce a 37 per cent survival.

From Eq. (12-2) it is evident that a cross section S can be deduced if there is a linear relation between log N and n. The value of S thus deduced must then be evaluated in terms of the molecular cross section.

12.04 INTERMEDIATE VALUES OF LET

The relations just developed express the effect produced in terms of the number of particles producing it for a constant, high value of LET. These equations do not relate effect with the amount of absorbed energy nor express effect as a function of varying LET.

Qualitatively it is evident that a particle with a high value of LET will be relatively inefficient in producing an effect requiring only a single hit in a given sensitive volume. More than one hit in

this volume will result in a waste of energy. Obviously, on this basis the most sparsely ionizing particle should be the most effective since with it the chance of overhitting is the least.

Of more immediate interest for calculations of target cross sections are particles with intermediate values of LET which do not quite fulfill the requirements leading to the equation of Sec. 12.03. Such a particle might be a recoil proton from a fast-neutron interaction (n,p).

Ionization is a chance phenomenon, whatever the ionizing particle, and values of LET can only be averages over many interactions. The interactions will actually be spread according to well-known probability laws, above and below the mean value. When the average distance between interactions is of the same order as the dimensions of the sensitive volume the probability of a hit in a passage through the volume is appreciably less than unity. For such particles allowance must be made for this reduced probability in calculating target areas.

Elementary probability theory * leads to the theorem:

If the probability of occurrence of an event in a single trial is p, the chance that it will occur exactly s times in n independent trials is

$$p_s = \frac{n!}{s!(n-s)!} p^s (1-p)^{n-s} \tag{12-5}$$

where $n! = n$ *factorial* is the product $1 \cdot 2 \cdot 3 \cdots n$. For small numbers Eq. (12-5) may be approximated by the simple form

$$p_s = \frac{(np)^s}{s!} e^{-np} \tag{12-6}$$

and since the expected number of events in n trials is $\varepsilon = np$

$$p_s = \frac{\varepsilon^s}{s!} e^{-\varepsilon} \tag{12-7}$$

The terminology of probability theory must be paraphrased for our application. Then

p_s = probability of exactly s hits in a path length n
ε = expected average number of hits
s = actual number of hits.

* Sokolnikoff, I. S and E. S. *Higher Mathematics for Engineers and Physicists.* McGraw-Hill, New York, 1934.

If a single ionizing event is effective, multiple events must also be effective, which complicates the calculation of p_s. It is easier to calculate the probability of *non-occurrence* ($s = 0$) and subtract this value from unity. If $s = 0$ Eq. (12-7) becomes

$$p_0 = e^{-\varepsilon}$$

and the probability of occurrence is then

$$p_1 = (1 - e^{-\varepsilon}) \tag{12-8}$$

In calculating ε from values of LET the number of primary ionizing events rather than the total number of ion pairs should be used. Although one ion pair may be produced for each 34 ev expended, each primary event, on the average, will require more nearly 100 ev because of cluster formation.

Illustrative Examples

Assume a target thickness of 40 A and calculate the probability of ionization in this distance for two particles having LET values of 80 Kev/μ and 20 Kev/μ respectively.

$$80 \text{ Kev}/\mu = 8 \text{ ev/A and } 20 \text{ Kev}/\mu = 2 \text{ ev/A}$$

Assuming an expenditure of 100 ev per primary event

$$\varepsilon_1 = \frac{8}{100} \times 40 = 3.2 \text{ events per target}$$

$$\varepsilon_2 = \frac{2}{100} \times 40 = 0.8 \text{ events per target}$$

$$p_1 = (1 - e^{-3.2}) = 1 - 0.04 = 0.96$$

$$p_2 = (1 - e^{-0.8}) = 1 - 0.45 = 0.55$$

From the example it is evident that calculations of area from data taken with the first particle can be made directly, and corrections of 45 per cent must be made in the second case.

12.05 IONIZATION RANDOM IN VOLUME

The concepts of Sec. 12.03 do not apply to ionization by electrons because of their low value of LET and their tortuous paths. The concept of target area has meaning only as an average if the ionizing particles approach at random directions. When ionization is random in volume rather than in area an argument parallel to that already used leads to

$$N = N_0 e^{-Vi} \tag{12-9}$$

where V is a target volume and i is the number of primary ionizations per unit volume. By analogy

$$V = \frac{1}{i_{37}} \tag{12-10}$$

If experiment shows a linear relationship between log N and i a value V can be calculated. In each case the value thus found must be interpreted in terms of the molecular configuration being studied.

Values of target area can be calculated from measurements using heavy charged particles and data from electron or photon bombardment lead to a target volume. From these values the approximate shape of the target volume can be inferred.

An alternate method * of determining target shape involves the use of heavily ionizing particles to determine an average target thickness d. In Eq. (12-8) the expected number of hits from a single particle, ε, is given by

$$\varepsilon = p_1 d \tag{12-11}$$

where p_1 is the number of primary ionization per unit-path length. The target cross section increases with p_1 according to

$$S = S_0(1 - e^{-p_1 d}) \tag{12-12}$$

where S is the cross section corresponding to a linear ion density p_1 and S_0 is the maximum value of S. A series of measurements can be extrapolated to give a value of S_0 and d can be determined from the slope of the $S - p_1$ plot.

12.06 TARGET SHAPE AND MOLECULAR WEIGHT

The theory as presented is somewhat incomplete since in its development the complicating effects of ion clusters and δ rays have been neglected. Lea † has developed the *associated-volume method* for taking these complications into account. In most cases the experi-

* Pollard, E. C., W R. Guild, F. Hutchinson, and R. B. Setlow. "The direct action of ionizing radiation on enzymes and antigens." *Progress Biophys. and Biophys. Chem.* **5**, 72, 1955.

† Lea, D. E. *Actions of Radiation on Living Cells.* Macmillan, New York, 1947.

mental data probably do not warrant this elaborate mathematical treatment.

Measurements by Deering * on the inactivation cross sections of invertase and ribonuclease by deuterons and alpha particles are typical of the experimental results obtained. The values obtained by Deering are

Invertase	$S_0 = 6.9 \times 10^{-13}$ cm^2	$d = 3.7 \times 10^{-7}$ cm
Ribonuclease	$S_0 = 1.1 \times 10^{-13}$	$d = 2.6 \times 10^{-7}$

If the cross sections, S_0, are considered to be circular, the invertase value corresponds to a cross-section radius of 4.7×10^{-7} cm. The average thickness through a sphere is 1.3r so the cross section leads to a d value of 6.1×10^{-7} cm for a spherical molecule. This is not compatible with the measured value of 3.7×10^{-7} cm and so the sensitive volume is probably not spherical. The data are consistent for a cylinder of 1.7×10^{-7} cm radius and length 1.47×10^{-6} cm if the direction of the incident beam is assumed perpendicular to the axis of the cylinder. The volume of one target will be 2.5×10^{-19} cm^3 and its mass 3.3×10^{-19} grams if a density of 1.3 is assumed. The molecular weight of the target molecule will then be $3.3 \times 10^{-19} \times 6.02 \times 10^{23} = 2 \times 10^5$, which is higher but not inconsistent with other data. Similar considerations of Deering's data for ribonuclease lead to a spherical molecule of radius 2.1×10^{-7} cm and a molecular weight of 27,000.

It would not be surprising to find different cross sections for different biological effects and this is indeed the case. For example, when chymotrypsin is bombarded with deuterons inactivation assays can be based on the ability to clot milk or the ability to digest casein. The former assay leads to a molecular weight of 28,000, the latter to 48,000. Obviously, different parts of the molecule are involved in the two functions.

12.07 MULTIPLE-HIT THEORY

As we have seen, many of the biological effects of radiation show a linear relation between log effect and dose, and these can be interpreted in terms of a single hit in a sensitive volume. In many other

* Deering, R. A. "Inactivation Cross Section of Dried Invertase and Ribonuclease as a function of LET." *Rad. Research* **5**, 238, 1956.

cases the dose-response curve is a sigmoid, and this requires that more than one hit be involved in producing the injury.

Consider a radiation such that a dose dD is delivered in a short interval of time. In the general case units for measuring D are not specified; they might be particles per cm^2, rad, or any other convenient unit. The probability of each single hit will be proportional to D and to the number of targets presented and so we have, by analogy to Eq. (12-1),

$$\frac{dN}{N} = -k\,dD \tag{12-13}$$

where dN/N is the fraction of available targets hit during the delivery of dose dD.

For small numbers the probability of obtaining a multiple number of hits is given by Eq. (12-6) and direct substitution gives

$$p_s = \frac{(kD)^s}{s!}e^{-kD} \tag{12-14}$$

The chosen event will be observed whenever there are s or more single hits in the sensitive structure. From Eq. (12-14) the probability of this will be

$$p = e^{-kD}\left[\frac{(kD)^s}{s!} + \frac{(kD)^{s+1}}{(s+1)!} + \cdots\right] \tag{12-15}$$

It is usually more convenient to calculate the probability of *non-occurrence,* to obtain data on survivals rather than on injuries. The probability of survival (or more generally non-injury) is just the fraction N/N_0 and this must be equal to the sum of all terms formed from Eq. (12-14) for which the number of hits is less than s. This leads to

$$\frac{N}{N_0} = e^{-kD}\left[1 + kD + \frac{(kD)^2}{2!} + \cdots + \frac{(kD)^{s-1}}{(s-1)!}\right] \tag{12-16}$$

If we put $s = 1$, Eq. (12-16) reduces to the single hit case, as it should.

Figure 12-1 shows dose-survival curves calculated from Eq. (12-16) for $s = 1$, 2, and 3. There are obvious differences between the curves but the differences are not large. The linear portion of each curve can be extrapolated back to zero dose to obtain the number of hits required, but experimental data must have an unusually high accuracy to establish unequivocally a value of s. Experimentally both exponential and sigmoid survival curves are

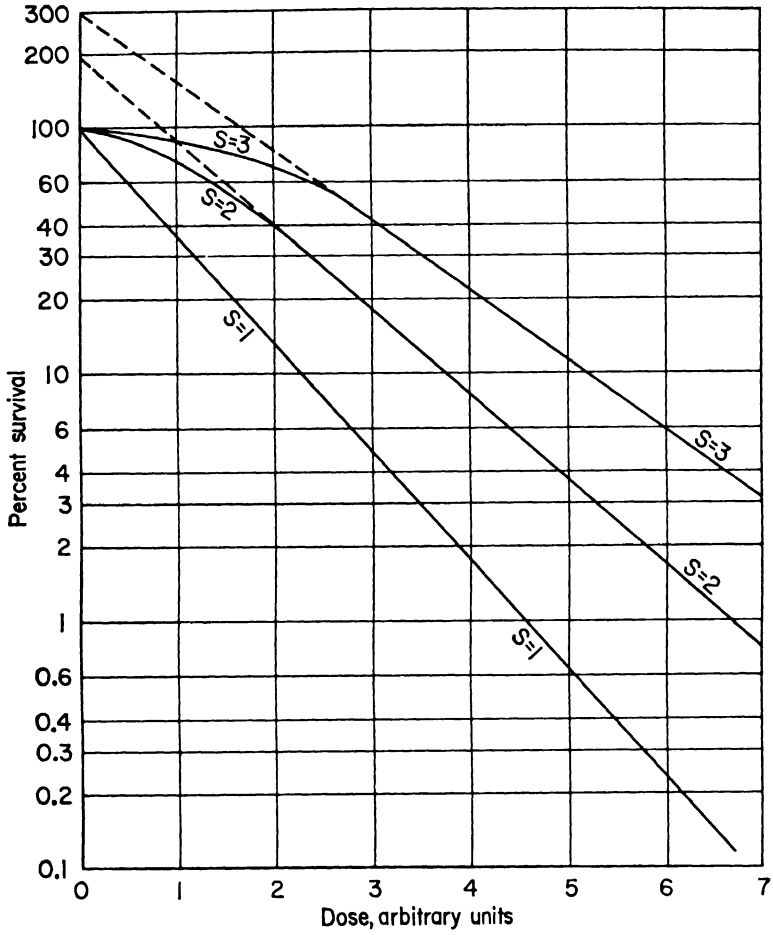


Fig. 12-1. Survival curves calculated for $s = 1, 2,$ and 3. The dose scale has been expanded to emphasize differences between the three curves.

found. For example, haploid yeast has a single-hit exponential inactivation curve,* while yeasts of higher ploidy may have multiple hit sigmoid curves.

PROBLEMS

12-1. The following data were obtained when an enzyme preparation was inactivated by bombardment with alpha particles from Po^{210}. Calculate the cross section for inactivation.

* Mortimer, R. K. "The relative radiation resistance of haploid, diploid, triploid and tetraploid yeast cells." *UCRL Report* 1922, 1952.

Per cent activity	100	59	32	18	8 6	3.1	1.5	0 8	0 3
(Alphas/cm^2) $\times 10^{-14}$	00	1.6	3.6	5.5	7.5	10	13	15	17

12-2. The following data were obtained when the enzyme preparation of Problem 12-1 was exposed to a beam of deuterons. What is the cross section for inactivation and what do you infer from this value?

Per cent activity	100	61	42	27	14	6.5	2.8	1.9	0 7
(deuterons/cm^2) $\times 10^{-14}$	00	2 0	4.0	5 8	9.0	13	16	18	22

12-3. An enzyme preparation is bombarded with gamma rays from Co^{60} and the dose for 37 per cent survival is found to be 5.8×10^7 rad. Calculate the sensitive volume of the enzyme.

12-4. The enzyme preparation of Problem 12-1 was bombarded with 250 KVP X-rays with the following results:

Per cent activity	100	61	33	25	11	7 2	3 5	1 6	1.0	0.5
(absorbed energy rad) $\times 10^{-7}$	00	1.2	3.0	3.7	5.1	7.1	9.0	10.8	12 0	13 9

Calculate the sensitive volume of this enzyme. Are the dimensions thus found compatible with a spherical molecule?

12-5. Inactivation-cross-section measurements with deuterons over a range of LET gave the following results:

Cross section (cm$^2 \times 10^{-14}$)	1 2	1 6	1.9	2.2	2.3	2.3	2 4	2.1	2.5
LET (Kev/μ)	22	29	45	60	74	87	98	112	136

Assume that 34 ev is required to produce one ion pair and calculate the inactivation cross section S_0 and the effective thickness d.

12-6. Calculate the inactivation cross section and the effective thickness from the following data:

Cross section (cm$^2 \times 10^{-14}$)	1.3	2.0	2.7	2.9	3.3	3.5	1.0	4.0	4.2	1.3
LET (Kev/μ)	18	30	47	56	68	82	96	108	121	130

12-7. From a series of measurements on an enzyme preparation the inactivation cross section is found to be 4.8×10^{-13} cm^2 and the effective thickness 5.3×10^{-7} cm. What is the probable shape and orientation of the sensitive volume? Calculate the molecular weight of the sensitive part of the molecule.

12-8. From a series of measurements on an enzyme preparation the interaction cross section is found to be 7.7×10^{-13} cm^2 and the effective thickness 4.5×10^{-7} cm. What is the probable shape and orientation of the sensitive volume? Calculate the molecular weight of the sensitive part of the molecule.

12-9. From the following data determine the number of hits required for inactivation.

Per cent activity	100	63	33	17	9	3	1.2	0.5
Dose (rads $\times 10^5$)	00	0 8	1 9	2.9	3.9	6.1	7.5	9.2

12-10. From the following data determine the number of hits required for inactivation.

Per cent activity	100	99 9	86	68	12	21	13	6.1	1.4	0.6
Dose (rads $\times 10^5$)	00	0 38	1 5	3 8	5 7	7 5	9.6	11.0	16	17

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A. Hollaender, Ed. *Radiation Biology* **VI,** Part I. McGraw-Hill, New York, 1954.

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13

RADIATION EFFECTS IN THE SINGLE CELL

13.01 CELLULAR SENSITIVITY

One of the intriguing features of ionizing radiation is the profound effect of small amounts of energy upon living tissue. Another is the long delay between absorption of energy and the appearance of effect, which in some cases may be many years. The production of radiogenic cancer in man, for example, seems to require at least five years to become manifest, and may take 15–20 years.

It is very probable that an explanation for these phenomena will be found in the detailed behavior of the irradiated cell. The necessary sensitivity can be explained in terms of the well-known property of genetic materials to reproduce themselves. An uninjured cell will continue to reproduce itself by division, with each daughter cell a replica of the parent. If a radiation injury is produced which is not promptly lethal, this injury, rather than the original characteristic, will be passed on in the course of cell division

until a substantial number of altered cells are present. Since a considerable time may be required for the necessary number of cell divisions this mechanism may be involved in the delayed effects of small doses of radiation.

13.02 LAW OF BERGONIÉ AND TRIBONDEAU

Reasoning from the effects of X-rays on rat testicles, Bergonié and Tribondeau * proposed in 1906 the law to which their names are now attached. Freely translated, the law of Bergonié and Tribondeau is: X-rays act most strongly on those cells with the greatest reproductive activity, longest period of mitosis, and the least morphological and functional differentiation. The actual facts are probably not as simple as the law implies, but it remains as a valid approximation.

Both normal tissues and malignant growths are classified into varying degrees of radiosensitivity or radioresistance, each according to its observed response to radiation. For example, bone marrow is considered to be radiosensitive, whereas nerve tissue is radioresistant. From the radiation-chemistry viewpoint a given dose will produce the same number of free radicals per gram in either tissue, small differences of absorption excepted. Many of the same chemical structures are present in the two tissues and many of the same chemical effects are to be expected. It may well be that the amount of primary injury in the two cases is more comparable than is apparent, and that differences in mitotic activity make it more obvious in one tissue than in the other.

13.03 REPRODUCTION BY MITOSIS

In a general way a cell can be considered to consist of a nucleus, the associated cytoplasm, and a membrane which forms the cell boundary. The nucleus contains the chromosomes, the structures which transmit the unvarying characteristics from a parent cell to its daughter.

In the resting state, known as *interphase,* the living cell has an

* Bergonié, J. and L. Tribondeau. "Interprétation de quelques Résultats de la Radiothérapie et essai de Fixation d'une Technique Rationelle." *C. R. Acad. Sci.* 143, 983, 1906.

essentially spherical nucleus which is separated from the cytoplasm by a nuclear membrane. During this phase the chromosomes have become so diffuse that they are not visible in the optical microscope.

When the cell proceeds toward division by *mitosis* the diffuse material condenses to form a series of long threads, or *chromosomes*, each having a length some thousands of times its diameter. These can be stained and made visible in the optical microscope. Along each chromosome there are hundreds or thousands of *genes,* the units which determine in detail the characteristics to be passed on to the daughter cell.

At *prophase* each chromosome is split lengthwise into two *chromatids* which remain close together and assume a helical configuration. The two chromatids are exact duplicates so that when division occurs later each of the resulting cells will receive identical contributions of genetic material.

Prophase passes into *metaphase,* which is characterized by the disappearance of the nuclear membrane. This permits the free movement of the chromosomes, which are still chromatid pairs, throughout the entire volume of the cell. During metaphase a *spindle* forms along a cell diameter. This spindle may be thought of as a sort of polar axis. The chromosomes assemble along the equatorial plane of the cell and attach themselves to the center of the spindle at the *centromere.*

At *anaphase* the pairs of chromatids divide very rapidly and migrate toward opposite poles of the cell. There are now two identical collections of genetic material and each chromatid is now known as a chromosome. Anaphase is followed by *telophase,* characterized by the formation of new nuclear membranes. The cell contracts at the equator and finally pinches off to form two daughter cells. As telophase ends the chromosomes uncoil and diffuse again into the expanded state characteristic of interphase.

13.04 REPRODUCTION BY MEIOSIS

Simple structures grow almost entirely by mitotic cell division but complex organisms reproduce by the process of *meiosis* which takes place in special reproductive cells. These cells are known as *gametes* and fertilization results from the union of two gametes, a sperm and an ovum.

Each cell undergoing mitotic division contains two sets of chromosomes and is called *diploid*. One set of chromosomes was derived from one parent and a second homologous set came from the other parent. Except for an occasional spontaneous mutation all homologous pairs are carried through mitotic division by exact duplication into two chromatids, and the subsequent splitting at anaphase.

Division by meiosis is initiated by the process of *synapsis* in which homologous chromosomes pair up so that each thread consists of a mother-father combination. Each paired chromosome then divides longitudinally into a pair of chromatids. During this process the chromatids break and exchange homologous segments so that the final product contains some genes from each parent. This *crossing-over* is the method by which chromosomes of the next cell generation acquire varying mixtures of characteristics from each parent.

After crossing-over is complete there is a *tetrad* of four chromatids. The nuclear membrane now disappears and two meiotic divisions take place with no further chromatid formation and without interphase. The final result is four cells, each containing only one-half of the full chromosome complement. Each of these cells is a gamete, destined to be either a sperm or an ovum. At fertilization the *haploid* cell becomes diploid by the acquisition of a second set of chromosomes from the other parent. In meiotic division some genes are not transmitted, since no chromatid can contain a full genic complement from both precursor chromosomes.

13.05 CHROMOSOME COMPOSITION

The exact chemical structure of chromosomes is unknown but evidence is increasing that desoxyribonucleic acid (DNA) is an important constituent. X-ray diffraction studies, among others, suggest that a chromosome may consist of a long thread of perhaps 10^5 DNA molecules alternating with proteins such as protamines of histones. DNA has a molecular weight of the order of 5×10^6 * and the histones about 10^4 so a chromosome is presumably a very large structure which is predominantly DNA. It is tempting to believe that the characterizing genes are actually DNA molecules, but proof of this is lacking.

* Davidson, J. N. *The Biochemistry of the Nucleic Acids.* Methuen, London, 1954.

DNA can exist either as a long straight molecule or as a more or less tightly coiled structure, and these two forms may be associated with the coiling and relaxing of chromosomes during mitosis. X-ray diffraction studies also show that the long DNA molecule is a double thread, another fact of interest when one considers the longitudinal splitting of chromosomes.

13.06 RADIATION EFFECTS ON DNA

The effects of radiation have been studied * using both solutions and dried preparations of DNA. The complex molecule is vulnerable to attack by both H and OH radicals as well as to direct action, and so a large number of reactions would be expected. One of the expected effects would be a breaking of the nucleotide chain. The efficiency of chain breakup is not known but an estimate can be made from viscosity studies.

Radiation decreases the viscosity of DNA solutions with an immediate effect followed by a continued decrease for several hours after the end of irradiation.†

In solution, with indirect action operative, a dose of 10,000 r may halve the viscosity. The relation between molecular weight and viscosity is unknown but as an approximation assume that halving the viscosity requires a halving of the molecular weight. Then 10,000 r will, on the average, produce one nucleotide break in each DNA molecule. If there are 10^5 DNA molecules in each chromosome, a 10,000 r dose would produce 10^5 breaks. Accordingly, a single chromosome break would be produced by only 0.1 r. Although this calculation is based on several assumptions, it is probably not greatly in error and serves to show the order of sensitivity of chromosomes with respect to breakage.

If DNA is a double threadlike structure it may be necessary to attack both threads to achieve a complete break. On this assumption radiations with high values of LET should be most effective and this is indeed the case.** Radiations with low LET will be effective because of ion clumping. If a double break is required the effect

* Davison, P. F., B. E. Conway, and J. A. V Butler. *Progress Biophys* **4**, 118, 1954.

† Taylor, B., J P Greenstein, and A. E. Hollaender. *Arch. Biochem Biophys.* **16**, 19, 1948.

** Gray, L. H. *Radiation Research* **1**, 189, 1954.

should increase with dose at a rate greater than the first power, and this also appears to be the case.

13.07 INHIBITION OF MITOSIS

One of the outstanding effects of radiation on the living cell is the interference with normal mitotic activity. If a cell receives radiation at late prophase, or beyond, mitotic division will proceed without interruption. Radiation received before late prophase may prevent the continuation of mitotic activity, or will delay it for a period of time which depends upon the radiation dose.

Temporarily inhibited cells may resume mitotic activity along with cells which would normally have been active at a later time. Thus temporary suppression is followed by an abnormally large number of cells in mitosis. If the radiation dose is too large this increase will not be seen because many of the dividing cells will have been killed.

Mitosis is inhibited by a radiation dose much smaller than that required to stop metabolic processes. As a consequence cells may continue to grow at a normal rate, and when division is inhibited cell size must increase. This effect is readily demonstrated in bacteria, where mitotic inhibition without killing can be maintained over a period normally occupied by several divisions. In plant and animal cells inhibition can usually be maintained for only a portion of a single mitotic cycle, and increase in cell size is much less marked.

13.08 CHROMOSOME ABERRATIONS

Radiation is quite effective in producing chromosome aberrations, many of which can be seen in the microscope. This dramatic demonstration of radiation injury has perhaps attracted undue attention, in spite of its great importance in the production of genetic abnormalities.

A number of signs of cellular injury are observed after a small dose of radiation:

1. Chromosome *stickiness* leading to the formation of temporary or permanent *bridges* and preventing clean chromosome separations.

2. Inhibition of anaphase movements.
3. Displacement of constriction relative to chromosomes.
4. Unequal division of chromosomes between daughters.
5. Chromatid and chromosome breaks.
6. Production of micronuclei.

The first three aberrations appear to be subject to repair and do not lead to alterations in the genetic material. They may, however, cause the death of the affected cell.

Drastic changes in genetic constitution become possible when there is an actual chromosome break. Occasionally there may be a reunion with no apparent change but frequently some genetic material may be lost, or fragments may unite in changed order. In the latter cases there will be an altered linear arrangement of the genes after the radiation injury.

When these chromosome aberrations are produced in somatic cells the injury will be restricted to the individual having the aberrations. Many or all of the cells that normally derive from the injured one will be missing, and this lack may lead to increasingly serious consequences. When chromosome aberrations occur in germ cells sterility may result or embryos may die because of an abnormal chromosome content. Some embryos will develop into apparently normal adults but will carry abnormal chromosomes into subsequent generations.

13.09 SPONTANEOUS CHROMOSOME ABERRATIONS

Chromosome abnormalities and mutations are known to occur at a low rate in the absence of any recognized abnormal environmental condition. Soon after radiation-induced aberrations were observed, studies were initiated to determine if natural background radiation was responsible for the observed spontaneous rate.

When Tradescantia was exposed to gamma rays from radium, chromosome breaks were seen after 5 hours. The breaks reached a maximum in 24 hours and disappeared after 70 hours. Using the number of breaks at 24 hours as an index, Sax * found the relation between percentage of breaks and dose in r to be

* Sax, K. *Genetics* **25**, 41, 1940

$$B = \left(\frac{D}{45}\right)^{1.1} \tag{13-1}$$

for a single hit.†

The spontaneous aberration rate in this material was 0.07, which would require a daily dose of about 4r. Natural background radiation amounts to about 0.0002 r/day so it is evident that most of the spontaneous aberrations must be due to other causes. Even if the form of Eq. (13-1) is not exactly correct at low doses, the discrepancy is too large to implicate radiation as the sole agent responsible for spontaneous aberrations.

13.10 POINT MUTATIONS

Point mutations are localized changes in chromosomes without loss or rearrangement of genetic material. Point mutations probably involve a single encounter between radiation or primary radiation products and the chromosome. In accord with this is the fact that the number of point mutations seems to vary with the first power of the dose. Thus point mutations become relatively more important at low doses.

Any population has a spontaneous point-mutation rate arising from unknown but natural causes. Radiation-induced mutations, which are indistinguishable from those occurring naturally, add to this genetic burden. On the whole mutations do represent a burden in spite of the fact that a small number may be beneficial.

Any given species such as man is the result of a long series of natural selections. At each generation natural processes have favored the survival of the strongest individuals and the elimination of those less vigorous or adaptable. Apparently natural selection is the mechanism by which each species is prevented from degenerating.

No one knows how big a burden of genetic abnormalities man can carry without degenerating. Even if deterioration as a species is avoided an increased point-mutation rate will mean an increased number of sub-standard adults. Obviously, radiation overexposure of the reproductive systems should be avoided whenever possible.

† Giles, N. H. *Genetics* **25**, 69, 1910.

13.11 GENETIC CONSEQUENCES OF MUTANT GENES

Because of the random nature of radiation injury, genetic damage to the affected cell will range from slight to lethal. For a large population, however, the total genetic burden of a mutation, from its origin to its elimination by death and meiotic loss, is essentially constant. A mutation which is highly deleterious results in a high percentage of deaths in early generations and so is rapidly eliminated. A less-severe injury produces fewer early deaths and so is eventually passed on to a larger number of descendants.

Let there be an injury such that the fraction x of those possessing it will not be able to reproduce and pass it on. Then in the first breeding there will be $(1 - x)$ individuals possessing this characteristic and after n generations there will be $(1 - x)^n$. The total number of individuals who receive this characteristic will obviously be the sum over all possible generations. This may be written as

$$N = \sum_{n=1}^{\infty} (1 - x)^n \tag{13-2}$$

Let $(1 - x) = y$ whence

$$N = \sum_{n=1}^{\infty} y^n$$

$$= \Sigma\, y + y^2 + y^3 + \cdots$$

$$= \frac{y}{1 - y}$$

and

$$N = \frac{1 - x}{x} \tag{13-3}$$

For example if $x = 0.1$ there will be a total of 9 individuals with this characteristic for each one originally carrying it.

13.12 RELATION OF NUCLEUS TO CYTOPLASM

In discussing radiation effects on a portion of a cell structure there is danger that the interrelations between the various portions will be forgotten. Under normal conditions nucleus, cytoplasm, and

cell membrane function as a unit, and injury to one constituent may be reflected in abnormal behavior of others.

Cellular energy-producing reactions appear to be centered in the mitochondria. Phosphorus uptake studies with P^{32} have demonstrated active oxidative phosphorylations, in liver mitochondria.* These energy-producing reactions are, however, partly under control of the nucleus since enucleated cytoplasm shows a reduced uptake. This control probably takes place through the synthesis in the nucleus of nucleotide coenzymes needed for the energy-producing reactions.

Cellular protein synthesis is also under close control of the nucleus, even though this synthesis can continue after removal of the nucleus. The rate at which amino acids, labelled with C^{14}, are incorporated into protein decreases promptly with enucleation.

Mitotic cell division certainly requires the presence of increased concentrations of synthesized products; it is possible that cell division is forced by the accumulation of these products. In this connection Bullough † has shown that an adequate tissue concentration of glycogen is necessary for mitosis to proceed. Bullough also showed that the lack of sugar blocked the passage of a cell from the resting stage to prophase. Once prophase is entered, energy no longer appears to be required, and cell division can proceed in the absence of both glycogen and oxygen. This finding is of interest since radiation received in late prophase does not prevent mitosis.

13.13 RADIATION EFFECTS ON CYTOPLASM

In general the cytoplasm appears to be relatively radiation-resistant. Zirkle and Bloom ** have produced a proton beam in which 80 per cent of the particles lie within a circle 2.5 microns in diameter. This beam was used to irradiate cells from the newt heart grown in tissue culture. The passage of about 100 protons through a nucleus produced typical radiation effects such as chromosome stickiness and chromosome fragmentation. No visible abnormalities were produced after several thousand protons had passed through the cytoplasm,

* Hogeboom, G. E., and W. C. Schneider. *The Nucleic Acids*. Academic Press, New York, 1955.

† Bullough, W. S. *J. Exptl. Biol.* **26,** 261, 1941; *Nature* **165,** 493, 1950.

** Zirkle, R. E., and W. Bloom. *Science* **117,** no. 3045, 487, 1953.

even when the beam was directed close to the nucleus. However, the cytoplasm may play a role in cellular injury, for isolated nuclei appear to be quite radioresistant.*

In another series of experiments Duryee found that a non-irradiated cell showed nuclear pyknosis following the injection of a small amount of cytoplasm from an irradiated cell. These results argue strongly for the presence of a toxic product in the irradiated cytoplasm. The absence of some critical enzyme in the irradiated material should produce no observable effect since this should be available from the normal cell constituents.

Critical enzymes may exist in cytoplasm in very low concentrations, so that only a few events, either direct hits or free-radical reactions, would be needed to inactivate the system. A necessary consequence of this low concentration is a corresponding reduction in the chance of a hit. To account for the observed radiation sensitivity it seems necessary to find a structure of considerable size which might be vulnerable to a single ionizing event. From this point of view cytoplasmic particles such as mitochondria deserve special attention.

Van Bekkum † has reported a decrease in the oxidative phosphorylation of mitochondria from rat spleen or thymus after only 50 r of X-rays. The decrease was observed within 1 hour after irradiation. These results suggest that in some systems, at least, cytoplasmic constituents may be radiation-sensitive, and may play a major role in the changes leading to cellular death or nuclear abnormalities.

13.14 RADIATION AND THE CELL MEMBRANE

Comparatively little is known about the effects of radiation on cell membranes. On theoretical grounds, however, membranes appear to be vulnerable structures in which small injuries might lead to dire consequences.

Normally, cells maintain an internal ionic composition considerably different from that of the surrounding medium. Although a cell may be in an essentially steady state it is not in equilibrium.

* Duryee, W. R. *J. Nat. Cancer Inst.* **10**, 3, 1949.

† Van Bekkum, D. W. *Radiobiology Symposium, Liège, 1954.* Academic Press, New York, 1955.

This state is maintained by a delicate balance between many factors such as metabolic processes, membrane integrity, activity gradients, and ionic transport systems. If the integrity of a membrane is destroyed at only a single point it might result in the eventual destruction of the entire cell. Membranes may be one of the very sensitive structures in which a few radiation interactions can lead to injury to a relatively large volume.

It seems reasonable to assume that an effective membrane injury might require several primary events, nearly contiguous in time and space. If this is true one would expect high RBE values from densely ionizing radiation, and this is in general the case. The meager experimental results do not always bear out the above predictions, however. Some increases in water permeability in beef erythrocytes was seen after 35 *Kr* * but arbacia eggs showed no changes in permeability † to water, ethylene glycol, and diethylene glycol after 100 *Kr*. In the latter case the cells were seriously injured, for after fertilization cleavage was delayed and atypical, and the cells later cytolyzed.

On the other hand, 7 *Kr* incident on the wild mushroom *Russula nigricans* was sufficient to break down enzyme-substrate barriers.** Again, the concentration of some enzymes is found to be increased in plasma after irradiation,†† and this may be due to an increased liberation from cells through membrane defects.

13.15 RADIOMIMETIC SUBSTANCES

In 1943 mustard gas, a chemical warfare agent, was found to be a powerful mutagenic agent. Prior to this discovery radiation had been considered to be unique in this respect and an elaborate target theory had been built up about it. The action of a chemical compound such as mustard gas can obviously not be interpreted in terms of columns of ionization and target size. Because of this, the discovery of the mutagenic activity of mustards led to a complete reexamination of genetic effects in terms of indirect action.

A considerable number of chemical mutagenic agents were soon

* Ting, T. P., and R. E. Zirkle. *J. Cell and Comp. Physiol.* **16**, 269, 1910.

† Lucke, B., R. A. Ricca, and H. K. Parpart. *J. Nat. Cancer Inst.* **11**, 1007, 1951.

** Bacq, Z. M., and A. Hervé. *Bull. Acad. Méd. Belg.* **18**, 13, 1952.

†† Ludewig, A., and A. Chanutin. *Amer. J. Physiol.* **163**, 618, 1950.

discovered. At first many of these compounds seemed to duplicate radiation effects almost exactly and were called *radiomimetic* but later work showed very significant differences.

A large number of radiomimetic compounds are now known with the most active classes having two functional alkylating groups. The basic structure of a nitrogen mustard is

$$R - N\begin{matrix}\diagup CH_2CH_2Cl \\ \diagdown CH_2CH_2Cl\end{matrix}$$

where the exact nature of R is of secondary importance to the presence of the two mustard groups. Di-epoxides are also active radiomimetic compounds.

$$CH_2\!-\!\!-\!\!-CH_2\!-\!\!-\!\!-(CH_2)_n\!-\!\!-\!\!-CH_2\!-\!\!-\!\!-CH_2$$
$$\qquad\quad\diagdown\diagup\qquad\qquad\qquad\qquad\qquad\diagdown\diagup$$
$$\qquad\quad O\qquad\qquad\qquad\qquad\qquad O$$

Most of these compounds have been tested as therapeutic agents in the treatment of cancer, with nitrogen mustards being rather widely used in the treatment of leukemia.

The similarities between radiation effects and the action of the radiomimetics have probably been overemphasized. Chromosome breaks and gene mutations are the end results of unknown primary actions; the observed similarities may merely represent the common response of nuclear material to a wide variety of injurious primary events. Radiomimetic compounds are most effective early in the resting stage, whereas radiation has its most pronounced action somewhat later.* Another difference lies in the distribution of breaks along the length of the chromosome. In a few cases radiation-induced breaks tend to concentrate near the centromere, but in general a random distribution is observed. Chemical-induced breaks, on the contrary, tend to concentrate at specific points along the threads.

13.16 EFFECT OF ENVIRONMENTAL FACTORS

If radiation-induced aberrations result from the action of chemical intermediates one would expect sharp changes in sensitivity with water content. Experimental results indicate a more complicated relation between water content and radiation sensitivity than would

* Revell, S. H. *Heredity*, Vol. 6, Supp. 107. 1953.

be expected. In barley seeds using inhibition of growth and numbers of chromosome aberrations as indices a maximum sensitivity appears at a water content of 4 per cent.† Minimum sensitivity occurs at about 8 per cent water content and remains reasonably constant with further hydration. Interpretation of these results is difficult because the absorbed energy will be a function of the water content. Rate of growth also depends strongly upon the amount and duration of hydration.

The effects of oxygen tension on cellular X-ray sensitivity are more clear-cut. With some exceptions, materials irradiated in oxygen show from two to four times the sensitivity observed when nitrogen is used. Some evidence indicates that the oxygen takes part in the production of the primary injury rather than in an alteration of the ability of the cell to withstand injury. Substantial portions of many solid tumors are relatively anoxic and an enhanced destruction of these by radiation would be anticipated if oxygen tensions can be increased. The results of clinical trials at 3 atmospheres of oxygen remain to be evaluated.

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† Caldecott, R. S. *Radiation Research* **2,** 339, 1955.

14

RADIATION EFFECTS IN MAMMALS

14.01 EARLY EXPERIENCES

A surprisingly short time elapsed between Roentgen's announcement and the discovery that penetrating radiations have a profound effect on living tissues. Within a month after Roentgen's first paper, a patient was admitted to Cook County Hospital * suffering from what was almost certainly a radiation injury. Medical uses of X-ray equipment and radium increased and many physicians received injuries which lead to death, usually from radiogenic cancer.

The radium dial painters in New Jersey are the best documented early group of radiation injury cases.† Luminous paint production

* Brown, P. *American Martyrs to Science Through the Roentgen Rays.* Thomas, Springfield, Ill., 1936.

† Details of the injuries sustained by the dial painters can be found in *Collections of Reprints on Radium Poisoning* by Harrison S. Martland. Technical Information Service, Oak Ridge, Tenn.

and application were introduced into the United States about 1913 and within a few years several hundred people were working in the new industry. Signs of radiation injury were recognized about 1923 and the first published reports appeared in 1925.

The extensive bone necrosis observed in the dial painters was caused by alpha particles from radium and its daughter products deposited, because of its chemical similarities to calcium, in bone. Non-specific effects included leucopenia, tumor formation, terminal infection, and sterility. This general non-specific pattern, varying in degree, is regularly seen after a gross overexposure to radiation from sources external to the body.

Signs of radiation injury appeared early in the hands of many pioneer radiologists because of the practice of checking X-ray tube operation, using the left hand as the test object. Dry cracked skin, brittle fingernails, and poorly healing ulcers progressed into malignancies and death, usually after many types of unsuccessful treatment.

Like the dial painters, radiologists received chronic, primarily localized radiation in a portion of the body. With the development of radiation-producing weapons and the increased use of high-intensity sources of penetrating radiation came an interest in the effects of whole body radiation. As nuclear energy becomes more widely used for power and propulsion it appears that the greatest biological threat will arise from low-level chronic overexposure of the whole body.

14.02 RADIATION SICKNESS

The expression "radiation sickness" was originally used to describe a syndrome that has plagued radiologists since the earliest days of radiation therapy. Recently there has been a tendency to apply the term to all phases of radiation injury, but it seems desirable to retain the original, restricted definition.

In its original sense radiation sickness refers to the *nausea, vomiting, anorexia,* and *fatigue* seen in humans after moderate or large radiation doses. Although there are individual variations, these symptoms can be expected after whole body doses of 100 r or more. The time of onset, severity, and duration of radiation sickness depend upon the dose and the tissues receiving it. Radiation received by the splanchnic region is particularly effective. Typically, radiation sick-

ness may appear within a few hours after exposure, and may last 24–48 hours. In cases of unknown exposure the course of the radiation sickness syndrome may be used as a rough estimate of the severity of the injury.

In many human exposures, either intentional or accidental, there are strong psychogenic components in the radiation sickness syndrome. Physiological disturbances must also be present, for comparable phenomena are seen in animal irradiations where psychogenic factors are almost certainly absent. Many animals show signs of discomfort during the administration of large radiation doses and some, notably swine and monkeys, will vomit.

A wide variety of drugs has been tried in attempts to relieve the patient discomfort associated with radiation sickness. All treatments have had indifferent success and no truly effective remedy appears to be available.

14.03 SURVIVAL TIME-DOSE RELATIONS

As the acute, whole-body radiation dose is increased the radiation sickness syndrome becomes more severe and a point will be reached at which a few individuals fail to survive the first 30 days (this is the rather arbitrary observation time used in most experiments). Continued increases in dose will produce correspondingly greater 30-day mortalities until finally 100 per cent of the population is killed within 30 days. The doses producing from 0 to 100 per cent mortality (LD_0–LD_{100}) make up the *lethal range.*

In animals the maximum number of deaths over the dose range LD_0–$2LD_{100}$ occurs at about 13–15 days after irradiation. The corresponding time for man is not known but is probably somewhat longer. This is known as the region of *infection death* because bacteremia is a prominent finding at autopsy.

As the dose is increased above $2LD_{100}$ survival time drops rather abruptly to 3–5 days and remains fairly constant until much higher doses are reached. This is the region of *gastrointestinal death,* characterized by gross damage to the intestinal lining.

At still higher doses survival times become progressively shorter, Fig. 14-1. Signs of central nervous system injury appear and become more intense with dose. Although there are few morphological signs of CNS injury at autopsy this is known as the *CNS death* from the

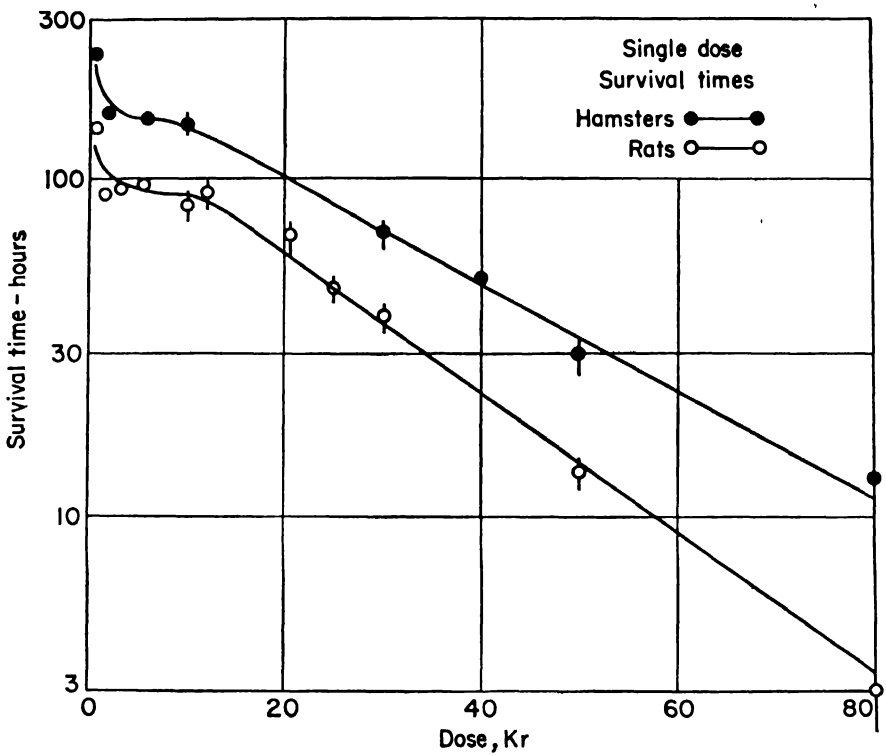


Fig. 14-1. Survival time-dose relationship for two species.

visible symptoms. Radiation death in animals is not instantaneous even at doses of 50,000–100,000 r. No data are available for man in the region of CNS death.

14.04 THE LETHAL DOSE RANGE

Whole-body irradiation reduces the natural resistance to infection and interrupts normal immune responses. Because of these actions the course of events following whole-body doses in the LD_0–LD_{100} range is strongly influenced by infectious processes. Post-radiation infections, mostly enterogenous, have been observed regularly both in experimental animals and in the Japanese exposed to nuclear weapons.

The course of an animal experiment can be grossly altered by the presence of a particularly virulent organism such as pseudomonas.

Antibiotics, particularly streptomycin, are of some help in combatting these infections, but no known agent has a sufficiently broad spectrum to control against all invaders until natural defenses can resume normal function.

It must not be inferred that infection is the only cause of death in the LD_0–LD_{100} range. Evidence from germ-free animals is incomplete but it appears, at least in rats, that an absence of bacterial infection will only raise the LD_{50} by perhaps 30 per cent. Acute survival times in germ-free animals will probably be several days longer than those in normals.

Epilation is a common finding in man after radiation doses in the lethal range. Hair loss usually starts abruptly about 2 weeks after exposure and continues for another 2 weeks. Epilation is not permanent among the survivors. Typically, regrowth starts within 3 months of the exposure. Color and texture may be different from those prior to the exposure.

Purpura is another consistent part of the radiation syndrome in the lethal dose range. Time of onset varies from 3 to 30 days, appearing earlier following larger doses. In survivors purpura will last about 15 days. Purpura is the earliest visible sign of radiation damage to the hemopoietic system leading to a hemorrhagic tendency. A combination of purpura and epilation is almost pathognomonic for radiation injury.

Extensive hemorrhages usually follow purpura, emphasizing the severe damage to the hemopoietic system. Bleeding from the gums and mouth was most common in the Japanese, but other areas were frequently involved. Bloody diarrhea was a common factor in heavily exposed Japanese. Diarrhea is regularly seen at somewhat lower doses; when accompanied by bleeding prognosis is poor.

14.05 VARIATIONS IN RADIOSENSITIVITY

The lethal dose range varies from one animal species to another, and there are substantial sensitivity differences even among individual members of an inbred strain of a given species. Values of LD_{50} are sensitive to many experimental conditions, including the type of microorganisms present.

Occasionally a laboratory using apparently standardized techniques will find shifts in LD_{50} for a fixed strain and species. These

shifts can usually be traced to some subtle and unsuspected change in the laboratory environment.

In larger animals variations in LD_{50} may arise from the use of radiations of different effective energy. There may be no essential difference in the intrinsic effectiveness of two radiations, but depth-dose distributions may be quite different, to make one appear more effective than the other. Depth-dose depends upon both photon energy and FSD.* If possible these should be chosen to make depth dose as uniform as possible. Because of variations like these the LD_{50} data given in table 14-1 must be considered as approximate values only.

Table 14-1. WHOLE-BODY DOSES FOR 30-DAY LD_{50}

Species	LD_{50}, r
Guinea pig	250
Dog	310
Goat	350
Monkey	500
Man	500
Mouse	500–700
Swine	550
Rat	600–700
Burro	600–800
Hamster	700
Rabbit	800

There is no correlation between values of LD_{50} and any obvious species characteristic. Size is certainly not an important factor. Basal metabolic rate, at least in the normal range is likewise not intimately related to LD_{50}. Metabolic rates are not without influence, however, for in hibernating animals, where the rate is very low, signs of radiation injury are suppressed, to appear when more active metabolism is restored.

Variations of radiosensitivity within members of even an inbred animal strain are perhaps not surprising. Whole-body radiation represents an insult to all parts of a living organism and the result is undoubtedly a complex reaction to leucopenia, hemorrhage, bacteremia, toxic products, impaired nutrition, blocked immune responses, and shock. Variable rates of repair enter to further complicate the picture.

Age at time of irradiation is one important factor in radiation

* Andrews, H. L. *Nuclear Instruments and Methods* **6**, 96, 1960.

sensitivity. Young and old animals are more sensitive than those in mid-life. Details of sensitivity dependence on age appear to vary with the species.

14.06 THE GOMPERTZ FUNCTION

Mortality studies are widely used in radiobiology to characterize a species and to assess the effects of treatments. Various mathematical relationships have been used to express mortality data in terms of parameters of possible biological significance. The Gompertz function is one relationship that seems applicable to radiobiological data.

Assume a population consisting of N_0 individuals at zero time and N individuals at some later time (age) t. *Mortality rate* R can be defined as the fractional decrease in N in unit time where the unit of time in dt is taken to suit the problem at hand.

$$R = \frac{dN/N}{dt} \tag{14-1}$$

Gompertz in 1825 found that a normal population could be quite accurately described if

$$\ln R = \ln R_0 + mt$$

or

$$R = R_0 e^{mt} \tag{14-2}$$

where R_0 is the rate corresponding to N_0. The value of R from Eq. (14-2) can be put in Eq. (14-1) and the functional relationship between N and t obtained by integration. This leads to the *Gompertz function*

$$N = N_0 e^{-\frac{R_0}{m}(e^{mt}-1)} \tag{14-3}$$

Equation (14-3) solved for t gives survival time as a function of the surviving population fraction N/N_0.

$$t = \frac{1}{m}\ln\left(1 + \frac{m}{R_0}\ln\frac{N_0}{N}\right) \tag{14-4}$$

Procedures are available * for determining the characterizing constants m and R_0 from experimental data.

* Davis, D. S. *Empirical Equations and Nomography*. McGraw-Hill, New York, 1943.

If a population obeys the Gompertz function Eq. (14-2) requires a linear relationship between mortality rate and age. Figure 14-2 is a

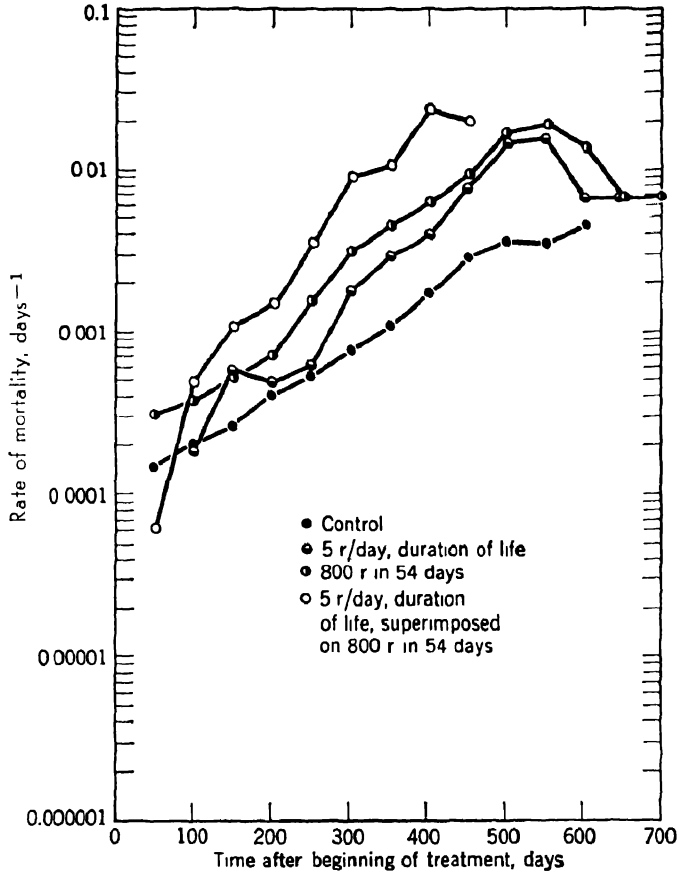


Fig. 14-2. Gompertz plot of mortality data for Carworth female mice. Courtesy of A. M. Brues and G. A. Sacher; *Symposium on Radiobiology*, J. J. Nickson, Ed., Wiley, New York, 1952.

Gompertz plot of data from mice, for all causes of death except lymphoma. The unirradiated control population shows an essentially linear plot, as predicted. The line for mice who received 800 r early in life is displaced upward, but has a slope about like that of the normal. Chronic irradiation at 5 r per day gave a line with a steeper slope, and combined acute and chronic irradiation resulted in both a displacement and a steeper slope. Thus irradiation effects on mortality can be expressed in terms of changes in two constants, m and R_0.

14.07 RADIATION MORTALITY STATISTICS

When dose-mortality studies are carried out on animal populations a narrow dose range is found between LD_{10} and LD_{90}. A homogeneous population such as an inbred strain will have a narrower dose range than is found for a more heterogeneous group.

In general the percentage mortality-dose curve is a sigmoid with a steep slope, Fig. 14-3. Various *LD* values can of course be taken

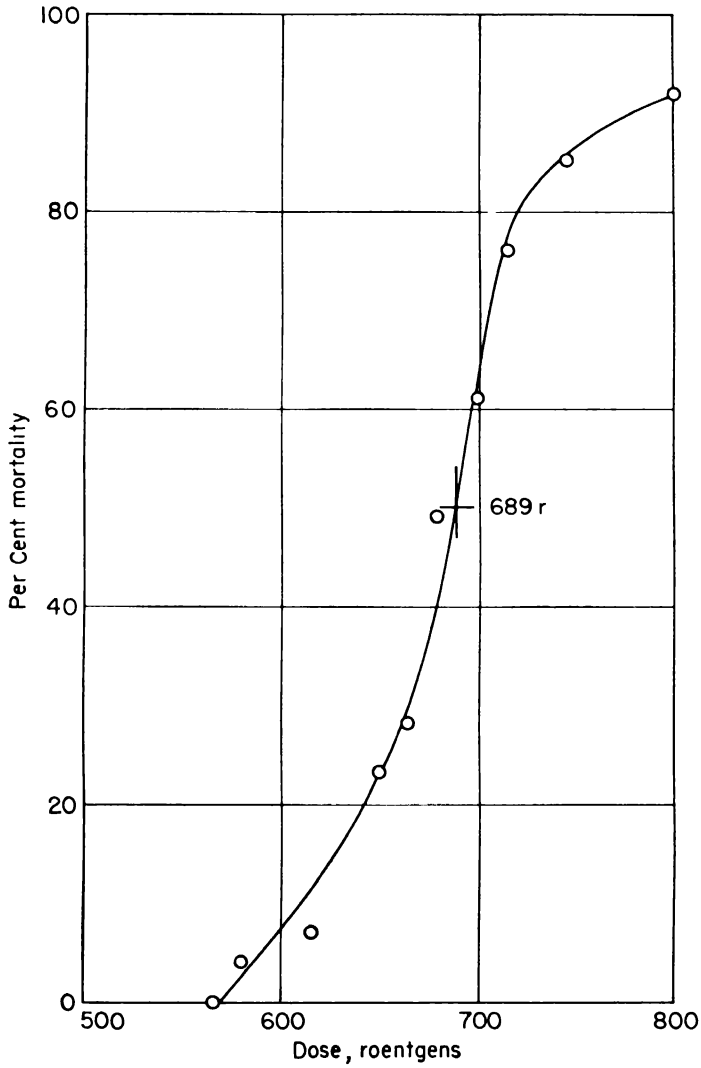


Fig. 14-3. Typical sigmoid mortality curve. $LD_{50} = 689$ r.

from such a plot but it is usually preferable to *transform* or *rectify* the curve to obtain a linear relationship between the variables. With well-controlled conditions dose-mortality data will have a Poisson distribution and the mathematics of normal probabilities can be applied. Direct application of the probability equations is difficult and cumbersome.

Graphical methods are regularly used to obtain the various *LD* values. The use of these methods will be illustrated with the data given in Table 14-2.

Table 14-2. ACUTE DOSE-MORTALITY DATA

Dose (r)	$\log_{10}$ dose	Percentage mortality
565	2.75205	0 0
580	2 76313	1 0
615	2 78888	7 0
650	2 81291	23
665	2 82282	28
680	2.83251	19
700	2.84510	61
715	2.85431	76
745	2.87216	85
800	2.87506	92

A plot of log dose against percentage mortality on a probability scale, Fig. 14-4, shows an essentially linear relationship as expected. A line of best fit can be determined by standard methods, but it usually suffices, as in the present case, to draw the line by inspection. From the line drawn in Fig. 14-4, $LD_{50} = 681$ r, as compared to 689 r obtained from the sigmoid plot of the raw data.

The probability plot is most easily made on specially ruled coordinate paper with one axis divided according to normal probabilities of deviation from a central mean value. This type of paper was used for the plot of Fig. 14-4, which shows only a portion of the probability scale.

14.08 THE PROBIT PLOT

Instead of using probability paper, one can convert each mortality percentage to the corresponding deviate from the curve of normal expectancy and express it in units of standard deviation. Minus signs can be avoided by adding 5.000 to each figure thus obtained. The resulting values are known as *probits*.

In practice the probits are taken from tables, since the conversion calculations are complicated. Table 14-3 lists probit values * for the data given in Table 14-2.

Table 14-3. PROBIT VALUES

Dose (r)	565	580	615	650	665	680	700	715	715	800
Per cent	0	4	7	23	28	19	61	76	85	92
Probit	—	3.249	3.521	4.261	4.117	4.975	5.279	5.706	6.036	6.405

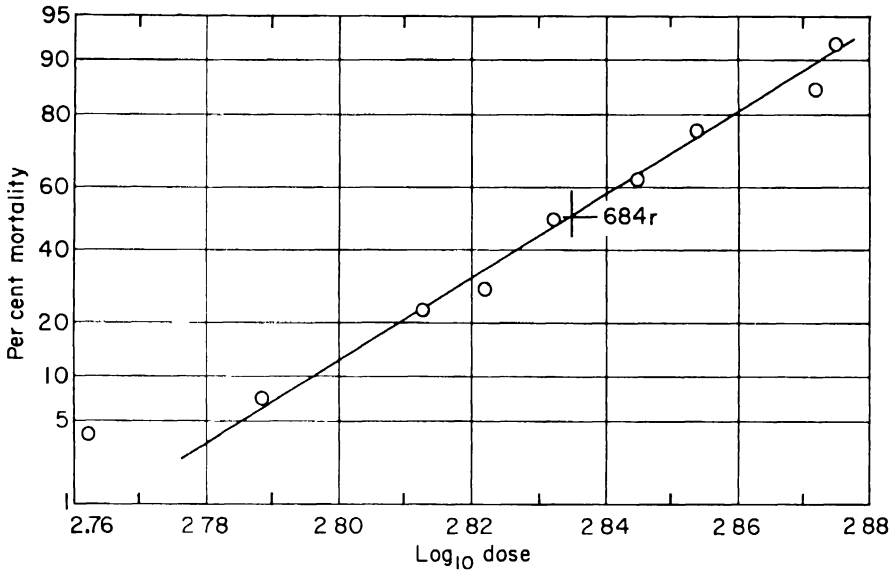


Fig. 14-4. Plot of mortality data on a probability scale. $LD_{50} = 684$ r.

A plot of log dose against probits will be linear, as in Fig. 14-5, and a best straight line can be drawn, usually by inspection. Then from the probit value corresponding to the desired value of *LD* one can read off the value of dose. In Fig. 14-5, $LD_{50} = 686$ r, since probit 50 per cent = 5.00. Methods are available for determining the line of best fit and the constants for this line † but these methods lie beyond the scope of the present text.

* Probit values taken from Fisher, R. A., and F. Yates. *Statistical Tables for Biological, Agricultural, and Medical Research.* Table IX, Oliver and Boyd, London, 1949.

† Kempthorne, O., Ed. *Statistics and Mathematics in Biology.* Iowa State College Press, Ames, Iowa, 1954.

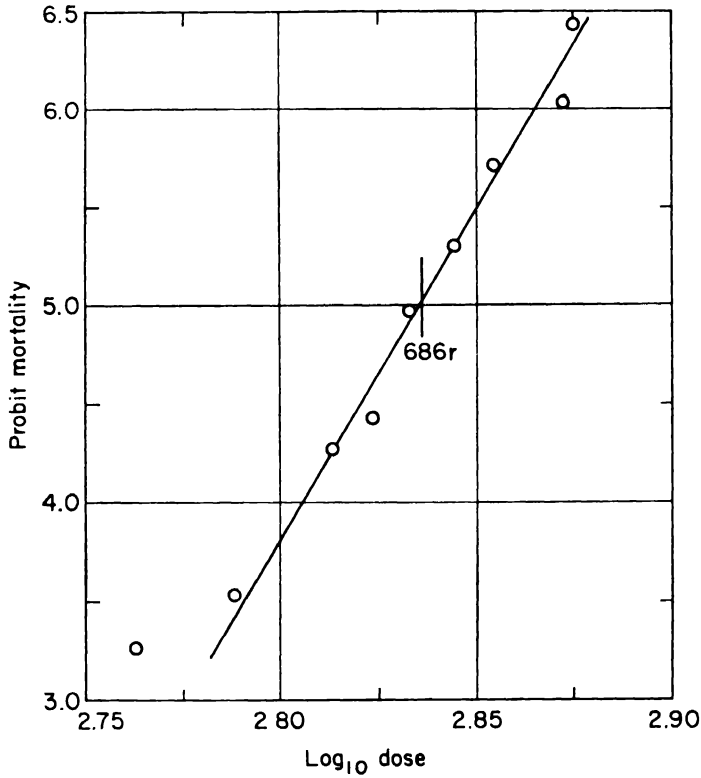


Fig. 14-5. Probit plot of mortality data $LD_{50} = 686$ r.

14.09 APPROXIMATE METHODS

Several other types of functions have been found useful in rectifying the sigmoid curves usually found with mortality data. For many sets of data some of these methods give as good results as those based on formal statistical considerations and have the advantage that the descriptive constants are more easily determined. The only function considered here is the *arcsine*. This is based on the assumption that the fraction dying, f, is related to dose D by

$$f = \sin^2[a(D - b)] \tag{14-5}$$

where a and b are constants to be determined. Equation (14-5) can be made linear by the transformation

$$y = \arcsin\sqrt{f} \tag{14-6}$$

where arcsin means "the angle whose sine is." With this transformation

$$y = aD - ab \tag{14-7}$$

Table 14-4 shows the data of Table 14-2 transformed for plotting according to Eq. (14-7).

Table 14-4. ARCSIN TRANSFORMATION DATA

Dose (r)	565	580	615	650	665	680	700	715	715	800
Per cent	0.0	4	7	23	28	49	61	76	85	92
$\sqrt{f}$	—	.200	.264	.480	.529	.700	.780	.871	.921	.959
y (radians)	—	.202	.268	.501	.556	.785	.875	1.06	1.17	1.29

A linear plot of dose against y is given in Fig. 14-6. At 50 per cent mortality $\sqrt{f} = 0.707$ and $y = 0.785$. The LD_{50} is then 688 r.

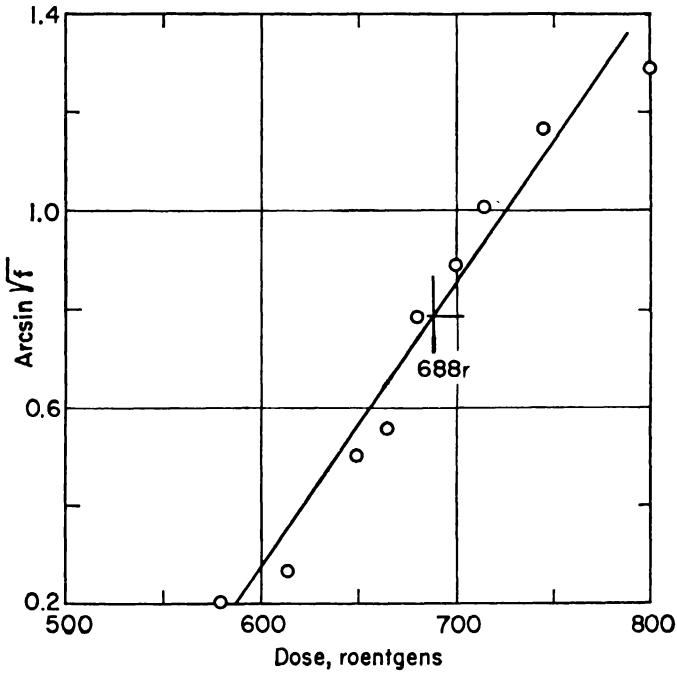


Fig. 14-6. Arcsin plot of mortality data. $LD_{50} = 686$ r.

14.10 GASTROINTESTINAL DEATH

There is no question of mortality statistics at dose levels high enough to produce the 3–5 day death; these doses are well above the LD_{100}. In man, symptoms follow promptly after whole body

doses of this magnitude. Nausea and vomiting may appear in an hour and become severe. Fatigue and general malaise without localized pain are prominent symptoms. Animals show a sharp decrease in activity, and appears to experience generalized discomfort.

Gross destruction of the intestinal lining is observed at autopsy after radiation doses sufficient to cause acute intestinal death. Fragmented crypt cells, denuded villi, edema, and hemorrhage are regularly seen. Although injury is general the crypt epithelium appears to be most sensitive. Bacterial invasion quickly follows the loss of integrity of the intestinal lining.

14.11 CENTRAL NERVOUS SYSTEM DEATH

At extremely high doses death occurs before generalized infection and gross intestinal injury have time to develop. The clinical signs, which include ataxia, nystagmus, and convulsions suggest abnormal central nervous system excitation.

Species differences are marked. In the guinea pig for example, the convulsions can be dramatically controlled by pre-irradiation administration of sodium pentobarbital; yet this drug shows no comparable action in other species. No human data are available at these extreme doses.

The cause of central nervous system death is not known. Neuropathology seems to be confined to the cerebellum * and here one sees only an increase in the number of pyknotic cells. Some functions are surprisingly unaffected by massive radiation doses. Threshold for pain stimulation, for example, is only slightly elevated in the guinea pig after 20,000 r. Fractionated dose experiments † indicate that repair processes are active even after doses of 10,000 r, although they can do no more than slightly increase survival times.

14.12 CHRONIC RADIATION EXPOSURE

When radiation is received at low dose rates over protracted periods of time, repair processes act to change the observed signs of injury. A whole-body dose of 100–200 r, received in a few hours or

* Alvord, E. C., and K. C. Brace. *J. Neuropath. and Exp. Neurol.* **16,** 3, 1957.

† Andrews, H. L. *Rad. Research* **12,** 195, 1960.

less, will produce changes in the peripheral blood count, and transient intestinal damage. These signs of injury may not appear if the same dose is delivered over a period of several years. In the latter case the chance of developing leukemia or some other malignant process has increased. Some life-shortening and genetic injury can also be expected.

There is considerable species variation in response to chronic irradiation, and various strains within a species may show quantitative differences. Dose-effect relationships are not well established at low dose rates because any unrepaired damage is small. It is most important to know if a threshold dose exists, below which there is no irreparable injury. Extensive experiments have not demonstrated either the existence or absence of a threshold.

One of the most comprehensive studies of chronic whole-body radiation was carried out by Lorenz * and his collaborators. Mice, guinea pigs, and rats received daily doses of gamma rays ranging from 0.11 to 8.8 r per 8 hour day. Except for the lowest dose-rate, effects seemed to increase with dose.

Mice showed few significant changes in the peripheral blood. A few died with terminal anemia, but only when the accumulated dose had reached at least 3,500 r. Blood changes in guinea pigs were more pronounced, all 8.8 r per day animals dying with anemia and thrombocytopenia or pancytopenia after 600–700 r. Rabbits showed a slight drop in platelets and lymphocytes, but there were no deaths attributable to hemopoietic injury, even after a total dose of 12,000 r.

14.13 LIFE-SHORTENING EFFECTS

Many animal experiments have demonstrated that doses of 1 r per day or more will lead to a reduced life expectancy. Life shortening as a result of radiation overexposure has not been directly demonstrated in man. An effect at high doses may be inferred from the results of the animal experiments and from the fact that large doses are known to increase the chance of developing leukemia.

Most exposures associated with the peacetime exploitation of nuclear energy will be considerably lower than those at which life shortening has been demonstrated. Data at low dose rates are con-

* Zirkle, R. E., Ed. *Biological Effects of External X and Gamma Radiation* National Nuclear Energy Series IV-22B, Chaps. 1–6, McGraw-Hill, New York, 1951.

flicting because relatively small differences must be determined out of a whole lifespan. Some experiments, notably those of Lorenz on mice, have shown an extension of life at low dose rates, Fig. 14-7.

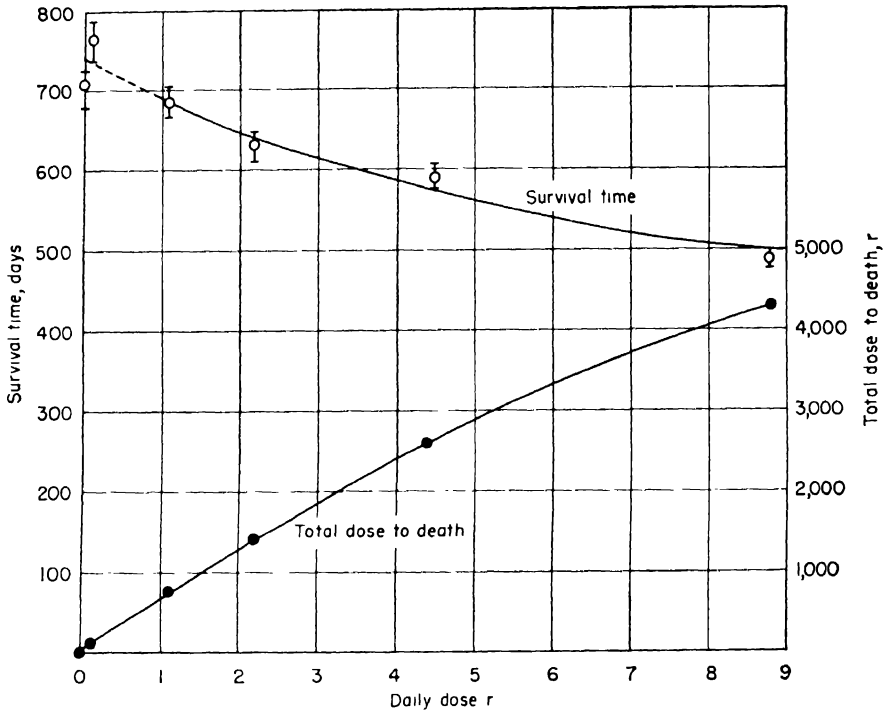


Fig. 14-7. Survival curves of LAF_1 mice subjected to chronic gamma radiation. Data from Lorenz, et al., MDDC Report No. 653.

An obvious explanation is that repair processes are stimulated sufficiently to more than overcome the injury, but this suggestion must be regarded as speculative.

It is most important to determine the presence or absence of a threshold for life shortening. If such a threshold exists, doses below it can be accepted with no shortening of lifespan. If there is no threshold even the smallest dose will cause some reduction in life expectancy. Experimental proof will be difficult to obtain because the effect at low doses is small.

In some respects chronic radiation exposures seem to hasten normal aging processes. Irradiated animals look old sooner than normals. Except for an increased cancer incidence, irradiated animals die from a wide variety of causes, suggesting a non-specific injury. On the other hand radiation does not hasten normal aging processes

such as alterations in collagen or the appearance of liver lesions.* Because of these differences it is probably more accurate to think of radiation as life-shortening rather than as a premature aging agent.

14.14 ANALYSIS OF LIFE-SPAN DATA

Several attempts have been made to obtain mathematical expressions relating life-shortening to radiation dose, dose rate, and other pertinent parameters. Simplifying assumptions must be made before the actual complex situation can be brought within the range of practical mathematics. In the simplification some detail is lost, but enough basic principles remain to make the treatment of considerable importance. A unique mathematical solution is not available, for a variety of reasonable assumptions appear equally plausible,† and lead to somewhat different mathematical forms.

The treatment of Blair ** will serve as an example. According to Blair, radiation injury increases proportionately to the dose rate, whereas repair takes place at a rate proportional to the injury existing. A certain fraction of the injury is assumed to be irreparable. These assumptions lead to a differential equation

$$\frac{dI}{dt} = A\gamma - \beta(I - \alpha t) \tag{14-8}$$

Where I = injury existing at time t
γ = dose rate, roentgens per unit time
β = constant controlling repair
α = irreparable fraction of injury

Equation (14-8) can be integrated to give

$$I = \frac{\gamma}{\beta}(A - \alpha)(1 - e^{-\beta t}) + \alpha\gamma t \tag{14-9}$$

Blair now relates injury and life shortening, $(S_0 - S)$, by

$$S_0 - S = I \tag{14-10}$$

* Alexander, P., and D. I. Cornell. *Rad. Research* **12,** 38, 1960.

† Berlin, N. I., and F. L. Di Maggio. *A Survey of Theories and Experiments on the Shortening of Life Span by Ionizing Radiation.* Armed Forces Special Weapons Project Technical Staff Study AFSWP-608.

** Blair, H. A. *University of Rochester Atomic Energy Project Reports.* UR-206, UR-207, UR-312 and UR-462.

For chronic irradiations until time of death the exponential term in Eq. (14-9) vanishes and $t = S$. Then

$$S_0 - S = \frac{\gamma}{\beta}(A - \alpha) + \alpha\gamma S \tag{14-11}$$

and if the total accumulated dose $\gamma S = \sigma$

$$S = S_0 - \alpha\left(\frac{A - \alpha}{\alpha\beta}\gamma - \sigma\right) \tag{14-12}$$

Equation (14-12) predicts a linear relation when survival time S is plotted against the sum of two terms, one proportional to dose and one proportional to dose rate. As Fig. 14-8 shows, the predicted linear relation is quite accurately obeyed.

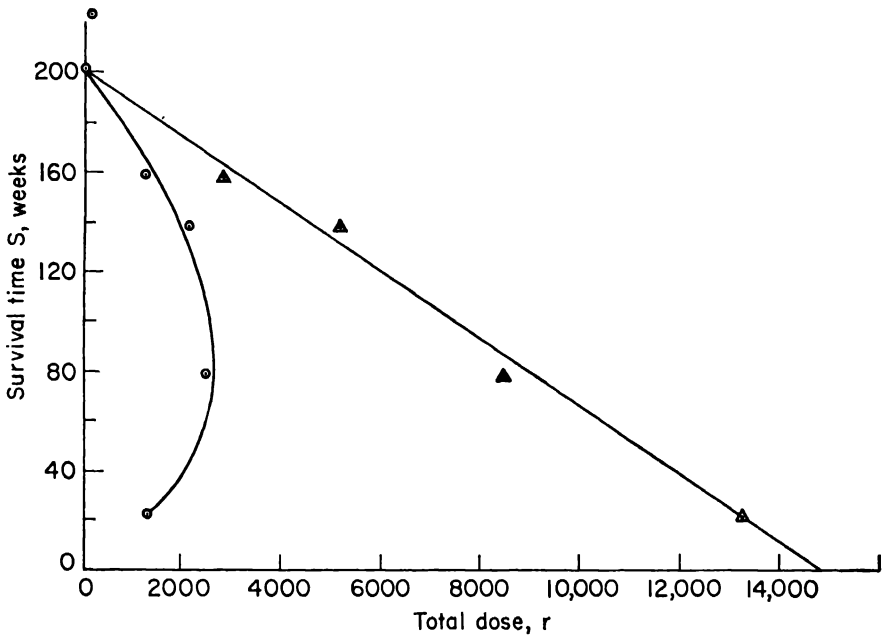


Fig. 14-8. Plot of Blair function for the guinea pig. A plot against dose alone gives a double-valued curve (open circles). When a dose-rate term is included the plot becomes linear (triangles). From H. A. Blair report UR-207.

The constants in the Blair theory can be evaluated from survival time data and the dose for acute radiation death $LD_{50/30}$. Table 14-5 shows some of the values obtained by Blair.

Table 14-5. CONSTANTS IN THE BLAIR THEORY

Animal	Radiation	S weeks	A	β	α
mouse *ABC*	X	77	0.13	0.80	0.012
mouse Swiss	n	68	0.79	1.3	0.18
rat	X	65	0.11	0.6	0.002
guinea pig	γ	202	0.19	0.18	0.014

The significance of analyses such as Blair's remains to be determined. Biologically, constants such as A, β, and α do not have the clear-cut mathematical significance assigned to them. It appears, for example, that some components of radiation injury are completely repaired whereas other components suffer permanent damage.

14.15 CARCINOGENESIS

Many early workers demonstrated in tragic fashion that large doses of X-rays are carcinogenic in man. Repeated moderate doses led to local epilation and a chronic dermatitis, which was frequently followed by the appearance of squamous cell carcinoma. A severe overexposure, as to the hands during experiments with unshielded equipment, might lead to telangiectasia and blistering of the exposed skin. Even if exposure was then limited large numbers of warts might appear. Some of these warts became sites of ulcers which were difficult or impossible to heal. In course of time malignant cells could be found and from then on the clinical course was steadily downhill. A good many underwent successions of amputations without stemming the course of the disease.

All of the early X-rays were relatively soft and so delivered the greatest dose at or near the surface of the body. It is not surprising that all of the early malignancies apparently originated in the skin. Later injuries include overexposure to more penetrating radiation from external sources, and to localized deposits of radioactive nuclides. From this evidence it appears that radiation may be carcinogenic to any cells capable of division. Cell types may have varying degrees of radiation sensitivity, but probably none are completely immune. Lymphocytes, for example, are quite radiation sensitive whereas reticuloendothelial cells are relatively resistant.

The exposure pattern and genetic makeup appear to have some influence on the development of radiogenic cancer. Thus in mice

repeated exposures are more leukemogenic than a single exposure. In mice susceptibility to leukemia is a function of both sex and genetic strain. Radiologists, whose pattern is a series of small exposures, have a leukemia incidence definitely higher than other physicians or the general population. A delayed increase in leukemia among the Japanese atomic bomb casualties shows that a single radiation exposure can be leukemogenic.

Radiogenic cancer in man appears to be indistinguishable from cancer arising spontaneously, a fact which may have important legal implications. Difficult compensation problems are bound to arise in cases where a cancer may be, but is not certainly, the result of a radiation overexposure. These problems will be complicated by the fact that a long induction period may intervene between an overexposure and the appearance of neoplastic processes. This period may be as long as 10 to 15 years.

With our present knowledge and control of radiation sources the greatest general danger of carcinogenesis may arise from chronic over-exposure to small doses rather than from a massive single event. It is therefore of the greatest importance to know the quantitative relationships between dose and the probability of cancer induction at very low dose rates. This information is not available and will be difficult to obtain because of the relatively low incidence.

The presence or absence of a threshold for cancer production has not been established and so there is no dose known to be absolutely safe. Since dose-effect proportionality has not been demonstrated at low dose rates, extrapolation from higher ranges cannot be done with any certainty. It seems most unlikely that very small doses are proportionately more effective than large ones. If they are, an assumption of no threshold and linear extrapolation from high doses will not underestimate the cancer incidence expected from small doses.

Since rapidly growing tissues appear to have increased radiation sensitivity, there has been considerable concern about the carcinogenic effects of radiation received in the course of prenatal radiography. In one study a group of children dying of leukemia and other cancers was compared with a group dying without malignant disease. A larger proportion of the former group had been exposed to prenatal radiation. This finding has not been confirmed in subsequent studies so that at present we can only say that the effect is small if it exists at the doses received during diagnostic radiography.

It has been suggested, but not established, that some radiogenic malignancies may result from somatic mutations. Experimental work is handicapped by the long times sometimes required for tumor induction and by the fact that most work must be done on animals, whose life span is short compared with that of man.

14.16 GENETIC EFFECTS

Genetic injury is perhaps the most serious consequence of radiation overexposure. With the possible exception of life shortening, all radiation injuries except mutations appear to be confined to the individual receiving the radiation. Genetic injury, on the other hand, may be latent for many generations, to appear long after the exposure. Again, radiation injuries may be very subtle, appearing as a reduced effectiveness of the affected individuals.

There is some disagreement among geneticists and others about the impact a given number of mutants will have on a population. Genetic injury will in general be deleterious, so an increased mutation rate will mean an increased number of under-par individuals. Thus we speak of a genetic burden on a population.

There is a normal spontaneous mutation rate and indeed a small rate may be necessary to permit natural selection of most favored types. There is general agreement that in man a gonadal dose of 50–100 r will double the natural mutation rate. There is not complete agreement on the long-range consequences of doubling, or of any other increase over the natural rate. It seems imperative to err on the side of conservatism in setting allowable exposure levels. Any serious consequences of a too-liberal policy will appear only after serious damage has been done, with a large genetic burden already in existence.

Any assessment of the impact of an increased genetic burden is handicapped by the difficulties of quantitating the injury. It seems impossible to describe numerically the effect of a stillbirth, a feeble-minded child, or an individual with a restricted food acceptance. Any one of these events might seem like a disaster to the immediate family but would have little effect on society as a whole. There is no reliable estimate of the number of abnormalities which a society can accept without degeneration.

In considering the impact of an increased mutation rate we must

keep in mind that radiation is not the only known mutagenic agent. Contemporary man is exposed to a host of industrial fumes, food additives, and many other chemical compounds whose genetic effects have not been intensively studied. Future research may show that some of these agents are also effective mutagens.

As in all other chronic radiation effects the question of threshold and linear dose-effect relations are of great importance. As in the other chronic effects there is little conclusive evidence on either of the two points. At low dose rates there are fewer genetic injuries in flies and mice than are found when an equal dose is given at a faster rate. Much of the needed evidence is missing. A conservative approach again is to assume no threshold and a linear extrapolation from higher values.

PROBLEMS

14-1. An animal population is characterized by a Gompertz function with $m = 0.005$/month and $R = 0.01$/month. Calculate and plot the Gompertz function for this population and determine the time at which half the population will be dead.

14-2. When the population of Prob. 14-1 is subjected to chronic gamma radiation the characterizing constants become $m = 0.06$/month and $R = 0.05$/month. Calculate the amount of life shortening at the 50 per cent point.

14-3. The following data were obtained in a dose-mortality study. Determine the LD_{50} by the method of probability plot.

Dose (r)	205	228	242	260	288	300
Percentage mortality	2.0	16.0	27.8	51.6	84.2	93.2

14-4. Use the data of Prob. 14-3 and determine LD_{50} by a probit plot.

14-5. Use the data of Prob. 14-3 and determine the LD_{50} from an arcsin plot.

14-6. Calculate the characterizing constants from the arcsin plot in Prob. 14-5.

14-7. The following data were obtained in a dose-mortality study. Determine the LD_{50} by the method of probability plot.

Dose (r)	700	740	780	820	860	900
Percentage mortality	3.6	15.2	29.4	58.0	77.8	88.3

14-8. Use the data of Prob. 14-7 and determine the LD_{50} from a probit plot.

14-9. Use the data of Prob. 14-8 and determine the LD_{50} from an arcsin plot.

14-10. Calculate the characterizing constants from the arcsin plot in Prob. 14-9.

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15

PATHOLOGICAL PHYSIOLOGY OF RADIATION INJURY

15.01 FROM IONIZATION TO INJURY

Many components of the acute and chronic radiation syndrome have been known for half a century. Over this time span an increasing effort has been devoted to research in all phases of radiation biology, yet none of the events leading to eventual radiation death can be traced with certainty beyond the initial energy absorption.

Water is a major constituent of nearly all living tissues and we know that most initial radiation interactions will involve water molecules. The reaction products of pure water are known, as are the modifications introduced by the addition of some dissolved gases such as oxygen. In a living system water is intimately mixed with both oxygen acceptors and donors, in a buffered system under hormonal and neural controls which usually act to counteract disturbing influences. It is not surprising that even the first reactions in this complex system are not understood.

Even the observed end effects of radiation absorption must be interpreted with caution. One of the most sensitive indicators of radiation injury in man is a decrease in the number of lymphocytes in peripheral blood. The mature lymphocyte is, however, relatively radiation resistant. The observed leucopenia is, then, due to a functional impairment of production centers such as lymph glands rather than to a direct effect on the circulating cells.

If the primary effect is on the source, life span of the mature element will be an important factor in determining the time course of injury development. In the formed elements of blood, life span increases progressively from lymphocyte, granulocyte, reticulocyte, thrombocyte, to erythrocyte, which is just about the order in which changes are seen after radiation.

Some injuries can be produced by radiation absorbed in another part of the body. For example, there is a weight loss in the thymus gland when it is directly radiated, or when it is shielded and the rest of the body is irradiated. Such an *abscopal* effect must be distinguished from *indirect action*. The latter term is reserved for radiation effects produced by chemical intermediates rather than by a direct hit.

15.02 TIME AND RADIATION INJURY

The remarkable sensitivity of living tissue to radiation has been mentioned. Thus a whole-body dose of 1000 r will certainly be fatal to man in a period of perhaps three weeks. This dose will deposit 8.7×10^4 ergs per gram of tissue to produce a temperature rise of about 0.002°C. In an average man the total energy absorbed will be about 6.1×10^9 ergs or about 140 calories.

One gram of tissue may contain some 10^{23} atoms and if we assume one ionization or excitation for each five ev expended only one atom in 10^7 will be affected by a dose of 1000 r. This is equivalent to saying that some action on 20 people today will result in the destruction of the entire population of the United States within three weeks. These figures suggest the presence of some sort of a biological amplifier to increase and extend the primary action. Several amplifying mechanisms have been proposed but none has been identified as acting.

The time interval of three weeks is an important factor in radia-

tion lethality. The radiation dose needed for essentially instantaneous killing is not known for man but it is probably more than 10^5 r. A large primary effect is required to equal the injury that develops from a smaller dose over a longer time interval.

The time course of injury development can be altered by changing the rate of metabolism. In the hibernating marmot development of radiation injury can be held in abeyance for several weeks. When more active metabolism is restored the suppressed injury appears in normal fashion. Conversely, the effects of a given radiation dose are enhanced by the administration of thyroid extract or dinitrophenol.

15.03 LYMPHOCYTES AND ACUTE RADIATION

The effects of acute radiation doses on the peripheral lymphocyte count were recognized early but the mechanisms involved in injury and recovery of the hemopoietic system are still far from being understood. Rate of development and depth of lymphopenia are indices of amount of radiation damage, and are of some prognostic value in cases of overexposure.* Lymphocyte count is useful over only a limited range. Below 25 r whole-body, no change can be detected with certainty; above about 400 r there will be too few cells for accurate counting.

An increased number of multinucleated lymphocytes is seen after an acute dose of only a few roentgens. A large number of cells must be studied by a trained observer to obtain useful information from these forms.

Whole-body radiation is usually followed by a transient leukocytosis but this effect is not the result of an increased number of lymphocytes. Lymphopenia may appear within an hour and continue to develop for 2–15 days, depending upon the dose. If the animal is going to survive, some lymphocyte recovery may be noted within a few days, although maximum recovery is delayed. Peripheral lymphocyte count is one of the most persistent indices of radiation injury; a depressed count may continue for many months after a large dose. Lymphopenia may persist long after lymphoid tissue and lymphocyte production have apparently returned to normal.

Repair processes are quite effective in the lymphocyte system.

* Hemplemann, L. H., H. Lisco, and J. G. Hoffman. *Ann. Int. Med.* **36**, 279, 1952.

Counts remain normal with low-level chronic exposures, even when total doses become large. Lymphopenia depends, at least in part, upon abscopal effects. Damage to lymphoid tissue has been observed in areas not directly irradiated, and in a protected parabiont partner. Irradiation with external sources of beta particles, having a penetration of only a few millimeters, is not followed by a lymphopenia.

Figure 15-1 shows the course of the peripheral lymphocyte counts

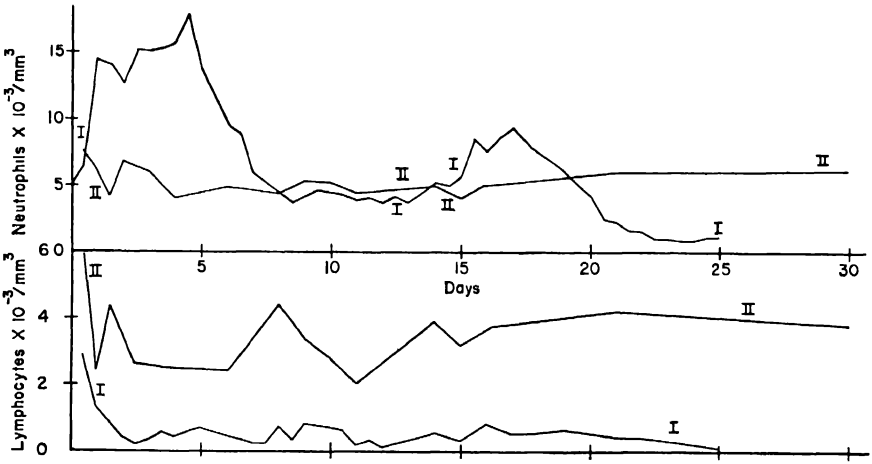


Fig. 15-1. Peripheral lymphocyte and neutrophil counts in two human accident cases

in two human accident cases. Case I received about 600 r to the body, with much higher doses to the hands and arms. Case II received a body dose of about 32 r.* In case I lymphopenia developed promptly and was maintained until death. Case II showed an initial depression of lymphocytes, followed by a period of instability, and a gradual rise toward normal values.

15.04 GRANULOCYTES

The initial transient leucocytosis, which may last for 24 hours after an acute exposure, results from an increase in the number of circulating granulocytic components. The reason for this increase is not known. Obvious explanations are a premature release of mature cells or an accelerated maturation of immature forms.

* Data for these cases obtained from Hemplemann, Lisco, and Hoffman, loc. cit.

With sufficiently large doses the transient leucocytosis will be followed by granulocytopenia. Recovery from this form is usually faster than from lymphopenia, so normal values may be regained in about 30 days, even after doses approaching the LD_{90}. Figure 15-1 shows the course of the neutrophillic component of the granulocytes in two human accident cases. Case I showed two periods of granulocytosis, the second of which was followed by a profound drop in counts. There was a questionable neutrophill rise in Case II, with a small decrease followed by a gradual return toward normal.

A lowered granulocyte count reduces the host defenses against bacterial invasion, permitting infection to play a major role in the radiation syndrome. This role is emphasized by the loss of integrity of the intestinal tract, one of the major barriers against invasion by endogenous organisms. When infection is present, granulocyte counts furnish important prognostic information. Survival appears to correlate more closely with the degree of granulocytopenia than with the degree of lymphopenia.*

15.05 ERYTHROCYTES

Red-cell counts, hemoglobin, and hematocrit determinations on peripheral blood show little change, even at doses approaching the lethal range. When a reduction is observed it may not appear until 7 to 10 days after the radiation experience. Figure 15-2 shows the delayed and relatively small response in man to even a fatal dose of radiation.

Although the mature erythrocyte is relatively radiation resistant, histopathologic studies suggest that its precursor, the erythroblast, is among the most sensitive tissues. From the observed radiation effects on bone marrow, red-cell output should practically cease within 24 hours after a near-lethal dose of radiation.

Erythropoiesis can be measured by the rate of uptake of radioactive iron, Fe^{59}. Studies of Fe^{59} uptake confirm the predicted cessation of erythropoiesis at high doses and have demonstrated impairment after only 5 r.

The relative constancy of the peripheral erythrocyte picture results from a simultaneous reduction in both red-cell mass and plasma

* Smith, W. W., L. Gonshery, I. Alderman, and J. Cornfield. *Am. J. Physiol.* **178**, 471, 1954.

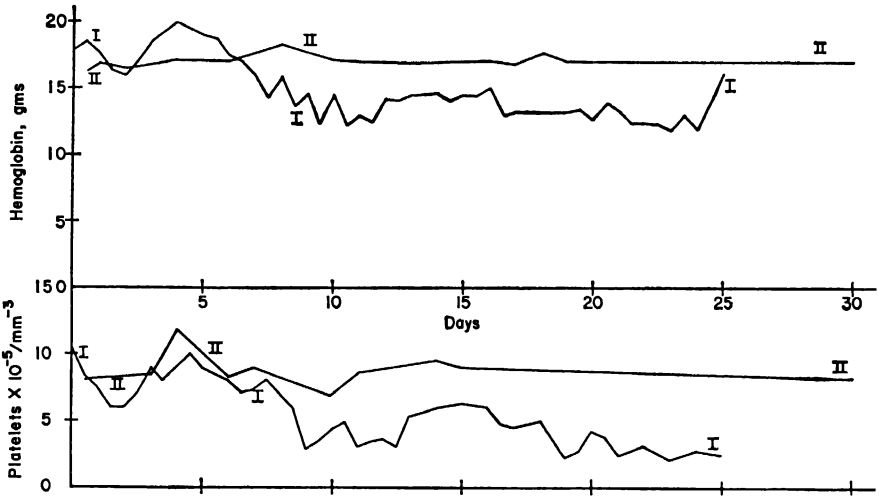


Fig. 15-2. Hemoglobin and platelet counts in two human accident cases.

volume. Reduction in red-cell mass results from the death of normally aged cells and from a loss through increased capillary permeability. In an animal that will survive, regeneration of erythropoietic tissues takes place before the red-cell losses are seriously reflected in the peripheral counts.

15.06 PLATELETS

Hemorrhage in various forms is a universal component of the acute radiation syndrome at doses of 100 r or more. Purpura, generalized petechiae, intestinal and gingival bleeding are among the most common signs of radiation injury.

Post-radiation hemorrhage is the end result of several factors, among which are thrombocytopenia, increased capillary fragility, and the formation of anticoagulants. Prolonged bleeding time, blood clotting time, and impaired clot retraction implicate platelet deficiency as an important factor in the hemorrhagic syndrome.

After a near-lethal dose of radiation a delayed, gradual reduction in circulating platelets sets in. The degree and duration of the thrombocytopenia increase with dose. Recovery is slow, platelet counts sometimes remaining depressed for several years. Figure 15-2 shows the platelet response in man in two accident cases.

The degree of thrombocytopenia appears to be a reliable index of the severity of radiation injury in the sub-lethal dose range, but its late appearance makes it of little prognostic value.

As with other blood elements, the mature form is relatively resistant, the greatest effect appearing at the precursors. Thus thrombocytopenia follows a sharp reduction or a disappearance of the megakaryocyte precursors.

Platelet transfusions in dogs have reduced the bleeding tendency if circulating platelets can be maintained at about 100,000 per mm^3. Hemorrhage can also be reduced, even in the presence of some thrombocytopenia, by the administration of various clotting or "anti-heparin" compounds. Although the hemorrhagic tendency can be partially controlled, these measures have no effect on the mortality statistics.

15.07 THYMUS AND SPLEEN

The radiation sensitivity of lymphoid tissue is well illustrated by the behavior of the thymus gland. Doses of 50 r or more produce a rapid reduction in thymus-gland weight, most of the reduction coming from a loss in lymphocyte mass rather than in connective tissue. A similar loss of weight has been observed in the spleen with enough consistency to warrant the use of splenic weight as a biological radiation dosimeter.* The decrease in weight five days after irradiation is linear with log dose except at low doses, where repair processes become appreciable.

In the sub-lethal range (LD_{10}–LD_{90}) the number of surviving mice is dramatically increased by surgically exteriorizing the spleen and shielding it from radiation with lead.† In addition to increasing the survival rate, spleen shielding sharply reduces the degree of leukopenia, thrombocytopenia, and anemia. Post-irradiation spleen transplants or injections of homogenized spleens from non-irradiated mice are also effective in reducing mortality rate and enhancing hemopoiesis.

Splenic transplants appeared to be a very promising treatment

* Carter, R. E., P. S. Harris, and J. T. Brennan. *Los Alamos Sci. Lab. Report* LA-1075-1, 1950.

† Jacobson, L. O., E. L. Simmons, W. F. Bethard, E. K. Marks, and M. J. Nobson. *Proc. Soc. Exptl. Biol. and Med.* **73,** 455, 1950.

for reducing radiation injury. Unfortunately it is effective in only a few species and at doses below about two times the LD_{50}. The dose-sparing effects of introducing unirradiated splenic material are almost certainly due to the presence of cellular components rather than to a soluble humoral factor.

15.08 BONE MARROW

Bone marrow, like other hemopoietic tissue, is radiation-sensitive, and the success with splenic homogenates led to the use of marrow injections * to reduce radiation effects. Isologous marrow (from the same species and strain) increased the survival rate of irradiated mice and hastened the recovery of hemopoietic tissue.

In later work heterologous bone marrow was used. Post-radiation injection of guinea pig or rat marrow gave substantial protection to mice during the usual 30 day observation period. During this period the donor marrow cells colonize in the host and appear to be carrying on the functions of the host's hemopoietic tissue. Unfortunately the animals later develop incompatabilities and die in 60–90 days after the introduction of the heterologous marrow.

Whole-body radiation is very effective in suppressing immune responses and consequently recently irradiated animals will tolerate the foreign antigens † in homologous (same species) or some heterologous marrows. As the animal recovers from the radiation normal immune responses return and then the host-transplant incompatibility will lead to death of the host or a rejection of the foreign colonies.**

15.09 THE EYE

In spite of some early injuries the eye has been considered relatively radioresistant. It became necessary to reassess this conclusion when several lenticular opacities were found among personnel work-

* Lorenz, E., C. C. Congdon, and D. Uphoff. *Radiology*, **58**, 863, 1952.

† Main, J. M., and T. R. Prehn. *J. Nat. Cancer Inst.* **15**, 1023, 1955.

** Vos, O., M. J. de Vries, J. C. Collenteur, and D. W. Van Bekkum. *J. Nat. Cancer Inst.* **23**, 53, 1959; Van Bekkum, D. W., O. Vos, and W. W. H. Weyzen. *J. Nat. Cancer Inst.* **23**, 75, 1959.

ing with high-voltage accelerators* These machines had been producing neutrons as well as gamma rays and it appeared that the *RBE* for opacity production was peculiarly high for neutrons. It now seems that neutrons are highly effective because of the large LET of the recoil protons.

The eye is somewhat more sensitive to photons than was originally supposed, with some opacities to be expected following 500 r. As with neutrons there will be a delay of months or years before the opacity appears. Irradiation of the lens is necessary to produce the opacity.

The term lenticular opacity has been used here to distinguish the lesion from the well-known cataracts of old age. Although the radiation-induced opacity seems to develop uniquely at the posterior capsule, there may be little difference between the two lesions. Production of opacity is one of the few ways in which the lens can respond to any insult.

15.10 NERVOUS SYSTEM

Peripheral nerve, as judged by action potential measurements, is one of the most radiation-resistant tissues. Doses in excess of 50,000 r are required to produce appreciable changes in either stimulation threshold or conduction velocity. In the guinea pig, pain threshold remains relatively unchanged after 10,000 to 20,000 r whole body, but the threshold for electrically induced convulsions is drastically lowered.† The pain-reflex response almost certainly involves some cerebral areas, so a substantial section of the nervous system is capable of normal response after a massive radiation exposure.

Some reports, primarily from Russian workers, suggest changes in behavioral response after doses of 1 r or even less. Established conditioned reflex patterns represent a high degree of CNS integration which might be more easily upset than simpler functions. However, these sensitive responses will require more confirmation before they can be accepted without question.**

There are no obvious nervous system components in the radiation syndrome in the LD_{100} range although delayed injury has been reported. Changes in the electroencephalogram are small or undetect-

* Abelson, P. H., and P. G. Kruger. *Science* **110**, 655, 1948.

† Andrews, H. L. *Proc. Soc. Exptl. Biol. and Med.* **96**, 345, 1952.

** Stahl, W. R. *J. of Nervous and Mental Disease* **129**, 511, 1959.

able until the animal is moribund. It is probable that in this dose range the CNS effects observed are secondary to an impaired blood supply rather than a primary effect on nervous system tissues.

At 20–50 times the LD_{100} signs of nervous system injury predominate. In guinea pigs and mice the change to this state occurs quite abruptly with dose, suggesting that some defense mechanism is suddenly overwhelmed. There is no evidence on the response of man to these supra-lethal doses.

15.11 GASTROINTESTINAL SYSTEM

The radiation sensitivity of the gastrointestinal tract was discovered early, and later work has confirmed that nausea, vomiting, and anorexia can arise from relatively small doses to the abdomen. In the dose range of 1000–10,000 r there is little difference in survival times between following whole body or primarily intestinal irradiation, and in this region death is almost exclusively the result of gastrointestinal injury.

At much lower doses gastrointestinal effects complicate the radiation syndrome and add to the generalized injury. Bacteremia of intestinal origin is found even with sub-lethal doses, and the anorexia can lead to a poorly nourished animal who becomes progressively unable to cope with his generalized injury. Anorexia may be due in a large part to the delayed gastric emptying resulting from radiation. There may also be some neural components because anorexia has been observed after irradiation of the head only.*

With doses just below lethal, damage to the small intestine may be seen within an hour and may reach a maximum in 8 to 12 hours. Repair processes are apparently quite effective, and are complete within a month. Injury in stomach and colon are less pronounced than in the small intestine.

15.12 MISCELLANEOUS ORGANS

Liver and kidney are quite radioresistant to external radiation and doses of more than 1500 r are apparently needed to produce

* Smith, D. E., E. B. Tyree, H. M. Patt, and N. Bink. *Argonne National Laboratory Report* ANL-4713, 1951.

definite injury. When large doses of radioactive nuclides are administered, however, the mode of excretion must be known and calculations must be made to determine the possibility that damage has been done to liver, kidney, or urinary bladder.

Mature bone is also quite radiation resistant, although extensive bone necrosis followed the deposition of radium in the dial painters. Growth of bone can, however, be inhibited by sub-lethal doses. Growth may be resumed after repair but permanent stunting will result. Care must be taken to insure that the deposition of bone-seeking nuclides does not deliver excessive radiation doses.

Skin is moderately radiation-sensitive; erythema has been used as a biological indicator of dosage. Pigmentation and epilation are also observed when the skin receives from 500–1000 r. Epidermis regenerating after extensive destruction is friable and easily injured, and a point of origin of radiogenic malignancies. Erythema from a single large dose may recur in waves with almost complete disappearance between stages.

15.13 RADIATION AND PHYSIOLOGICAL STRESS

Since radiation produces non-specific injuries in all cells of the body it might seem that these injuries would be enhanced by adverse environmental factors either during or after the irradiation. Conversely, an injury that appears to mimic if not duplicate aging would be expected to make an animal less fit to cope with an unfavorable environment. In general the superposition of radiation and physiological stress does not produce the expected enhancement.

Rats, for example, when forced to walk continuously for 7.5 hours a day for 9 days after radiation, showed only a moderate mortality increase from 60 to 76 per cent.* When exercise is pushed to extreme limits some deleterious effects of radiation appear. Thus weighted rats, forced to swim to exhaustion in cold water, showed a 61 per cent mortality compared to 16 per cent for the radiated, non-exercised group.†

Within limits the state of nutrition appears to play a minor role in radiation mortality although a low-protein diet (6 per cent casein) is slightly deleterious. To be effective the low-protein diet had to

* Smith, W. W. *Nucleonics* **19**, 80, 1952.

† Kimeldorf, D. J., and D. C. Jones. *Am. J. Physiol.* **167**, 636, 1951.

be instituted several days before irradiation and continued throughout the period of observation. High-protein diets and increased vitamin feeding have no effect on radiation mortality.

Sub-lethally irradiated rats have an impaired hemopoietic system but they tolerate acute hypoxia as well as normal animals. Conversely, the hypoxia associated with simulated altitudes of 20,000–25,000 feet does not increase the death rate from radiation in rats and mice.

15.14 OXYGEN EFFECT

An increased oxygen tension at the time of irradiation enhances the effects of X and γ radiation, but has little effect on injury produced at high values of LET. This oxygen effect is easy to demonstrate with microorganisms or cell cultures where the amount of available oxygen can be changed radically. The effect in mammals is less dramatic, for here the tissues are usually at or near maximum oxygen tension and heroic measures are required to increase it.

The fact that normal tissues are at or near oxygen saturation offers hope for a real improvement in radiation therapy of solid tumors. Many of these tumors are poorly vascularized, particularly near the center, and hence are far from oxygen-saturation. With an increased oxygen availability there is a chance of increasing tumor oxygen without a corresponding increase in normal tissues, and if this can be done the differential effect in tumor over normal tissue may be enhanced.

Oxygen lack reduces the effect of radiation on some simple systems so that it is natural to look for a comparable protective effect in mammals. A protective effect can be demonstrated, but it is small and probably of no practical value. Some chemical protective agents are thought to operate by consuming oxygen, thus reducing the amount available for producing intermediates such as peroxides.

15.15 CHEMICAL PROTECTIVE AGENTS

An ideal protective agent would be one which, when administered post-irradiation, would reverse the previously produced injury. Such an agent is not to be expected because it seems inconceivable that

generalized molecular disruptions can be restored to normal. Many radiation effects are delayed, however, and there is real hope that at least some of these can be prevented or reduced by chemical agents.

Indirect actions might be reduced by pre-treatment with strong competitors for the radiation-produced intermediates. Post-treatment based on competing compounds will be useless. The number of chemical agents tested is legion, and many have shown small beneficial effects when given prior to irradiation. Many of these compounds have no practical value but will be of use in furthering our understanding of radiation action.

Barron * demonstrated the relatively high *in vitro* sensitivity for the oxidation of —SH groups to —S—S by radiation and pointed out that a number of enzymes require —SH groups for activity. The —SH-containing amino acid, cysteine, does indeed show some protective action † in a wide variety of organisms and the tripeptide glutathione, which contains cystein, is also effective. Later work showed the corresponding amine ** cysteamine, to be strongly protective.

In spite of the effectiveness of cysteine and cysteamine many —SH compounds give little or no protection. Thus it is not clear as a generalization that radiation effects on —SH group *in vivo* are an outstanding part of the total radiation-injury syndrome.

The protection afforded by cysteine and some of the amines prompted large-scale investigations of related compounds. Many have been found with varying amounts of protective action. Others have had no effect on the mortality rate.††

It is impossible to discuss here the protective compounds in detail. Studies of a series of compounds related to 2-mercaptoethylamine (MEA) led to a series of generalizations relating chemical structure and protective action. Thus a basic group and an —SH separated by not more than three carbon atoms seemed to give a maximum protective action.

Investigations of a series of isothiuronium compounds led to the discovery of *S*-β-aminoethylisothiuronium Br—HBr (AET). This compound was more effective in mice than any of the mercaptans

* Nickson, J. J., Ed. Symposium on Radiobiology. Wiley, New York, 1951.

† Patt, H. M., E. B. Tyree, R. L. Straub, and D. E. Smith. *Science* **110**, 213, 1949.

** Bacq, Z. M., et al. *Arch. int. Physiol.* **59**, 442, 1951.

†† Kimball, A. W., W. T. Burnett, J. and D. G. Doherty. *Rad. Research* **7**, 1, 1957; Doherty, D. G., W. T. Burnett, Jr., and R. Shapira. *Rad. Research* **7**, 13, 1957; Shapira, R., D. G. Doherty, and W. T. Burnett, Jr. *Rad. Research* **7**, 22, 1957.

studied. Again studies of a series of compounds led to the conclusion that protective action requires two functional groups (guanido and thiol) separated by not more than three carbon atoms. All these compounds appear to act through interference with the free-radical reactions that normally take place at the time of irradiation. It is not sufficient to provide —SH groups to compensate for those oxidized to —S—S.

The oxygen effect suggests the use of compounds known to produce anoxia, and many of these do have a protective action. Among these are carbon monoxide, cyanides, and malononitrile. Ethanol and *p*-aminopropriophenone are also protectors but their actions may not depend upon the production of anoxia. None of these agents appears to have practical applications because of high toxicities in the required doses.

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16

RADIATION HEALTH PROTECTION

16.01 PREVENTION AND NOT CURE

Penetrating radiations from external sources or from radioactive substances which have entered the body are among the most insidious threats to living tissues. Even a gross overexposure may not be sensed, and severe damage can be done long before clinical signs are evident. The end results of radiation overexposure are many and at least three; genetic injury, shortening of life span, and carcinogenesis are of serious import, with long-delayed consequences.

If overexposure is mild many years may elapse between the event and the appearance of injury. Once radiation has been absorbed little can be done to counteract its deleterious effects. Some reduction in dose can be achieved by *replacement therapy* against internally deposited isotopes, but the increased rate of elimination is discouragingly small. Thus a high calcium intake may slightly increase the elimination of ingested radium, but once radium has been

incorporated into the bony structures calcium therapy has little to offer.

Because of the long-delayed actions protection requires preventive, rather than therapeutic measures. Maximum permissible dosages, MPD, must be set at levels believed to be certainly without harmful effect and a constant watch must be kept to insure that these levels are proper ones. Even conservative MPD values must be considered to be upper limits rather than recommended operating values.

It is most important to know if a threshold dose exists for various types of radiation injury. If there is a threshold, absolute safety can be achieved by keeping exposures below the critical level. If there is no threshold some injury will be produced by the smallest dose. In the absence of a threshold an MPD is merely a level at which the risk of injury seems acceptable to a group of informed scientists.

Unfortunately the existence or absence of a threshold is very difficult to establish experimentally. Radiation effects become so small at low doses that millions of test animals must be used to determine the injury produced by a dose of a few roentgens. The numbers required to obtain statistically significant information for a dose of a few milliroentgens becomes impossibly large.

16.02 PHILOSOPHY OF ACCEPTABLE RISK

In the absence of definite information about radiation thresholds the conservative approach is to assume that there is none. It then becomes necessary to replace the concept of a safe dose with that of some risk associated with a dose of any size. According to this view the injury to be anticipated from a given radiation exposure must be balanced against the expected benefits. Although this theory seems sound in principle there may be practical difficulties in the way of establishing it. Thus, each individual may strike a different balance between injury and benefit, which would quickly lead to a chaotic situation in any attempt to set up working environments.

It will be impossible to keep the general population informed at the level needed for independent judgments. Some responsible group must, then, be given the task of establishing values of acceptable risk for various situations. The responsibility for setting these values is very great. If the levels are unnecessarily low some of the benefits

of radiation may be lost. If the levels are too high excessive injury may appear in later years.

It must be remembered that radiation is only one of the hazards of modern living. Although much remains to be known, radiation is one of the best understood contemporary hazards. Industrial and automobile fumes, food and food additives, tobacco, drugs, antibiotics, hormones, cosmetics, contraceptives, and agents of chemical warfare have been mentioned * as possible sources of genetic damage to man. The use of many of these agents is so widespread that there is much less public concern about them than about the more mysterious penetrating radiations.

16.03 EARLY PROBLEMS

Some of the dangers inherent in radiation were quickly recognized, but safe practices could not be established until the biological actions were at least partially understood and satisfactory methods of measurement had been developed. The belief that X-rays produced by electrostatic machines were relatively safe persisted for over 20 years, even though many radiologists were suffering from radiogenic cancer.

Early workers were handicapped by a lack of means for accurately measuring radiation dose. One of the first attempts at quantitation utilized a *chromoradiometer* based upon the discoloration of a mixture of potassium chloride and sodium carbonate, developed by Holzknecht in 1902. Many types of chromoradiometers were used, and there was a corresponding number of radiation units. One could, for example, express a radiation dose as that necessary to produce a given tint in a Saubauraud pastille. It was recognized that a color change in a pastille might bear little relation to the biological effects of the absorbed radiation, so attempts were made to develop biological units of dosage. The most commonly used biological unit was that dose which just produced skin erythema, known as a *unit skin dose* or *skin erythema dose,* SED. Another guidepost, rather than a unit, was the amount of radiation required to produce epilation.

Chromoradiometers were used extensively as late as 1926 in spite

* National Academy of Sciences, National Research Council Summary Report, *The Biological Effects of Atomic Radiation,* May, 1960.

of growing knowledge about the ability of the radiations to produce ionization in gases. In 1926 the use of vacuum tubes was limited, but electroscopes and electrometers had been developed into reliable and sensitive instruments. Means of measurement of small charges and currents were, then, available when a change was made to ionization-chamber measurements.

16.04 INTRODUCTION OF THE ROENTGEN

A new era in radiation-protection techniques began on July 27, 1928 when the Second International Congress of Radiology, meeting in Stockholm, adopted a series of most important resolutions. Among these was one defining an international unit of X-radiation to be called the "Röntgen" and to be designated by lower case r. The definition was based on ionization in air and was essentially the definition of the roentgen as used today.

Another resolution recommended that comparative measurements be made with ionization chambers in which wall effects were made as small as possible. The importance of quantum energy was recognized in a resolution calling for radiation quality to be expressed in terms of half-value layer.

A series of recommendations for protection against X-rays and radium were adopted by the Second Congress. Among the more important were:

> Not more than seven working hours a day.
> Not more than five working days a week.
> Off-days to be spent as much as possible out of doors.
> Not less than one month's holiday a year.

Maximum permissible dose for operators of X-ray units was taken care of by the following:

> It should not be possible for a well-rested eye of normal acuity to detect, in the dark, appreciable fluorescence of a screen placed in the permanent position of the operator.

The vagueness of this resolution is matched by the film-badge standards in vogue during this period. An exposure was considered allowable if a newspaper could be read through the film, which might consist of almost any type of emulsion processed by almost any procedure.

16.05 NATIONAL COMMITTEE ON RADIATION PROTECTION

Prior to World War II, recommendations for radiation-protection standards in the United States came from the *Advisory Committee on X-ray and Radium Protection.* This committee was composed of members from the National Bureau of Standards, various interested scientific Societies, and equipment manufacturers. The National Bureau of Standards sponsored this committee and its recommendations were published in a series of NBS handbooks. The committee has no legal standing, but the handbooks carried the weight of informed opinion.

The small Advisory Committee could not cope with the problems raised by the discovery of nuclear chain reactions and in Dec. 1946 the group was expanded and renamed the *National Committee on Radiation Protection.* The basic structure remains as before, with no legal status, under the sponsorship of the National Bureau of Standards.

NCRP, as it is familiarly known, has among its members and consultants many of those best informed on all phases of radiation injury and protection. As a consequence the various handbooks prepared by NCRP Subcommittees carry a considerable weight of authority. This authority has not been challenged in litigation; to do so would be a formidable task.

NCRP, which has been an active organization, has made available handbooks covering almost all phases of radiation protection. Revisions have been made at frequent intervals to keep recommendations current with the latest available information. A partly overlapping membership keeps NCRP in close touch with the deliberations of the *International Commission for Radiological Protection,* ICRP.

16.06 MPD VALUES

In setting MPD values the aim of the NCRP is to specify levels at or below which there will be no detectable signs of radiation injury. Thus if the recommended 300 mr/week for occupational exposure is not exceeded there should be no signs of radiation in-

jury at the end of a working lifetime. Similarly, a single accident resulting in an exposure dose of up to 25 r will presumably result in an undetectable effect.

Obviously, absolute, immutable MPD values are not to be expected. The values are selected after a careful analysis of all cases of human overexposure, and with due consideration to pertinent data from animal studies. As new knowledge is gained, and more delicate means of detecting radiation injury are developed, it may be necessary to revise the MPD values. In the past both the values themselves and the type of exposure limits recommended have been changed.

In 1945 the MPD was established at 100 mr per day of *X*- or γ radiation, and allowable body burdens of internal emitters were calculated from this basic figure. Later the allowable daily dose was reduced but some dose integration was allowed so that the weekly 300 mr/week could be obtained at any rate. Partial body exposures were recognized by allowing 1500 mr/week to the hands or feet alone.

Originally the MPD values were designed for the protection of the individual receiving the radiation. As the importance of genetic effects became recognized a further restriction of 5 r/year was added for workers below 30 years of age. Large numbers of people are now potentially exposed to small, non-occupational doses of radiation, and to meet this situation an MPD of 14 megaroentgens per million people up to age 30 is recommended.

The figures given show the increasing complexity of the permissible-dose structure resulting from increased knowledge of radiation effects. Still more changes are to be anticipated. The prime consideration of any safety program is the protection of all individuals potentially exposed. When only a small number of special installations are involved, over-protection can be justified to insure complete safety from overexposure. As commercial exploitation of nuclear energy develops, economic considerations enter and accurate design data must be available so that protection is adequate but not overdone.

16.07 RADIATION-SOURCE REGULATION

The exposure levels set up by the NCRP serve only as guidelines —no user of radiation sources is required to keep within them.

There are, however, an increasing number of legal restrictions governing many radiation sources.

No radioactive nuclides, except for a few small, exempt quantities, can be obtained from the United States Atomic Energy Commission except by license. The licensee must have furnished evidence of competence and the possession of instruments capable of measuring the expected radiation levels.

When the possession license is issued the licensee becomes legally bound to maintain radiation-exposure levels within bounds specified by the USAEC. These specified levels include the area in which the radioactive nuclides are used and also all routes of waste disposal, so that involuntary exposures can be minimized. Each licensee is subject to inspection and may lose his license if he is found to be in violation.

Transfer of radioactive nuclides produced by the USAEC can only be from one licensee to another, and during any transfer, all shipments must conform to regulations promulgated by the Interstate Commerce Commission. These regulations specify allowable radiation levels, methods of packaging, and labelling, and are designed to protect individuals and shipments of radiation-sensitive materials.

In addition to these Federal regulations there are frequently State and local laws or codes governing the use and disposition of radioactive materials and other sources. In most cases a simple notification of receipt of material is all that is required but more formal local authorizations may be necessary in some areas.

It might appear that in attempting to control radiation hazards an impossibly complex regulatory system has been set up. Actually this is not the case. Since most regulations follow closely the recommendations of the NCRP there is some consistency in the requirements; it is not necessary to retain legal counsel to use radioactive materials.

16.08 RADIATION SAFETY OFFICER

It is almost mandatory that an organization using high-energy radiations make one individal or group responsible for maintaining safe operating practices. Those persons actually using the radiations can seldom be relied upon to insist upon proper working conditions.

The worker is more interested in results than in safe methods of getting them, just as the motorist is more interested in arriving at his destination than in obeying intervening speed limits. Even in well-informed personnel, enthusiasm and a desire to get on with the job can readily interfere with good judgment. Since no immediate untoward symptoms follow moderate overexposure a false sense of security is readily developed.

Radiation safety officers, known by a variety of titles, came into being during the development of atomic weapons. Whatever his title, this officer is the bearer of heavy responsibilities in all phases of the use of radioactive nuclides. It is not enough to insure that the individuals for whom he is responsible do not exceed levels as set by the NCRP.

The radiation safety officer must be aware of all regulations and restrictions applying to his locality and must plan all operations to conform. He must know that each individual for whom he is responsible is qualified to use the materials requested. During the execution of the operations the safety officer must insure that the working environment is indeed safe. In the event of an accident he must direct pre-planned localization and decontamination procedures. At the end of the operation he is responsible for the proper disposal of all radioactive wastes. His responsibility does not, however, end with waste disposal. His records must be capable of demonstrating, without question, 10 or 20 years later, the actual working conditions that existed during the exposure period.

For effective operation the radiation safety officer must have authority as well as responsibility. He need not have the power to forbid a given operation, but he must be able to insist upon the methods employed. Insistence upon safe procedures may bring the radiation health officer in sharp conflict with those whom he is trying to protect, and technical information must frequently be combined with the proper mixture of tact, firmness, infinite patience, and an insensitivity to abuse.

16.09 DISTANCE, TIME, AND SHIELDING

During operations with radiation sources the radiation safety officer can reduce exposure hazards by various combinations of increased distance, decreased exposure time, and interposed shielding.

Frequently these are not mutually exclusive so that a best balance must be achieved between them. Thus increased shielding may make operations more difficult so that time and exposure are actually increased.

Potential radiation hazards are so great near isotope production facilities and high-voltage accelerators that special precautions are required. In most of these cases the structures will be specially designed and constructed. Massive concrete walls will provide shielding and establish minimum distances. Ingenious remote-control manipulators permit operations of amazing complexity to be carried on with no human access. Necessary vision is obtained through windows composed of many sheets of glass. To prevent light loss by reflections at air-glass interfaces these are assembled with thin films of special oil between them. At least part of the glass will be of special composition to resist darkening by radiation. In an alternate construction water or absorber solutions such as zinc bromide are used in place of the glass. Closed-system television systems may supplement direct vision.

Most radiation safety officers are not faced with problems of extreme radiation levels and do not need highly specialized facilities. However, the problems of maintaining proper radiation safety conditions differ only in magnitude. Distance, time, and shielding are still the methods of reducing exposure. A temporary shield of lead bricks may be used instead of a permanent concrete cell, but the principle remains the same.

16.10 MONITORING PROCEDURES

During an operation the radiation safety officer must ascertain that conditions are as planned. *Area monitoring* is in general done with portable survey meters, although permanently installed monitors are also used. The latter are particularly useful when equipped with an audible signal, since the ear is rather quick to notice a speeding up of the normal background rate.

Usually an occasional check on the hazard area is sufficient but sometimes the continued presence of a monitor is needed. Area monitoring is very apt to be inadequately done if left to the individual using the radiations. He is almost certain to become so engrossed in his work that safety considerations become secondary.

Even fixed radiation sources such as accelerators and X-ray generators must be monitored occasionally. Seemingly unimportant structural changes may weaken radiation barriers; safety devices such as door interlocks may become inoperative. With high-intensity sources dangerous levels may exist after one or two scatterings, so even small radiation leaks must be looked at with suspicion.

Personnel monitoring is the determination of the radiation dose received by the whole body or that part most heavily exposed. Film badges are almost universally used because they provide a permanent record. Where exposure rates are changing rapidly or may be high the delays inherent in film processing may be unacceptable and the film badges can then be supplemented by ionization-chamber instruments.

Pocket dosimeters are ionization chambers with built-in electroscopes and optical magnifiers. They can be read by merely looking through them at the image of the electroscope fiber on the graduated scale. Pocket dosimeters are suitable for issue to trained personnel who are able to interpret the readings in terms of necessary action.

Pocket ion chambers may be issued to personnel less well-versed in radiation safety practices. These chambers can only be read by use of an auxiliary electrometer, so that some responsible member of the radiation safety office is usually aware of the reading and can take any necessary action.

16.11 CONTAMINATION AND DECONTAMINATION

Pre-planning is an important function of the radiation safety officer. Once a safe procedure has been developed accidental variations of it must be considered. Frequently prompt action is needed at the time of an accident, and without prior study wrong decisions can easily be made. Accidents can range from serious events with dangerous radiation levels to minor incidents involving annoying quantities. *Annoying* is used intentionally: air-borne contaminants well below levels dangerous to health may ruin low level assays, and require an expensive decontamination of a counting laboratory.

Proper prompt control of ventilating systems is essential when a radioactive nuclide has accidentally been released. Protection of personnel is the first responsibility of the radiation safety officer and may require ventilation to reduce local radiation levels. Any ven-

tilation system will discharge somewhere and it is quite possible to spread contaminants over wide areas and unduly expose personnel not otherwise involved.

In most cases personnel can be promptly evacuated from the immediate area. The ventilation can then be shut off and the contamination restricted. Failure to turn off ventilation systems has resulted in some very expensive decontamination procedures.

When a building or equipment has become contaminated the decontamination program must be carefully planned. If, for example, the top layer of a concrete floor must be removed, elaborate plans must be made to control dust, so that local contamination does not become widespread.

16.12 WASTE DISPOSAL

Almost any use of radioactive nuclides will result in some waste products, which in general must be disposed of by the radiation safety organization. The most convenient disposal route is the regular municipal sewer system, but quite properly this is subject to rigid ceilings as to the amounts involved. Dilution with uncontaminated water will greatly reduce the concentration of many radioactive nuclides but the possibility of a later biological reconcentration must be kept in mind whenever the regular sewer system is used.

Disposal by storage is a useful method for short and moderately long half-life materials but is obviously out of the question for many important nuclides. If storage facilities are available a considerable amount of contaminated equipment can be reclaimed eventually when residual activity has become negligible.

Burial on land or at sea appears to be the other alternative, although there are objections to either method. Whichever method is chosen, a special disposal license must be obtained from the USAEC if their products are involved. The license will contain definite specifications as to the methods and places of burial, and all phases of the disposal operation are subject to AEC inspection.

Waste disposal from ordinary tracer operations presents few problems but enormous quantities of waste fission products will result from an expanded reactor program. It is quite possible that waste disposal may become the limiting factor in the exploitation of nuclear energy.

16.13 LEGAL IMPLICATIONS

There has been relatively little litigation involving radiation injury, but more can be anticipated as potential exposures increase. Many legal questions cannot be answered until such litigation has taken place. Much of our law depends upon precedents established and opinions handed down. Without an adequate background of precedent and opinion one can do little more than point out certain rather obvious problems that are bound to arise.

One of the most knotty problems involves the long delay between moderate overexposure and clinical signs of overexposure. Assume that a cancer, or perhaps leukemia, develops 10 to 20 years after a known radiation overexposure. In the first place, is the lesion radiogenic? At the present time there is no known way of differentiating radiogenic neoplasms from those originating spontaneously, so who is to say that a particular cancer resulted from earlier radiation?

Many problems remain even if radiogenic origin is granted. For example, how does the statute of limitations apply? One can hardly expect to escape responsibility for long-delayed injury that is known to be incapable of detection during the normal time of application of limitations.

Again, the long time-lag may bring those injured into a period of more rigid values of MPD. An individual may then be deemed overexposed by standards in vogue at the time injury is claimed, even though well within tolerance limits under the standards of the time the exposure took place.

Assume that the present indication of life-shortening by radiation exposure is definitely proved. This may lead to a compensation schedule for any exposure incurred during gainful employment, and if such compensation is instituted, safeguards will be required to prevent willful overexposure for the sake of immediate gain. Compensation rate, exposure measurements, and record keeping may well become future bargaining points.

Present evidence suggests that for some effects at least, radiation injury is cumulative. Assume then that Mr. *A* receives some radiation exposure while working for firms *B*, *C*, and *D*, and later develops a proved radiation injury. How can damages against *B*, *C*, and *D* be assessed? *D* can argue that his radiation was ineffective since the

time between it and detectable injury was too short. *B* on the other hand can maintain that his radiation would have been ineffective without contributions from *C* and *D*. This point is yet to be decided in a radiation case but will certainly come up eventually.

In any case the radiation safety organization has a grave responsibility to both management and labor to insure that proper exposure records are available. Most of the records will come from film-badge readings and if badges have not been issued there will be no permanent exposure data. Film badges are comparatively cheap and one should err on the side of needlessly issuing them even to personnel whose radiation contacts are casual.

16.14 RADIATION EXPOSURE RECORDS

The pathological consequences of small radiation overexposures require years to develop and injuries, real or imagined, will be presented only long after the event. None of the injuries produced by radiation are peculiar to it alone and consequently an accurate evaluation of the radiation history is most important.

Unimpeachable records are needed and in many cases these records will be 10–20 years old. Probably the persons originating the records will no longer be available to identify them. If available, memory about detail is apt to be faulty.

Obviously, all records of radiation exposure, area surveys, and any incidents or accidents must be carefully documented and preserved. Every entry in the record books must be initialed or otherwise marked to insure positive future identification. Standard procedures for monitoring, film processing, and instrument calibration must be established, written out in detail, and scrupulously followed.

Film badges occupy a unique position in radiation exposure records, for they are the only permanent evidence available. With proper processing and storage film badges can be kept for many years and re-evaluated at will.

Because of this long-term availability all procedures involved in film-badge dosimetry must be carefully described in detail so that exact duplication is possible. Not the least important detail is the method of identifying a given badge with a particular individual. In most establishments a good many people are working with radiation and will be on the film-badge service. Issue, processing, and

reading of the badges will be done on a large scale, and errors of identification are quite possible. The records must show in detail the methods of identification employed, so that the chance of mixup can be evaluated.

Occasionally a film badge will show a high reading, which may not be representative of the exposure to the individual. Each of these cases must be investigated to determine the reason for the high reading. If it represents an overexposure prompt steps should be taken to prevent a recurrence. If it is an artifact, this information should be entered in the records, with the explanation initialed by both the wearer and the safety officer.

It is evident from this incomplete description of a radiation safety program that radiation sources of any kind are not for casual use by the uninitiated. Misuse can readily lead to presently unobserved but eventually inescapable injury, not only to the overexposed individual but also to his progeny. It is for this reason that the use of radiation sources is so guarded by seemingly unnecessary precautions. If these precautions are heeded the full potential of these sources can be utilized with safety to those concerned.

PROBLEMS

16-1. A 1 Mev X-ray unit is located in a room which is adjacent to a corridor used for casual passage between hospital wings. Measurements in the corridor show exposure rates of 30 mr/hour when the main beam impinges directly upon the wall. What safety precautions should be instituted if machine time is expected to be about 1 hour per day?

16-2. Overcrowding requires that a receptionist's desk be placed in the corridor described in Prob. 16-1. At the same time the load on the machine rises to require 3 hours of operation per day. What restrictions should be placed on the receptionist? Should she wear a film badge?

16-3. A 1 gram source of equilibrium Ra^{226} is to be loaded into a special holder. It is estimated that during the transfer the body will be 150 cm from the source and the hands 90 cm away. "Dry runs" will be made with a dummy source to insure skill in all manipulations. How much time can be allowed for the transfer without exceeding allowable weekly doses? Will whole-body or hand exposure govern the allowable time?

16-4. A portable ionization-chamber survey meter reads exposure rates up to 50 r/hour. What size Co^{60} source will be required to calibrate this instrument if the closest approach to the source is to be 30 cm?

16-5. Calculate the radiation-dose rate in rad/week delivered by the normal K^{40} content of the body. Potassium composes 0.35 per cent of the body by weight.

16-6. An investigator desires to administer 2 μc of C^{14} to a normal human volunteer. The compound administered is presumed to distribute uniformly and to have a very low rate of excretion. Estimate the tissue dose for the first week after administration.

16-7. An ampoule containing 35 mc of Kr^{85} is broken in a laboratory 22 ft x 14 ft x 18 ft. This space is about 3 per cent of the total building volume, which houses 72 people. There are two laboratories engaged in radioactive counting. The accident, which occurred outside the hood, was discovered immediately. The building is conditioned by forced air circulation with inlet and exhaust louvers in each room. Assume a maximum tolerance value of 2×10^{-7} μc/ml of room air for continuous occupancy. As radiation safety officer outline your plan of attack.

16-8. A 1 mg needle of equilibrium Ra^{226} was lost from a clinic and presumed to be on the municipal dump. At what distance could this needle be detected with a G-M survey meter capable of responding to 0.04 mr/hr? At what distance could the needle be detected if its gamma rays were reduced to one-half by overlying shielding material?

16-9. An ampoule containing 50 mc of K^{42} as KCl in HCl was dropped on the floor and broken. Because of false economy there was no protective covering over the basic concrete floor. Room size 19 ft x 10 ft x 8 ft, other building characteristics as in Prob. 16-7. Assume a maximum tolerance value of 3×10^{-6} μc/ml of room air for continuous occupancy. As radiation safety officer outline your plan of attack.

16-10. An X-ray unit operating at 1 Mv has an output of 75 r/min at 1 meter TSD and an effective photon energy of 0.6 Mev. Calculate the thickness of a concrete wall 15 ft from the target to reduce the beam intensity to 7.5 mr/hr.

16-11. A factory using Po^{210} in the manufacture of static eliminators has an average daily waste of 60 μc. Calculate the amount of water needed to reduce the concentration to 2×10^{-6} μc/ml, which the

radiation safety officer set as the maximum to be admitted into the municipal sewer system.

16-12. A local radioisotope committee allows the administration of isotopes to human subjects in amounts that will not exceed, during the first hour, the dose rate corresponding to 30 mrad/week. Assume uniform distribution and calculate the amount of Na^{24} that can be administered to a 72 kg man under this restriction.

16-13. An 80 kg man is to receive a dose of I^{131} for diagnostic purposes. Assume that 40 per cent of the I^{131} concentrates promptly in the thyroid, estimated to weigh 22 grams. Calculate the amount of I^{131} that can be administered if the allowable tissue dose is set at 15 mrad/hour.

16-14. Assume the thyroid in Prob. 16-13 to act as a point source and calculate the gamma-ray intensity at a distance of 75 cm.

16-15. Some very uncertain animal measurements suggest that human life may be shortened about 10 days for each r of whole-body exposure. Estimate the life-shortening in a radiation worker who works at the maximum permissible level for a period of 10 years. Estimate similarly the life-shortening produced by a background intensity of 0.15 r/year.

16-16. An air sampler drawing 100 liters/min through a filter paper is run for 2 hours. The filter paper, counted in 45 per cent geometry yields 320 cpm above background, of an activity identified as P^{32}. Calculate the concentration of air-borne P^{32} and compare this to the maximum allowable concentration for continuous exposure of 1×10^{-7} μc/ml.

16-17. A 50 mg capsule of equilibrium Ra^{226} was customarily moved from a lead shield into measuring position by a blast of compressed air. The capsule jammed and broke on one trial and about half of the contents became air-borne as a fine powder. Automatic monitoring equipment shut down the ventilating equipment and sounded an alarm. Outline the activities of the radiation health officer who arrived 5 min later. Include the steps necessary to restore the room to operation.

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APPENDIX

Table 1. CONSTANTS AND CONVERSIONS *

Quantity	Symbol	Value
Velocity of light in vacuum	c	2.99792×10^{10} cm/sec
Planck's constant	h	6.6253×10^{-27} erg sec
Avogadro's number	N_0	6.0218×10^{23}/ (gram mole)
Molar volume	V_0	2.212×10^{4} cm^3/gram mole
Boltzmann constant	k	1.3801×10^{-16} ergs/°C
Electron mass	m	9.1081×10^{-28} gram 5.1876×10^{-4} amu
Electron charge	e	4.8029×10^{-10} esu 1.6021×10^{-20} emu 1.6021×10^{-19} coulombs

1 ampere	$= 6.241 \times 10^{18}$ e/sec	1 amu	$= 931.17$ Mev
1 Angstrom	$= 10^{-8}$ cm	1 gram	$= 5.6099 \times 10^{26}$ Mev
1 joule	$= 10^{7}$ ergs	1 ev	$= 1.6021 \times 10^{-12}$ ergs
1 calorie	$= 4.185$ joules	1 electron	$= 0.51098$ Mev

1 hour $= 60$ min $= 3600$ sec
1 day $= 1140$ min $= 8.64 \times 10^{4}$ sec
1 year $= 5.26 \times 10^{6}$ min $= 3.15 \times 10^{7}$ sec

Table 2. VALUES OF $e^{-0.693x}$

The tabulated values give the function in terms of x-values rather than as the true value of the exponent. Decimal points are located to the left of the left-hand tabulated value in every case.

x	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	1.00	9931	9862	9791	9727	9659	9593	9526	9461	9395
0.1	9330	9266	9202	9138	9075	9013	8950	8889	8827	8766
0.2	8705	8645	8590	8526	8467	8409	8351	8293	8236	8179
0.3	8122	8066	8011	7956	7901	7846	7792	7738	7684	7631
0.4	7579	7526	7474	7423	7371	7320	7271	7220	7170	7121
0.5	7071	7022	6974	6925	6878	6830	6783	6736	6690	6643
0.6	6597	6552	6507	6162	6417	6373	6329	6285	6242	6199
0.7	6156	6113	6071	6029	5987	5946	5905	5864	5824	5783
0.8	5744	5704	5665	5625	5586	5548	5510	5471	5434	5396
0.9	5359	5322	5285	5249	5200	5177	5141	5105	5070	5035

* From DuMond, J. W. M., and E. R. Cohen. *Rev. Mod. Phys.* **25**, 691, 1953, and *American Institute of Physics Handbook*, McGraw-Hill, New York, 1957.

x	0.0	0.1	0.2	0 3	0.4	0.5	0.6	0 7	0.8	0.9
1.0	5000	4665	4353	4061	3789	3535	3299	3078	2872	2680
2.0	2500	2333	2176	2031	1895	1768	1649	1539	1436	1340
3.0	1250	1166	1088	1015	0948	0885	0826	0770	0719	0670
4.0	0625	0584	0516	0509	0471	0412	0412	0386	0359	0336
5.0	0312	0292	0272	0254	0237	0221	0207	0193	0180	0168
6.0	0156	0146	0136	0127	0119	0111	0103	0096	0090	0084
7.0	0078	0073	0068	0064	0059	0055	0052	0048	0045	0042
8.0	0039	0036	0034	0032	0030	0028	0026	0024	0022	0021
9.0	0019	0018	0017	0016	0015	0014	0013	0012	0011	0011
10	0010									

Table 3. Characteristics of Some Radioactive Nuclides *

Z	Element	A	Half life	Emission	Max β energy, Mev (per cent)	$\bar{E}_\beta$ Mev	Gamma range Mev	Γ rhm
20	Calcium	45	164 D	β^-	0.254(100)	0.076		
		47	4.8 D	β^-,γ	1.4(40), 0.46(60)		1.3–0.15	
6	Carbon	14	5,570 Y	β^-	0.154(100)	0.049		
55	Cesium	137	30 Y	β^-,γ	1.17(8), 0.51(92)	0.23	0.662	0.32
17	Chlorine	36	3.1×10^5 Y	β^-	0.714(100)	0.24		
24	Chromium	51	27.8 D	K,γ	0.0049(100) X-ray	0.0049†	0.323	0.036
27	Cobalt	58	72 D	K,β^+,γ	0.47(15), 0.006(85) X-ray	0.035†	0.81–0.511	0.60
		60	5.3 Y	β^-,γ	0.31(100)	0.095	1.33–1.17	1.33
79	Gold	198	2.69 D	β^-,γ	0.96(99), 0.28(1)	0.33	0.68–0.41	0.23
1	Hydrogen	3	12.3 Y	β^-	0.018(100)	0.006		
53	Iodine	131	8.1 D	β^-,γ	0.81(1), 0.61(87) 0.34(9), 0.25(3)	0.19	0.72–0.08	0.22
		132	2.33 H	β^-,γ	2.1(18), 1.5(24), 1.2 (23), 0.9(20), 0.73(15)	0.5	2.2–0.52	1.2
77	Iridium	192	74.4 D	K,β^-,γ	0.67(44), 0.54(40) 0.24(16)	0.17	0.613–0.136	0.41
26	Iron	55	2.94 Y	K	0.0059(100)	0.0059		
		59	45 D	β^-,γ	0.46(54), 0.27(46)	0.12	1.29–0.191	0.62
36	Krypton	85	10.3 Y	β^-	0.695(100)			
15	Phosphorous	32	14.2 D	β^-	1.71(100)	0.69		
19	Potassium	40	1.3×10^9 Y	K,β^-,γ	1.32(91), 0.0037(9) X-ray	0.46†	1.46	0.72
		42	12.4 H	β^-,γ	3.6(82), 2.0(18)	1.5	1.5–0.31	0.15
88	Radium	226	1,620 Y	γ	As used in 0.5 mm Pt primary α and β absorbed		2.45–0.184	0.84
11	Sodium	22	2.6 Y	β^+,γ	0.54(100)	0.19	1.28–0.511	1.3
		24	15 H	β^-,γ	1.39(100)	0.55	2.75–1.37	1.9
38	Strontium	89	53 D	β^-	1.46(100)	0.56		
		90	20 Y	β^-	0.53(100)			
	and							
39	Yttrium	90	64.6 H	β^-	2.25(100)	1.0		
16	Sulphur	35	87 D	β^-	0.167(100)	0.049		

* Data taken from a variety of sources or computed by the author. Among the sources are *American Institute of Physics Handbook*, McGraw-Hill, New York, 1957 and *Radiation Dosimetry*, Hine and Brownell, Eds., Academic Press, 1956.

† In calculating $\bar{E}_\beta$ characteristic X-rays were treated as beta emissions.

Table 4. Characteristics of the Standard Man

From recommendation of the International Commission on Radiological Protection, *Brit. J. Radiol.* Supp. 6, 1955.

Total body 70 kg

Tissue	Mass, gms	Per cent
Muscle	30,000	43
Total fat	10,000	14
Bones without marrow	7,000	10
Red marrow	1,500	2.1
Yellow marrow	1,300	2.1
Blood	5,400	77
Subcutaneous tissue	4,100	5.8
Skin	2,000	2.9
Gastrointestinal tract (empty)	2,000	2.9
Liver	1,700	2.4
Brain	1,500	2.1
Lungs (total)	1,000	1.4
Lymphoid tissue	700	1.0
Kidneys (total)	300	0.43
Heart	300	0.43
Spleen	150	0.21
Urinary bladder	150	0.21
Pancreas	70	0.10
Testes (total)	40	0.057
Eyes	30	0.013
Thyroid	20	0.029
Adrenals (total)	20	0.029
Thymus	10	0.014
Miscellaneous	500	0.71

Chemical Composition

Element	Mass, gms	Per cent
Oxygen	45,500	65.0
Carbon	12,600	18.0
Hydrogen	7,000	10.0
Nitrogen	2,100	3.0
Calcium	1,050	1.5
Phosphorous	700	1.0
Sulphur	175	0.25
Potassium	140	0.2
Sodium	105	0.15
Chlorine	105	0.15
Magnesium	35	0.05
Iron	4	0.006
Copper	0.1	0.0001
Iodine	0.03	0.00004

Table 5. Biological Properties of Some Radioactive Nuclides

Element	Critical organ	* Per cent ingested reaching critical organ	* Biological half life, days
Calcium	Bone	25	∞
Carbon	Fat	50	35
Cesium	Muscle	48	17
Chlorine	Whole body	100	29
Chromium	Kidneys	0.07	110
Cobalt	Liver	0.4	8.4
Gold	Kidneys	0.24	50
Hydrogen	Whole body	100	19
Iodine	Thyroid	25	180
Iridium	Kidneys	1	23
Iron	Blood	80	65
Phosphorous	Bone	20	1,200
Potassium	Muscle	70	33
Radium	Bone	1.5	∞
Sodium	Whole body	100	29
Strontium and Yttrium	Bone	25	3,900
Sulphur	Skin	8	22

* These values may vary widely depending upon the form in which the nuclide is administered.

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