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Author Burton, E. F. and Kohl W. H.

Title Electron microscope 1946

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MAN HAS TAKEN MEASURE

Shown below is a scale of the dimensions of the universe as atom's nucleus, as the universe's inside dimension, to the dis-



ATOM'S NUCLEUS — $\frac{1}{1{,}000{,}000{,}000{,}000}$ CENTIMETER



ATOM'S OUTSIDE DIAMETER — $\frac{1}{100{,}000{,}000}$ CENTIMETER



ELECTRON MICROSCOPE'S LIMIT OF VISION — $\frac{1}{1{,}000{,}000}$ CENTIMETER

FLU VIRUS — $\frac{12}{1{,}000{,}000}$ CENTIMETER

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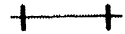


RED BLOOD CELL — $\frac{4}{1{,}000}$ CENTIMETER



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CENTIMETER



INCH



OF ATOMS AND GALAXIES

so far measured by man. It ranges from the diameter of an
tance to the farthest galaxy recorded by astronomers.



SIX-FOOT MAN — 72 INCHES



NEW YORK TO SAN FRANCISCO — 3,000 MILES



DIAMETER OF EARTH — 8,000 MILES



DIAMETER OF SUN — 864,000 MILES



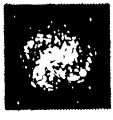
EARTH'S ORBIT DIAMETER — 186,000,000 MILES



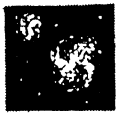
ONE LIGHT YEAR — 6,000,000,000,000 MILES



NEAREST STAR — 25,000,000,000,000 MILES



DIAMETER OF OUR GALAXY — 100,000 LIGHT YEARS



DISTANCE TO FARTHEST OBSERVED GALAXY — 300,000,000 LIGHT YEARS

Courtesy *Life* Magazine



Courtesy University of Toronto

Wing of Midge (*Chironomidae*), ×19,400. Electron microscope picture taken through the wing of a small insect called a midge or gnat. It shows structures on the wing which could never be revealed by any optical microscope. The "hairs" on the wing are distributed at the rate of over 400 million per square inch. What their function is no one at present knows.

The
ELECTRON MICROSCOPE

AN INTRODUCTION TO ITS FUNDAMENTAL PRINCIPLES AND APPLICATIONS

By

E. F. BURTON
Head of the Department of Physics
and Director of the McLennan Laboratory
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and

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Toronto

Drawings by Dorothy Stone

SECOND EDITION

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Preface to First Edition

"I was received very kindly by the warden [of the Grand Academy of Lagodo], and went for many days to the academy. Every room hath in it one or more projectors [researchers] . . . .

"The first man I saw was of a meager aspect with sooty hands and face, his hair and beard long, ragged and singed in several places. His clothes, shirt, and skin were all of the same color. He had been *eight years upon a project for extracting sunbeams out of cucumbers*, which were to be put into vials hermetically sealed, and let out to warm the air in raw, inclement summers. He told me he did not doubt, in eight years more, he should be able to supply the governor's gardens with sunshine at a reasonable rate; but he complained that his stock was low, and entreated me to give him something as an encouragement to ingenuity, especially since this had been a very dear season for cucumbers. I made him a small present. . . . . ." *Gulliver's Travels, Voyage to Laputa*, etc., Chapter V.

With the exception that sartorial and sanitary arrangements may have advanced with our civilization, there is an uncanny parallel between the "projector" of Lagodo in 1741 and the electron microscope investigators at Toronto in 1941. We have "*been eight years upon a project*" *for taking magnified pictures without light*, an investigation which is, to the modern Gulliver, no less foolish than the cucumber experiment was to the original Gulliver.

We "do not doubt, in eight years more," that there will be an electron microscope in every "project" laboratory and that it will contribute greatly to our knowledge of things as remote from each other as industry and medicine.

A third item in the parallelism is apparent, namely "that our stock is low," and we still entreat contributions "as an encouragement to ingenuity," especially since our "cucumbers" are still expensive. In spite of the fact that the electron microscope bids

fair to reveal to the eyes of man in the domain of the very minute things quite as wonderful as Galileo's telescope revealed of the wonders of space, we still have the feeling that it is ever "a dear season for cucumbers."

E. F. Burton
W. H. Kohl

Toronto, Ontario
March 1, 1942.

Acknowledgements
(from first edition)

First in the list of acknowledgements, I wish to thank my co-author, Dr. W. H. Kohl, for the great help he gave the Department of Physics of the University of Toronto, at the beginning of the work on the electron microscope. It is on account of this assistance that Dr. Kohl was the natural person to call upon for co-operation in the preparation of the present book. For many years he has been a member of the staff of the Research Laboratory of the Rogers Radio Tubes Limited at Toronto, and for the greater part of this time he has served as special lecturer at the University.

His first course of lectures was on electron optics and, as he was engaged in development work on cathode ray tubes in an industrial laboratory, he was in a position to repeat some of Brüche and Johannson's experiments on the electrostatic electron microscope and produce images of oxide cathodes which revealed helpful information on the structure of the coating. Such an electron microscope was demonstrated before the seminar of the McLennan Laboratory in April, 1934; this probably was the first such demonstration in Canada. Images of oxide cathodes produced with magnetic lenses were demonstrated during a special course of lectures on electron optics in January, 1935.

Active research work was begun in this field at the Toronto laboratory during the fall term of 1935, by C. E. Hall, who constructed a simple electrostatic electron microscope and repeated quantitative measurements of Johannson on the properties of the immersion objective. In 1937 Mr. Hall joined the research laboratory of the Eastman Kodak Company, Rochester, New York, where he continued work in this field.

In the fall of 1937 J. Hillier, B.A. (Toronto), and A. Prebus, B.A. (Alberta), undertook the construction of a high-voltage magnetic compound microscope with the aim of applying it to the

investigation of biological specimens. Their work was highly successful and was first described in the *Canadian Journal of Research* in April 1939.

In February 1940, Mr. Hillier joined the laboratories of the R.C.A. Manufacturing Company and proceeded to design, in collaboration with Mr. A. W. Vance and under the direction of Dr. V. K. Zworykin, a type of electron microscope adapted to industrial research. Mr. A. Prebus joined the Ohio State University in July 1940. To Messrs. Hall, Hillier and Prebus we are greatly indebted, and also to Professor Arnold Pitt.

The work in Toronto is now being carried on by Mr. W. E. Ladd, Dr. L. T. Newman and Mr. J. H. L. Watson, who have assisted in the construction of a second instrument.

For financial assistance and encouragement, I wish to thank very heartily the following:

The National Research Council of Canada for direct grants in aid and scholarships.

The Banting Department of Medical Research of the University of Toronto, through the interest of the late Sir Frederick Banting and his staff.

The Banting Foundation for Medical Research for grant in aid toward work on viruses being carried out with the excellent co-operation of Dr. J. Craigie of the School of Hygiene, University of Toronto.

The Columbian Carbon Company of New York City and particularly Mr. W. B. Wiegand, their Director of Research, and the members of his staff, Mr. H. A. Braendle and Dr. Carl Sweitzer; this financial aid came at a time when it was needed most. It is pleasant to recall that all three are former students of the undersigned.

The Ontario Mining Association for a grant for the study of mine dust as related to silicosis. This work was undertaken through the interest of Dr. D. A. Irwin of the Banting-Best Medical Research Department.

The President and Board of Governors of the University for sympathetic assistance at all times.

The staff of our workshop and glass blowing plant, through whose ability and energy the successful construction was made possible. Two complete instruments were entirely produced in our own shops.

E. F. Burton

Preface to Second Edition

This book addresses itself essentially to the non-technical reader who is nevertheless interested in modern techniques. It aims at presenting the physical principles upon which the operation of the electron microscope is based, without any assumptions in regard to the technical knowledge of the reader. The subject matter is such, however, that a large amount of ground must be covered and many intricate problems solved. This requires more than a superficial interest and a great deal of patience and perseverance on the part of the reader. In return, much useful knowledge may be gained, which applies to general physics and electronics. Thus it is hoped that the book will appeal not only to laymen and advanced high-school students, but also to members of various professions, in particular those in which the electron microscope has made, or promises to make, a considerable contribution in specialized research.

The second edition has been prepared at the suggestion of the publishers. The text has been re-arranged and revised in many places to attain greater coherence in the presentation of the subject matter. In this the authors are obliged to critical reviewers of the first edition for helpful criticism. The changes are too many to be enumerated here but they will be apparent from the table of contents, if this is compared with that of the first edition.

In order to indicate the aim of the book a subtitle has been added to the original title. Some material has been eliminated as being of too specialized a character for the scope of this book. This applied in particular to the detailed description of the Johannson-Brüche electrostatic electron microscope. The chapter on the history of the electron microscope has been eliminated and part of its content incorporated in other chapters. The chapters on electron optics have been enlarged and the material on electron lenses consolidated therein. The chapter on the compound magnetic electron microscope has been re-written

completely and much new material added. The description of iron-clad magnetic lenses was removed from this chapter and included in the chapter on magnetic lenses, where it properly belongs. The chapter on the applications of the electron microscope has also been largely rewritten and the plate illustrations of the accomplishments of the electron microscope are collected here. Some plates were eliminated and new ones added. A complete bibliography, prepared and published recently by Claire Marton of Stanford University and Samuel Sass of the University of Michigan, is included with the kind permission of the authors and the publishers of the *Journal of Applied Physics;* this has been added to by references to the more recent papers. In order to emphasize the importance to which the electron microscope has grown on this continent, some data have been included on the organization of the Electron Microscope Society of America.

While both authors have been handicapped in their efforts by the unusual load of pressing war work, it is hoped that this second edition will meet with some favor among those interested in this young branch of physics, which promises to grow ever stronger and yield fruit beyond the fondest expectations of pioneers in this field.

The authors wish to thank those who have taken part in the work on the electron microscope at Toronto during recent years: namely, Mrs. B. M. Deacon, Ph.D., Dr. L. T. Newman, Dr. J. H. L. Watson and Mr. S. G. Ellis, who helped considerably in the preparation of the later chapters. The 1944 Toronto microscope was constructed in our own workshop, almost entirely by Mr. Grantley Woodward.

We also wish to acknowledge with gratitude the continued assistance given by the National Research Council of Canada and also support from the Shawinigan Chemicals Limited, Shawinigan Falls, Quebec and the Imperial Oil Company, Limited, of Sarnia, Ontario.

E. F. Burton
W. H. Kohl

Toronto, Ontario
December, 1944

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Portland Cement (hydrated 18 days), ×20,000.

Chapter 1

VISION

The human eye is a wonderful optical instrument, more wonderful than any that man has ever devised. It unfolds to our mind the world that surrounds us and is the link which enables us to take a conscious part in it. But fascinating and manifold as is the scene which the naked eye presents, it does not satisfy our curiosity. We like to see things which the unaided eye cannot see, to bring far distant and ordinarily invisible stars within our view and to penetrate into the realm of the very small things, the microcosmos. For this purpose we need *artificial aids:* telescopes in the field of astronomy, and microscopes in the study of the very minute.

Whenever we interpose an artificial optical system between the eye and an object we are attempting merely to assist our eyes so as to widen their scope of vision. The eye is always the indispensable part of a sequence: object—vision aid—eye. In this book we are particularly concerned with the microscope. We must then keep in mind that it is only a link in this chain which we have just described.

Two almost self-evident conditions of vision must be recalled at the very beginning; first, an object is made visible by the light which it diffuses, scatters or reflects, and secondly, the position of the object viewed is judged to be in the direction of the line along which the light finally enters the eye. This latter circumstance lies at the basis of most optical illusions.

The Bending of Light Rays: Refraction

The following simple parlor trick illustrates quite well what happens to a beam of light as it passes from one transparent medium to another. Place a coin on the bottom of a mug and see that the coin is well enough illuminated to be seen when

viewed from above. Have an observer keep his head in such a position that he just *can't see* the coin as he peers over the edge of the mug (Fig. 1a). If, while the observer keeps his eye fixed

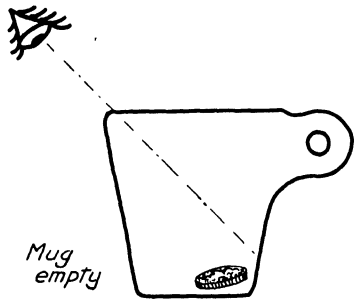


FIG. 1a.

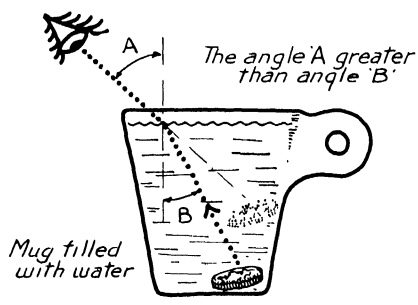


FIG. 1b.

How light bends as it passes from water to air.

in position, the mug is filled with water, the coin comes into view (Fig. 1b). The broken straight line represents the path along which the light appears to travel from the coin to the eye. But we know that the coin has not changed its position. Therefore the real path of the light from the coin to the eye must be that marked by the dotted line.

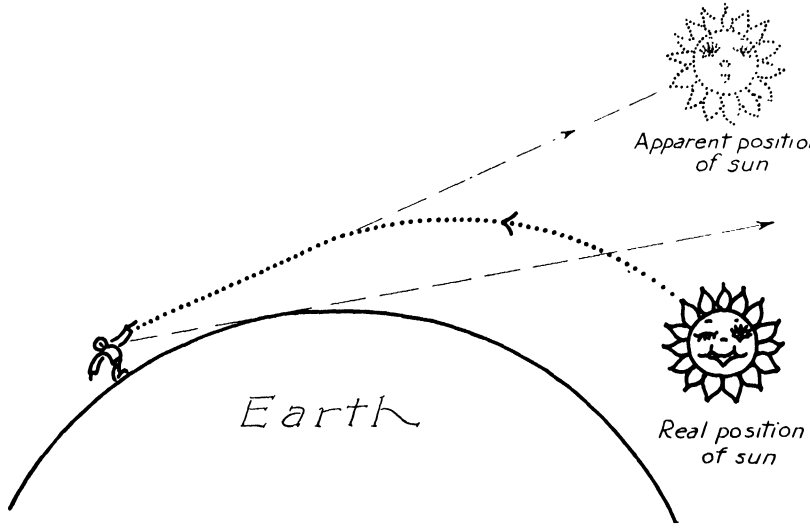


FIG. 2. How one can see the sun after it has set.

Another example of such an optical illusion, on a grand scale, is the fact that we see the sun at sunset for some considerable

time after it has really sunk below the horizon. The reason for this is that the light from the sun is gradually bent around in going through layers of the atmosphere of differing densities as shown in Fig. 2. Our judgment of the position of the sun is dictated by the direction along which the light finally enters the eye.

These two phenomena are perhaps the earliest recorded observations relating to light; they were described by Cleomedes in A.D. 50.

The Direction of Bending of a Light Beam

Very cursory examination of Fig. 1b tells us how the light bends as it passes from water to air: the angle which the emergent ray makes with the side of the mug, or rather with the perpendicular to the surface of the water, is *larger* than the angle which the ray of light from the coin makes with that perpendicular. In general, we may say that when light is going obliquely from a dense medium (water) into a less dense medium (air) it bends away farther from the normal to the surface of separation of the media.

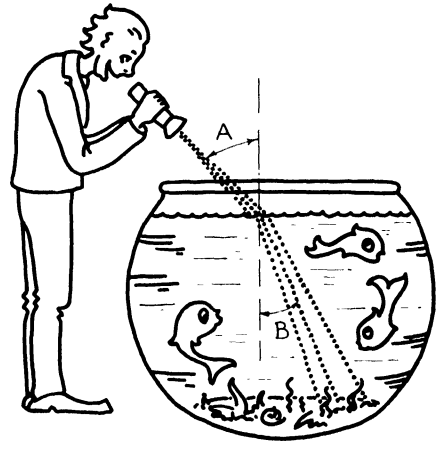


FIG. 3.

How light bends as it passes from air into water.

We can also perform the reverse experiment. If we direct a narrow beam of light, say from a flash-light, obliquely onto the surface of some slightly turbid water contained in a glass bowl,

we can see easily that, as the light goes from the air (the less dense medium) into the water (the denser medium), the direction of the ray is bent nearer to the normal to the surface (Fig. 3). This change of direction which a light beam undergoes when it passes from one transparent medium into another is described by the term *refraction.*

The Prism and the Lens

We are all familiar with effects produced by blocks of glass or automobile lamp lenses in causing a change in the direction of light passing through them. Fundamentally all such effects can be simply illustrated by tracing a ray of light through a glass prism, which is a uniform block of glass with a triangular cross-section (Fig. 4).

Consider a candle placed at the point, P, and one's eye at the point, E. If we interpose a glass prism, ABC, in our line of vision, EP, we would judge that the candle is displaced to the position Q. Light travelling along the line PE will now be turned off the track at K and will not reach the eye. The ray which

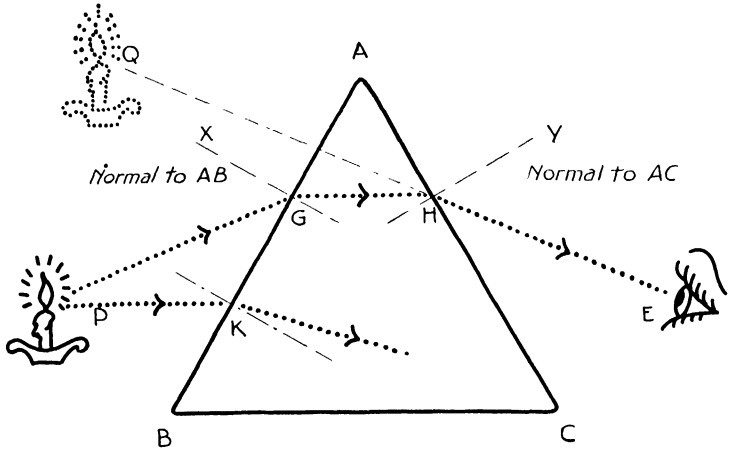


FIG. 4. How a light beam is deviated by a prism.

does reach the eye is one travelling from the candle in some such direction as PG. At the point G, as the light is passing from a rare medium (air) to a dense medium (glass) its direction of travel inside the prism makes an angle with the normal to the

surface at the point G, which will be less than the angle XGP; and then as it passes out of the glass again into the air the angle YHE will be larger than that which the ray, GH, makes with the normal to AC. The eye then judges the candle to be along the direction EHQ, which is the direction of the straight line along which the light enters the eye. The prism has thus caused a distinct change in the direction of the ray which ultimately enters the eye.

After this account of the deviation of a beam of light caused by a prism, it is easy to understand the action of a simple lens, such as a reading lens, when it is used to "focus" on a screen the image of a distant source of light or a brightly illuminated object.

It is quite common practice to interpose such a lens between a bright object, (O, Fig. 5), and a screen, e.g., one's hand, and to produce on such a screen an image as indicated at I. The position of the lens and the screen always has to be adjusted in order to obtain the position of I where the image is sharp. If the experiment is performed in a darkened room and the source is shielded

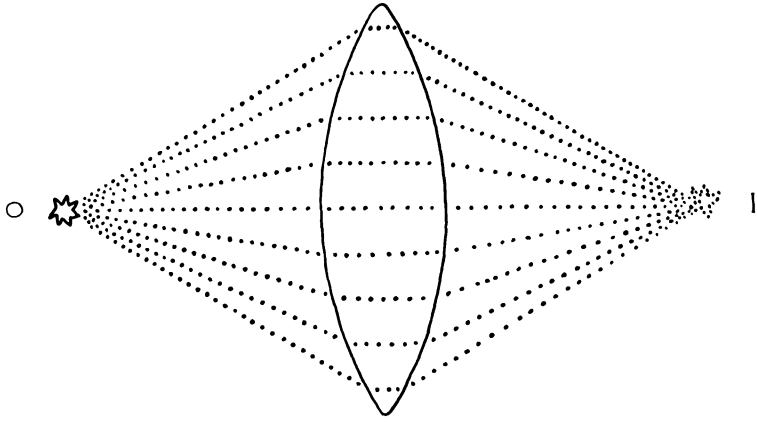


FIG. 5. How a lens bends light.

so as to send out light only in the direction of the lens, the actual path of the light from O to I can be seen, particularly if some smoke or chalk dust is blown into the region round the lens.

The reproduction at I is called the *image* of the object O, and the process of obtaining a sharp image by adjustment of the

position of the lens and screen is spoken of as *focussing* the lens.

The explanation of this action of the lens is quite clear when we realize that any lens can be considered as being built up of a great number of portions of prisms, as indicated in Fig. 6. By following the paths of rays from O through the various prism sections, it is apparent that it is quite possible for the emergent rays all to pass through the point I.

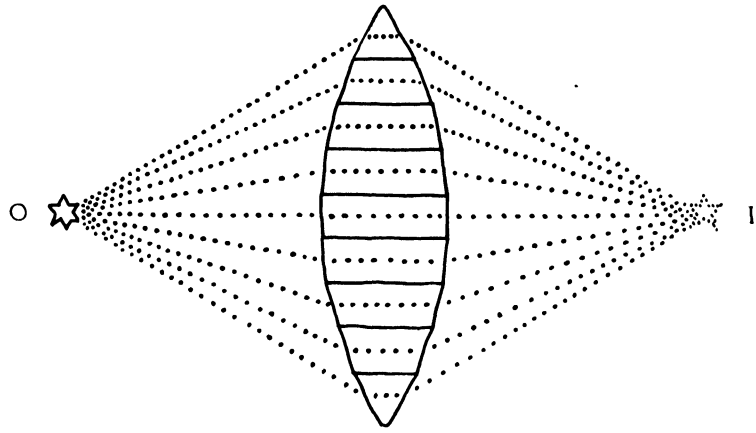


Fig. 6. How a lens may be considered as made up of sections of prisms.

The greater the number of prism sections that we put in Fig. 6, the more nearly the outline of this prism structure approximates that of the ordinary lens. The surfaces of lenses are usually spherical. We can, however, draw the path of a ray through such a lens without recourse to the prism structure.

Fig. 7 illustrates the path of a ray of light from air through a single surface of glass which has spherical curvature. The construction is made just as in Fig. 4; the normal to the glass surface, N, is along the direction of the radius of the curve.

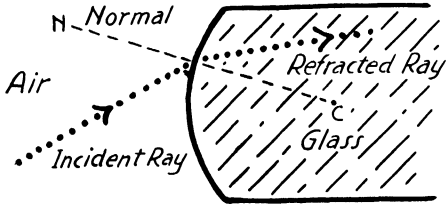


Fig. 7.
Path of ray through a single surface of glass, with spherical curvature.

Similar construction is carried through for the two curved surfaces of a lens in Fig. 8. The amount of deviation of the incident

ray, OP_1, caused by a curved surface depends on the curvature of the surface, or, in other words, on the length of the radius of the curve; for example, on the lengths of C_1P_1, and C_2P_2 in Figure 8. The shorter the radius, the greater the curvature of the surface, and the greater the deviation of the ray. This deviation fixes what is known as the power of the surface or of the lens.

Through the action of such lenses we can explain the functioning of the eye and the role played by the microscope as an aid to vision.

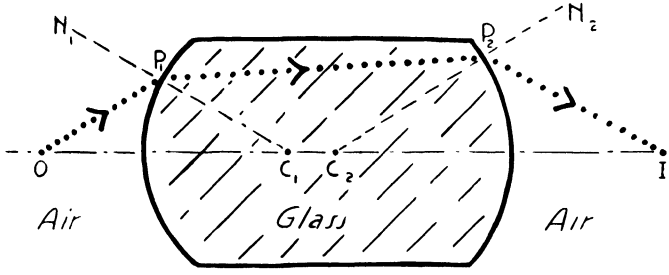


FIG. 8. Path of ray through two spherical surfaces of a lens.

The Eye

The eye is nature's camera, the prototype of all cameras. The structure and function of the various parts of the eye can be very well understood by referring to the corresponding parts of an ordinary camera.

The simplest possible form of camera is the so-called pin-hole camera—a light-tight box with a pin hole in the center of one side and a photographic plate or film placed against the inner side directly opposite the hole (Fig. 9).

If the box is turned with the pin hole toward an object, such as the animal at AD, and the hole is uncovered so as to let light into the box, an image of the animal will be impressed on the plate or film. This image will be produced in the following manner. Each part of the animal that faces the camera sends light into the pin hole, the aperture. The amount of light which is diffused by any portion of the surface of the animal depends on the natural color of the surface. Practically no light will come from black

patches and a great deal of light from white patches. Since light travels in straight lines from any surface point on the animal to the aperture, all rays will cross one another in the aperture and continue on to the photographic plate. Thus the light ray coming from a point A on the head of the animal will impinge on the film at point A′ and blacken the film according to its intensity. The distribution of light and shade at the surface of the object will thus be accurately reproduced on the film and a picture of the animal obtained on developing the film.

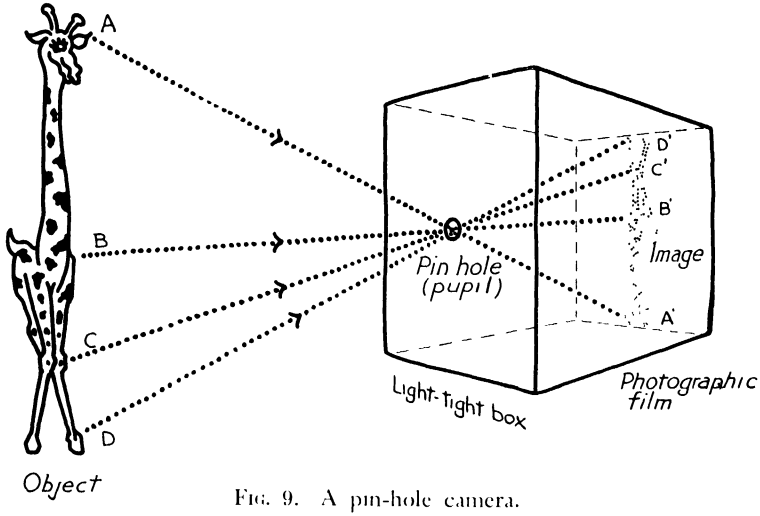


FIG. 9. A pin-hole camera.

The pin-hole camera, though interesting as a hobby and instructive as a scientific experiment, has its limitations. The amount of light entering the pin hole is so small that a long exposure is always necessary and so the use of this camera is limited to still objects. As the distance from the pin hole to the film is fixed there is no means of adjusting for variable focus, and consequently no one part of the picture is more sharply in focus than any other.

We now turn to the simple camera, which is familiar to all (Fig. 10). It consists of a light-tight box provided with a convergent lens through which the light enters, and a plate or film on which the image formed by the lens can be focussed. Since

the light-tight box is furnished with a bellows body the lens-film distance may be adjusted without letting in any extraneous light.

The advantage of such a camera over the pin-hole type is that more light from any point on the object is concentrated at the corresponding point on the image, and therefore a much smaller exposure is necessary in order to cause a definite effect on the film. It is consequently possible to take "instantaneous" exposures of moving objects.

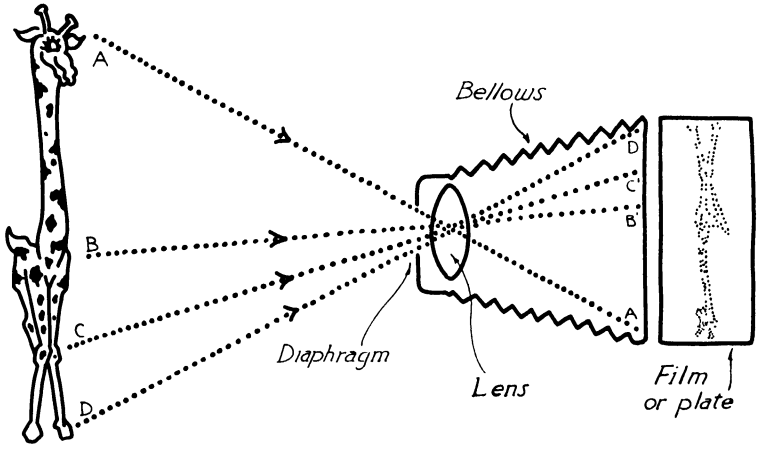


FIG. 10. An ordinary camera; at the right is a representation of what is seen in looking into the back of the box.

The functioning of the human eye may now be readily understood, at least in its basic principles, from what we have said about the working of a camera.

The eye-ball is a light-tight spherical box with a great part of the inner surface covered with a sensitive film, called the retina, from which light impressions are transferred to the brain (Fig. 11). Just as in the case of the camera, the relation between the positions of the lens, the object and the image must be adjustable in order to obtain a sharp image on a light-sensitive surface, the retina. With the eye, however, these adjustments are not made by changing the *position* of the lens but by the individual adjusting the size and shape of the lens itself, so that the image is always formed on the retina, which remains at a fixed distance from the pupil of the eye. If we wish to look at a distant object we automatically adjust the eye lens so that the image of the distant

object will be focussed on the retina; as the object comes nearer and nearer the eye lens is adjusted through muscular control until we see the object distinctly in any new position. A normal person sees with the greatest comfort when the eye is allowed to rove over distant objects and no effort is exerted to bring any particular thing into focus. When one concentrates on carefully viewing near objects, the eye tends to become tired and suffers from strain. It is impossible for the normal eye to focus on

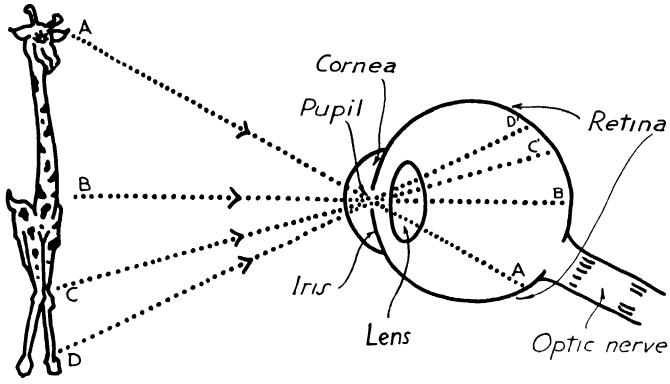


FIG. 11. How the eye forms an image.

objects nearer than about 10 inches (25 cms.). This distance is known as the least distance of distinct vision and represents a very important natural limit of vision. No matter how we try to help the eye by artificial aids, say by a microscope, we must end up with at least the illusion that we are observing the objects or images as though they were placed 10 inches from the eye.

The Scope and Limitation of the Eye

The normal eye has a very wide field of vision and a great range in distance. It will be apparent from Fig. 12 that, as the object recedes from the eye, the area of the retina covered by the image, *e.g.*, at A′B′, becomes smaller and smaller, and finally, as the distance increases very greatly, we say the object disappears. Light does not cease to come from the object, but the area of the retina affected by the light coming from the object becomes so small that, for some physiological reason, it ceases to produce a sensation of vision in the brain. It has been found that, if the

angle subtended at the eye by the object becomes less than about 1.4 minutes (about two one-hundredths of a degree), the object ceases to be distinguishable.

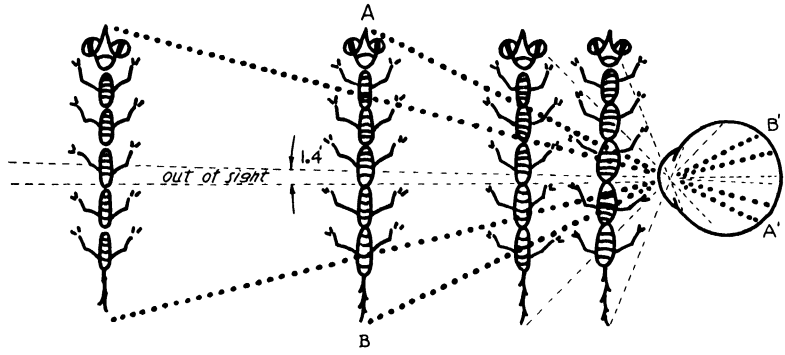


FIG. 12. How the size of the image on the retina decreases as the object is moved farther and farther from the eye.

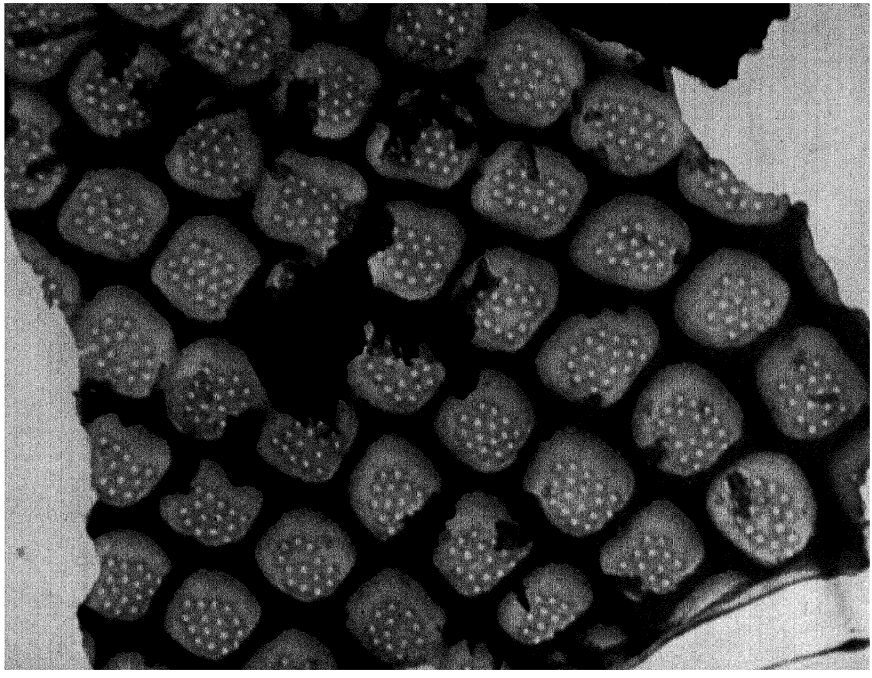
From this it follows that whether any particular object is visible to the eye or not depends on *both its size and its distance from the eye*; in any case the visibility is limited by the angle subtended at the eye (see Table 1). Of course, we take for granted that the object is always brightly enough illuminated to make vision possible within the limits just expressed.

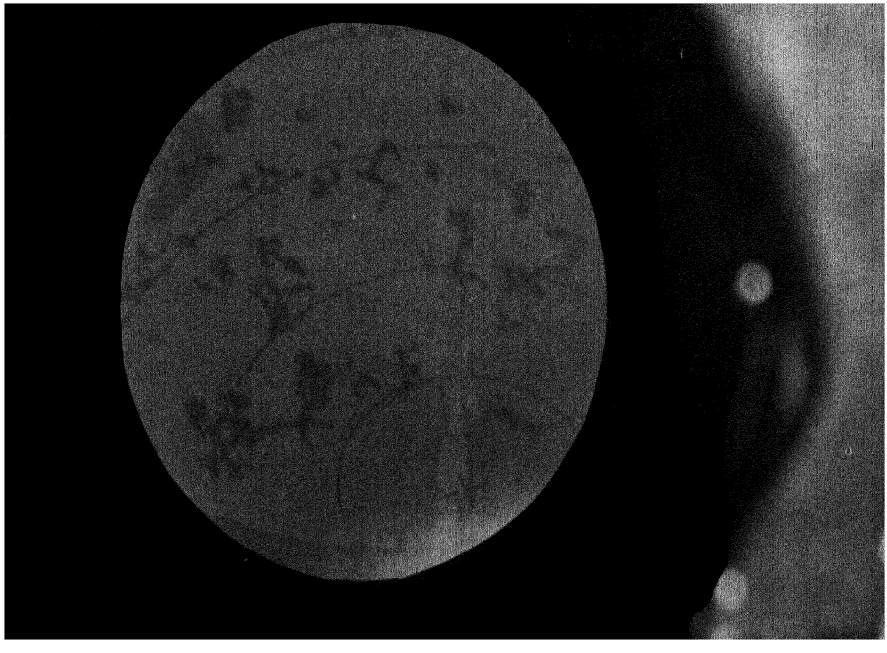
Table 1. Sizes of Objects Just Visible to the Eye at Different Distances.

Distance of Object from the Eye	Linear Dimension of Smallest Object Visible
10 miles	20 feet
1 mile	2 feet
100 yards	1 inch
10 feet	1/20 inch
10 inches	1/250 inch, 4 mils, 1/100 cm., or 1/10 mm.

Now an object may be so small that it is invisible at a distance of 10 inches from the eye; this is true if it is so small that it subtends an angle at the eye of less than 1.4 minutes. Since the eye cannot focus on anything which is closer to it than 10 inches, we must conclude that the unaided ("naked") eye cannot see any object less than 1/250th of an inch in diameter, nor can it make out any detail of any marking on a large visible object if the linear dimension of the pattern is less than 1/250th of an inch.

In this extremity we call on the *microscope* to assist the eye.





(Above) Diatom, ×36,000. The original electron micrograph was taken at a magnification of ×12,000 and afterwards enlarged in the ordinary optical manner by ×3. *Courtesy American Cyanamid Co.*

(Below) View of image of grease specimen on fluorescent screen used for final focussing, made with Toronto 1944 microscope. *Courtesy University of Toronto.*

Chapter 2

LIGHT MICROSCOPES

Aids to Defective Vision

Everyone is fairly familiar with the simplest cases of defective vision, such as short-sightedness and long-sightedness, and the means used to correct such defects. In one case, the eye is able to focus the image distinctly on the retina only when the object is held abnormally near the eye; in the other case, the object must be held abnormally far from the eye. If the position of the object is at the normal distance for distinct vision, *i.e.*, ten inches, then for such defective eyes the image is formed either in front of the retina or behind it. In either case the object is not seen distinctly (see Fig. 13).

These defects are corrected by the use of eye-glasses or spectacles; for the case illustrated in Fig. 13a the eye-glass throws

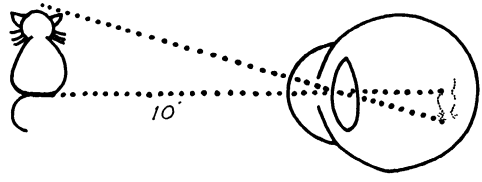


FIG. 13a. Near-sightedness.

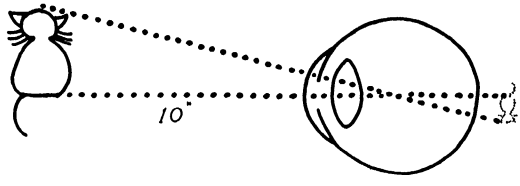


FIG. 13b. Far-sightedness.

the image farther away from the lens of the eye on to the retina (Fig. 14a), while, for that in Fig. 13b, the convergence of the

light is increased as it enters the lens of the eye and thus the image is brought back to the retina (Fig. 14b).

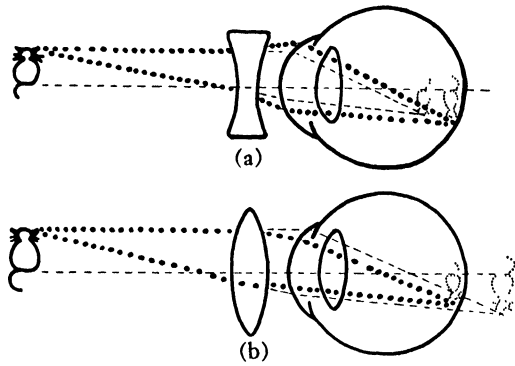


FIG. 14.
How glasses correct near- and far-sightedness.

How to Tell the Position of the Image Formed by a Single Lens

Before explaining further the operation of these aids to vision, we shall have to present a few simple rules which enable us to estimate by means of a diagram the position of images formed by any lens. Simple lenses are of two general classes, converging and diverging, depending on what happens to a beam of light falling on the lens. This can be illustrated experimentally by observing what happens to a beam of sunlight, say, admitted through a hole in a window blind, when the beam falls on the lens. A simple application of the principles described in the first chapter regarding the bending of the light ray as it goes from dense to rare or from rare to dense media will justify the representation given in Figs. 15 and 16.

In the case of the converging lens the rays parallel to the axial line XY all pass through a point F on the axis; this point

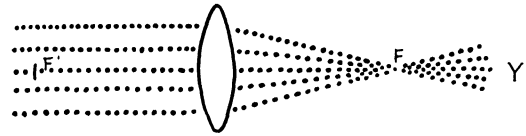


FIG. 15.
Converging Lens.

is called the *focus* of the lens. If the beam of parallel rays were sent through the lens in the opposite direction, from Y to X, there would be found a similar point, F′, on the opposite side of the lens; this is also called a focus. If the lens is symmetrically

shaped on the two sides, the distance of F from the center of the lens will be the same as the distance of F′ from the center; this distance is called the *focal length* of the lens.

Rule 1: *Every ray entering the lens parallel to the axis XY passes out through the focus F, or F′, as the case may be.*

Using a beam of sunlight, if a screen or the palm of the hand is held at the focus F, or F′, a sharp point of light will be seen—in reality an image of the hole in the window blind.

If a diverging lens is used no such image will be formed on a screen placed anywhere; but, if the eye is placed in the position represented in Figure 16, the observer will have the illusion that

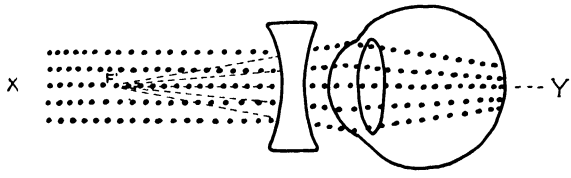


FIG. 16.
Diverging Lens.

the light seems to come from a point F′ on the side of the lens remote from the eye. This point F′ is called the focus of the diverging lens; so for this case Rule 1 becomes: *Every ray entering the lens parallel to the axis XY passes out in a direction as though it proceeded from the point F′, the focus of the lens.* As in the case of the converging lens, if the diverging lens is symmetrical as to its two sides there will also be a similar focal point on the other side of the lens at the same distance from the center of the lens as F′.

There is a second rule applicable to both kinds of lenses. Rule 2: *Every ray entering the lens at any inclination and passing through the center point of the lens will emerge with no perceptible deviation from its original direction* (Figs. 17a, 17b). This is strictly true only for very thin lenses, but it is permissible to use it when one is just approximating to the real conditions.

The two rules given above enable us to find the position of the image of any object very easily (Fig. 18). The image of A will be on the line AO produced through the lens and also along PF produced; these lines meet in the point A′ which is consequently the image of the point A. Similar procedure gives B′ as the image

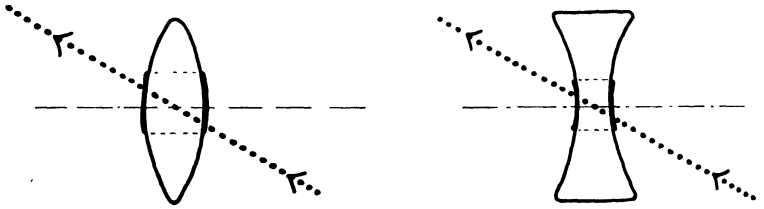


FIG. 17a. FIG. 17b.

For a thin lens the ray through the central point is not deviated perceptibly.

of B; consequently the figure A′B′ marks the image of AB, since all points on the object between A and B will produce image points in corresponding positions between A′ and B′.

It is important to note that the image A′B′ produced by the biconvex lens (Fig. 18) is inverted, both vertically and horizontally, in relation to the position of the object, AB, and that the image is larger than the object. In other words, the object has been enlarged or magnified by the lens. This principle is applied in the lantern slide projector where the enlarged image is thrown upon a screen. The slide must be inserted in the slide carrier upside down and left to right in order that the image may be presented in the proper aspect. This rule is only too frequently neglected; many a potentially first-class lecture has been spoiled by inexperienced lantern operators.

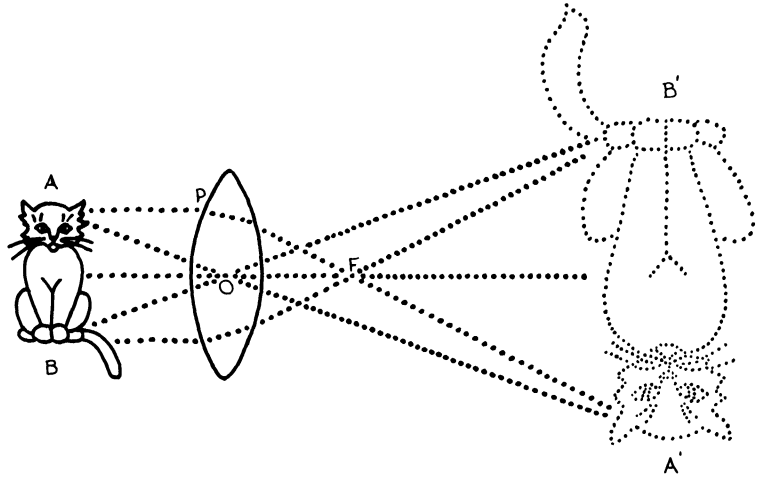


FIG. 18. How to determine graphically the position of the image of an object when using a single converging lens.

The Simple Microscope, Reading Lens or Magnifying Glass

It has been pointed out above that the unaided eye cannot see objects distinctly when they are at a distance less than 10 inches from the eye and that it ceases to perceive small objects even at the optimum distance of 10 inches when these objects are less than 1/250th of an inch in linear dimension.

It is in the latter circumstance that we call to our aid the magnifying power of lenses such as are illustrated in Fig. 18. The eye itself contains a single converging lens. Fig. 19 shows what happens to the image of an object as the object is brought closer and closer to such a lens.

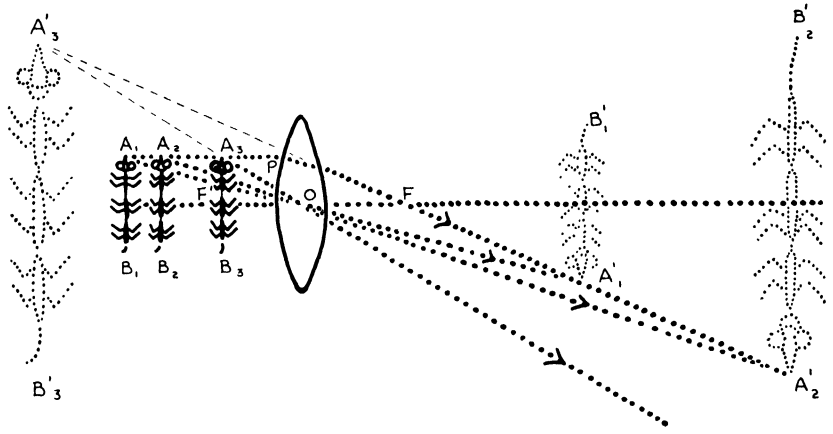


FIG. 19. How the position of the image changes as the object is moved closer and closer to a converging lens.

The ordinary rules give the positions of the images of A_1B_1 and A_2B_2 at $A'_1B'_1$ and $A'_2B'_2$ respectively. However, when we follow the two standard rays from the point A_3 of the object A_3B_3 the light emerges from the lens along the lines PF and A_3O, which never meet to the right of the lens; but if the eye is placed to the right of the lens and close to it (Fig. 20) the observer will have the impression that the light appears to come from the position $A'_3B'_3$. Thus to the eye the object is enlarged and the position of the image must be at least ten inches from the eye in order to be in focus. This shows why we have to adjust the relative positions of the eye, the lens and the object in using such

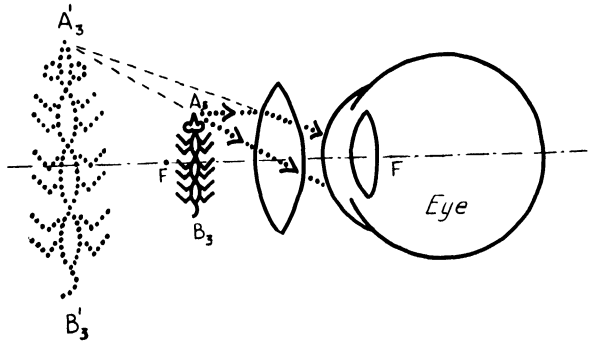


FIG. 20. How the eye sees the image.

a simple microscope. It is at once apparent that the object must be placed between the focus of the lens and the lens itself.

The Compound Microscope

The ordinary form of a compound microscope merely uses two individual lens systems to produce magnification in two stages.

There are really two fundamental forms of the compound microscope; the first is represented by a combination of two separate systems, each similar to that shown in Fig. 18, and the second by a combination of two separate systems, as shown by combining Figs. 18 and 20.

For example, we may produce an enlarged image, A′B′, of an object, AB, by a simple lens (or single lens system) as in Fig. 18 and then, using this image as a new object, produce a still larger image by a second lens, as illustrated in Fig. 21. This new image, A″B″, can be thrown on a screen or frosted glass and examined by the eye; it can also be projected on a photographic film or plate; thus we may obtain a permanent record of the enlargement. The first lens or system, L_1, is known as the *objective* and the second lens system, L_2, as the *projector*. It is apparent that the second image, A″B″, can be treated again as a new object, and a still larger image may thus be obtained by another projector lens system.

The common usage of the term *compound microscope* refers to an instrument used directly by the eye. One looks into the

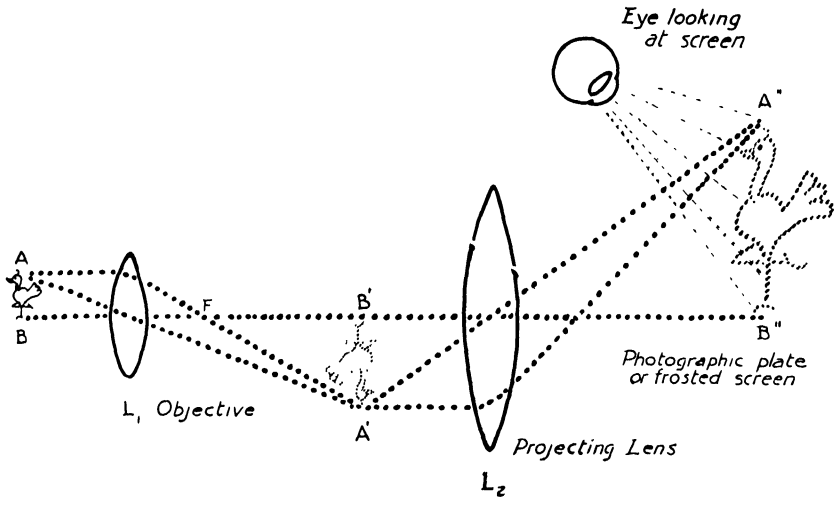


FIG. 21. A compound microscope as used to project or photograph the image.

eye-piece at the top of the instrument and sees the image. Fig. 22 shows diagrammatically the lay-out of the component lenses. The objective, L_1, forms the first image, A'B', as shown in Fig. 21. This image, A'B', now serves as the object for the eye-piece which acts merely as a simple microscope. Consequently, the right-hand portion of Fig. 22 is merely a repetition of Fig. 20, and, as described under the section on the simple microscope, the eye gets the impression that the light is proceeding from the image, A"B", at a distance of ten inches from the eye.

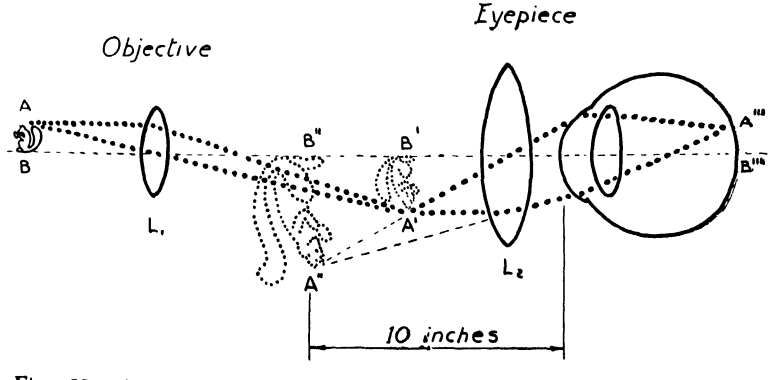


FIG. 22. An ordinary compound microscope for visual observation.

The lens of the eye gathers in the slightly diverging beam which leaves the eye-piece and focusses this beam on the retina. Of course, this same eye-piece might have been used on the image, A″B″, of Fig. 21, and the eye would have seen a final image of much greater magnification.

In fact theoretically there is no limit to the magnification that one might attain by using lens after lens after lens. However, in practice, there are limitations in construction and lighting which make a progressive magnification, ad infinitum, impossible. Some of these difficulties are noted in the next section.

Aberrations of Lenses and Lens Systems

In the preceding discussion we have tacitly assumed that all the lenses acted in an ideal fashion, that is, that the lens produced in the image a true representation of the object, point for point. But there are many ways in which actual practice falls far short of this ideal. These shortcomings are known by the general name *aberrations.*

If we look back at Figs. 5 and 18 we will find that we have assumed that light emanating from an object point is sharply focussed at a definite corresponding point in the image. But this is not so if we use only one lens. For one thing, the outer annular zone of the lens does not cause the light from a point to converge to exactly the same point as does the central zone; this defect of the lens is known as *spherical aberration.* Again, if we use ordinary white light, which as we know is just a mixture of light of different colors, we find that the different colors do not all converge to the same point. As a result the images are fringed with color—a defect known as *chromatic aberration.*

These are only two of the shortcomings of lenses. In order to overcome such defects, it is necessary to use a system of several individual lenses of differing shapes and made of different kinds of glass, instead of one single lens, as indicated in our figures. It would be quite beyond the scope of this book to deal at all fully with the subject of aberrations and their corrections. In fact, no matter how elaborate the system of lenses which makes up the

objective or the eye-piece of an ordinary compound microscope, we may treat each system as equivalent to a single converging lens as far as our present needs require. But we must remember that striving for perfection in the reproduction of an object introduces complexity into the optical systems *in theory* as well as *in practice;* attempts to produce a theoretically perfect microscope add greatly to the cost of a fine instrument.

The Resolving Power of a Microscope

The purpose of any microscope may be looked upon as *either* to enable us to see objects so small that they cannot be distinguished by the naked eye *or* to show us the finest detail in a large object. These two features really amount to the same thing, because if a small detail, (Fig. 23), is visible in a microscope it is because two points, which are separated by a distance equal to A-B on the object, can be distinguished as *separate* points. We have seen that for the unaided eye this limiting distance is about 1/250th of an inch. The limiting distance for any given microscope is known as its *resolving power.*

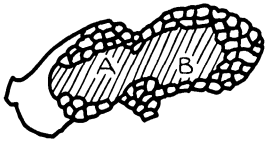




FIG. 23.

Separation of points and linear dimensions of objects as involved in discussion of resolving power.

Whether any two neighboring points on an object can be seen separated in the image given by any compound microscope depends on the objective alone. If they are not separated in the image formed by the objective, no amount of additional magnification by a projecting lens or by eye-pieces will ever succeed in separating them. This is illustrated in the series of photographs in the plate on page 38. Fig. A is the photograph of the image of a diatom shell with an initial magnification ×240; Figs. C and E are successive enlargements of A, *i.e.*, ×480 and ×960 respectively. It is quite apparent that little really new comes out with the successive enlargements. On the other hand if different objectives are used, which give successively better and better

resolving power, we obtain the results shown on page 38, Figs. D, F and G. The actual magnifications in the latter series of figures are ×420, ×900 and ×900 respectively. Fig. B has a magnification about ×100, and the smallest resolving power.

We may now ask, "What is the closest distance by which two points can be separated and still appear as separate in the image?"

The Phenomenon of Diffraction

In order to answer the last question it is necessary for us to speak of the nature of light. Up to the present we have been content to represent rays of light by means of straight lines and to follow the direction of the light by the path indicated by these

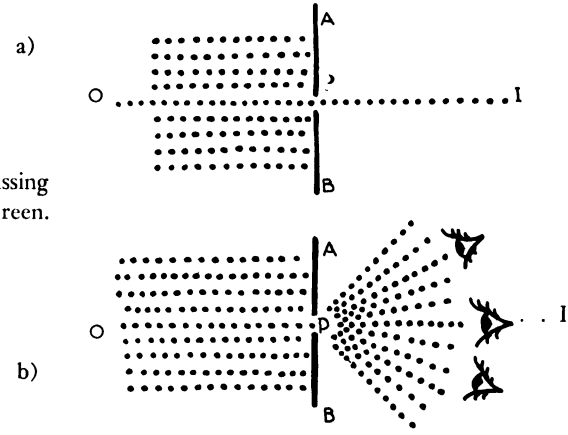


FIG. 24.

How light spreads on passing through a small hole in a screen.

lines or rays. In other words we have tacitly assumed that light travels along straight lines in any homogeneous medium as though it consisted of luminous particles shot out from the source. This theory of light is known as the *corpuscular theory*. If we followed this reasoning, we would judge that there could be no limit to the minuteness of detail in any object which we might be able to resolve and magnify, as long as the light particles are assumed to be infinitely small.

We have already applied the principle of the corpuscular theory in the presentation of the simplest image formation by

means of a single lens (Fig. 5). In this figure we represented an ideal point, I, on the image, as corresponding to an ideal point, O, on the object. This linear representation, which connects object points with image points by straight lines, does not always give a true picture of observed effects.

If we let a wide beam of parallel light rays fall upon a screen (AB, Fig. 24a) which has a small hole at P, we should expect a bright beam to emerge from P in the direction OPI, in such a manner that an observer's eye placed above or below the line PI would not receive any light from O. Actually this is not the case. An observer placed above or below PI does receive light from O (Fig. 24b). The orifice, P, behaves as though it had become a source of light itself, sending out a luminous cone toward the right of the screen.

This is an example of the phenomenon called *diffraction*—an expression which means that light has the property of being able to bend around corners or obstacles and so does not travel exactly in straight lines throughout its course in any one medium, for example, in air.

This phenomenon of diffraction of light has a very important effect on the formation of images by lenses. If a small hole in a screen, S_1, is illuminated from the left (Fig. 25) and used as an object point for a lens, L, the image formed at the point, I, on a second screen, S_2, will not be merely a sharp point of light but a

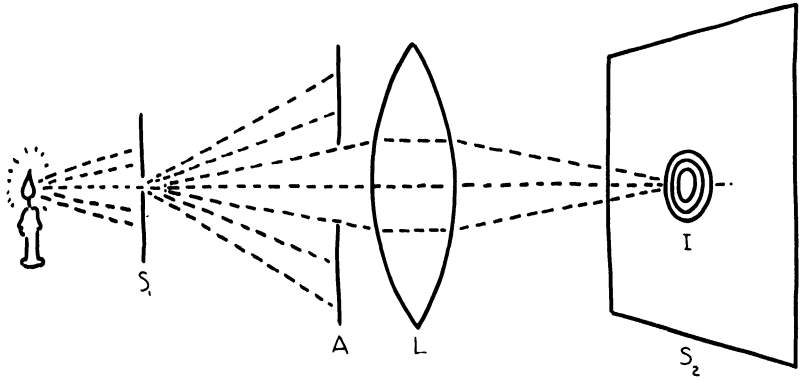


FIG. 25. The spurious disk or anti-point.

regular pattern as shown—a bright central disk surrounded by alternate dark and bright rings. This experiment is best carried out by using an aperture stop, A, so that only the central part of the lens is used. If one uses a telescope to view the image given by the lens, L, quite a number of rings can be observed and easily photographed. Such a ring image of a point source came to be known to microscopists as a *spurious disk* or *anti-point*. By no amount of manipulation can one get rid of this departure from an ideal image point.

If, instead of considering the object point as a bright point of light, we look at a small particle through a system of lenses, we observe in the image the converse of the image shown on the screen in Fig. 25, that is, a dark central disk surrounded by a series of alternate bright and dark bands. Now if we imagine a second small particle at O′ very near to the original particle at O, and just above it, the image pattern of the two points is as depicted in Fig. 26. The spurious disk images may overlap to such an

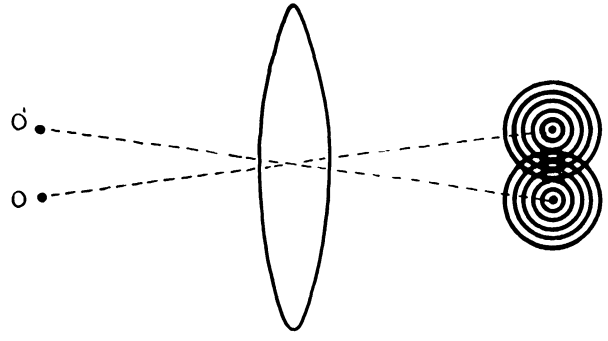
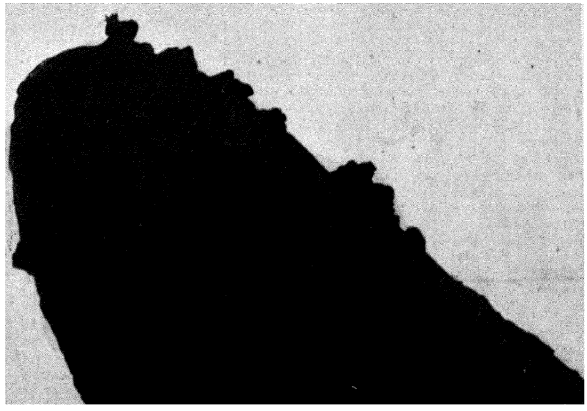


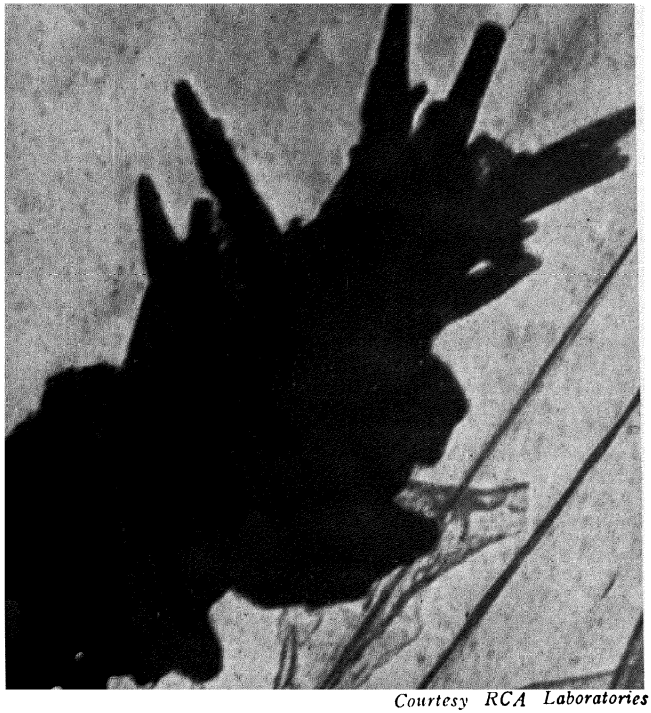
FIG. 26. Overlapping of the images of two neighboring object points.

extent that it becomes difficult to determine that there really are *two particles* in view. In such a case we say that the two particles in the object are not resolved. The critical problem is, "How close together can O and O′ be and still be distinguishable as two separate points in the image?"



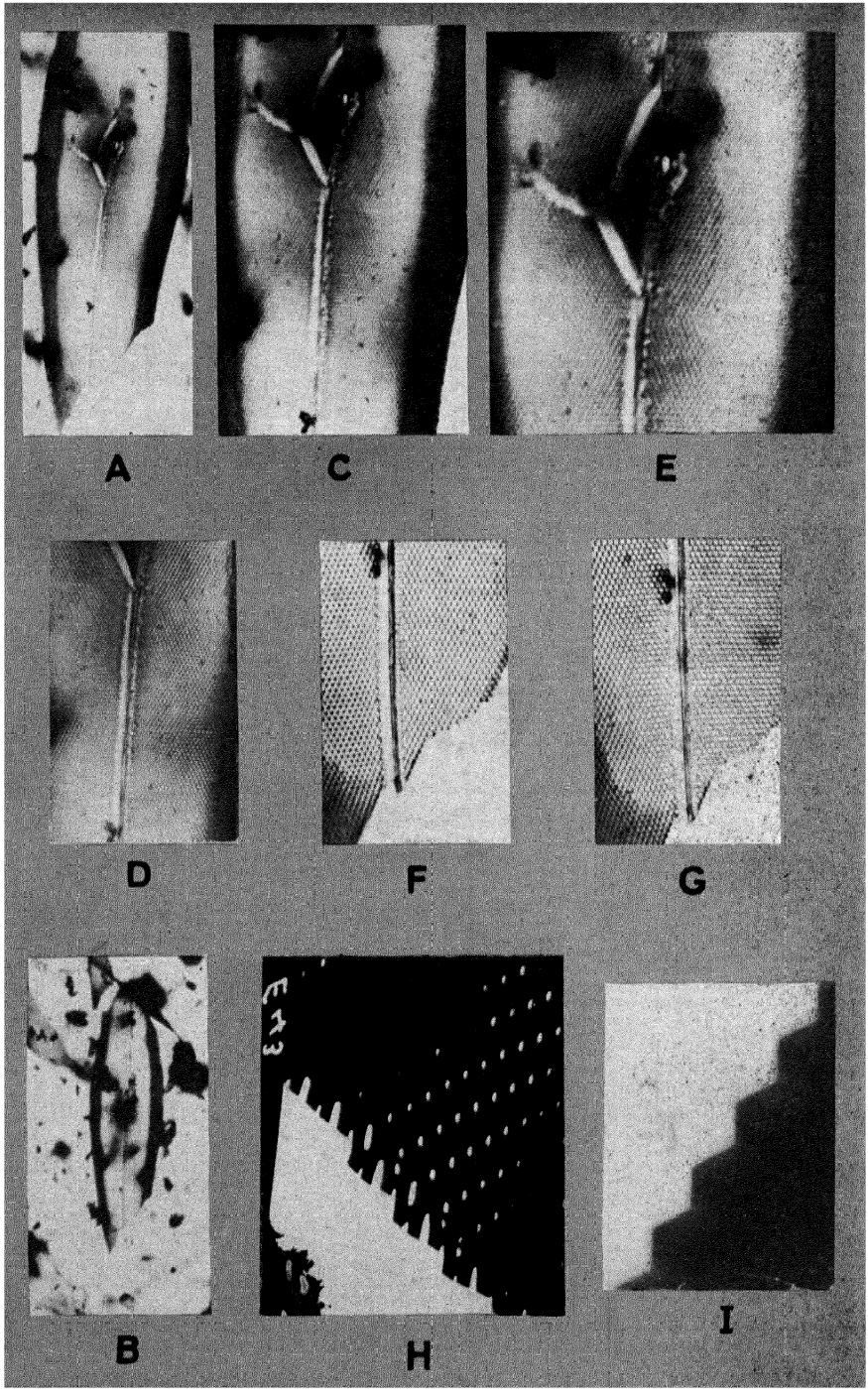
Courtesy University of Toronto

Tip of a cat's whisker magnified 4,600 times.



Courtesy RCA Laboratories

Face powder particle magnified 47,800 times.


A
C
E
D
F
G
B
H
I

Explanation of plate on page 38

The plate is arranged to show the relation of magnification to resolving power, which depends on the numerical aperture (N.A.) of a microscope. All the pictures are of portions of the shell of a species of diatom, *Pleurosigma angulatum.*

A to **G** are optical (light) microscope pictures.

H and **I** are electron microscope pictures.

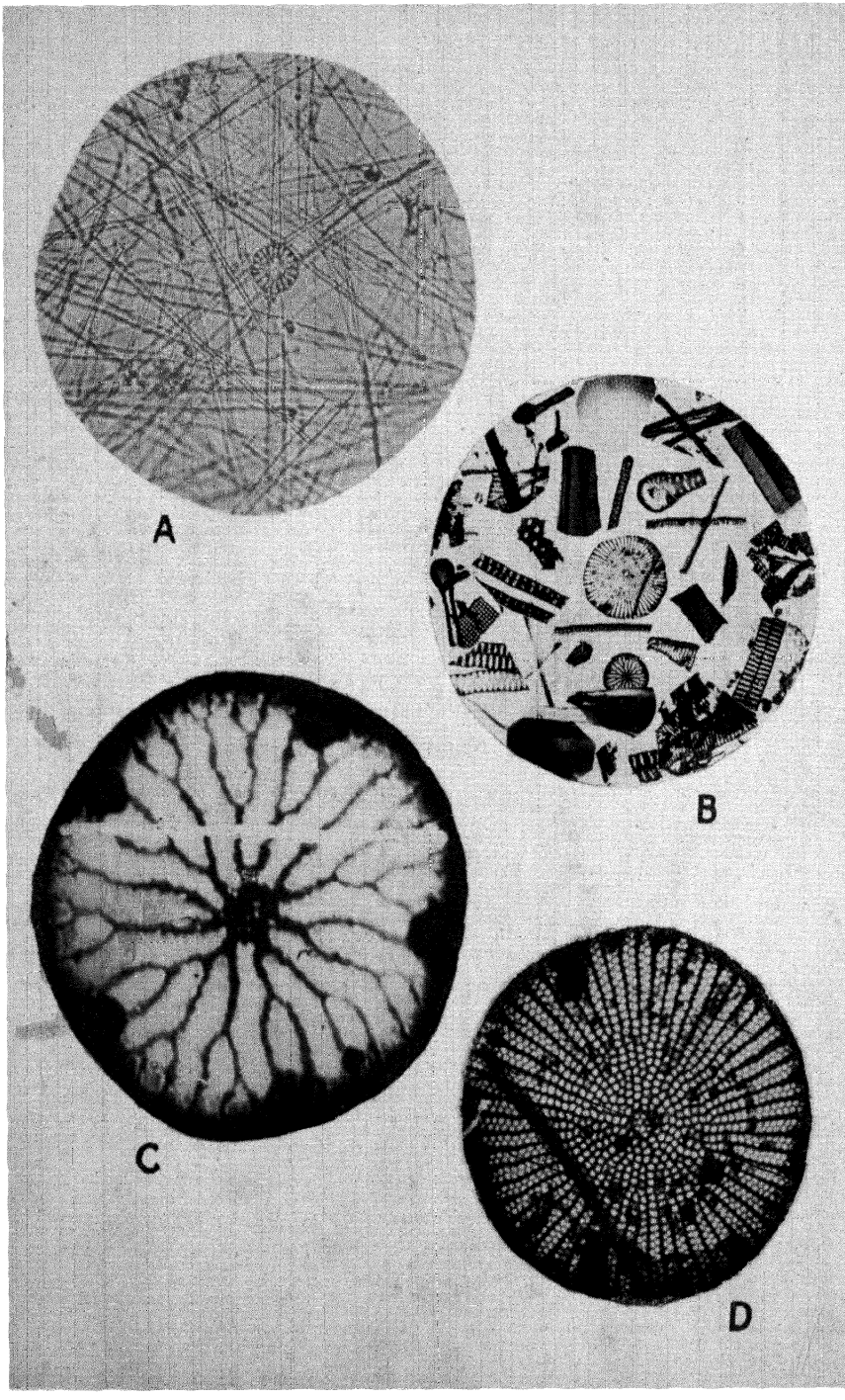
B is taken with N.A. equal to 0.5, magnification ×100.

A, C, and **E** were each taken with the N.A. equal to 0.75 but with magnifications ×240, ×480, and ×960, respectively; there is not much increase in detail visible as the magnification increases.

D, F, and **G** were taken with progressively greater N.A., *viz.*, 0.85, 1.00, and 1.25, respectively, and with magnifications: ×420, ×900, and ×900. The detail is progressively better as the N.A. is increased.

H is an electron microscope picture with magnification about ×5,000. This shows the real position of the holes in the shell. **I** is a broken edge of the shell of about the same magnification as **H.**

The optical microscope pictures were taken by Dr. D. H. Hamly of the Department of Botany, University of Toronto.


A
B
C
D

Explanation of plate on page 40

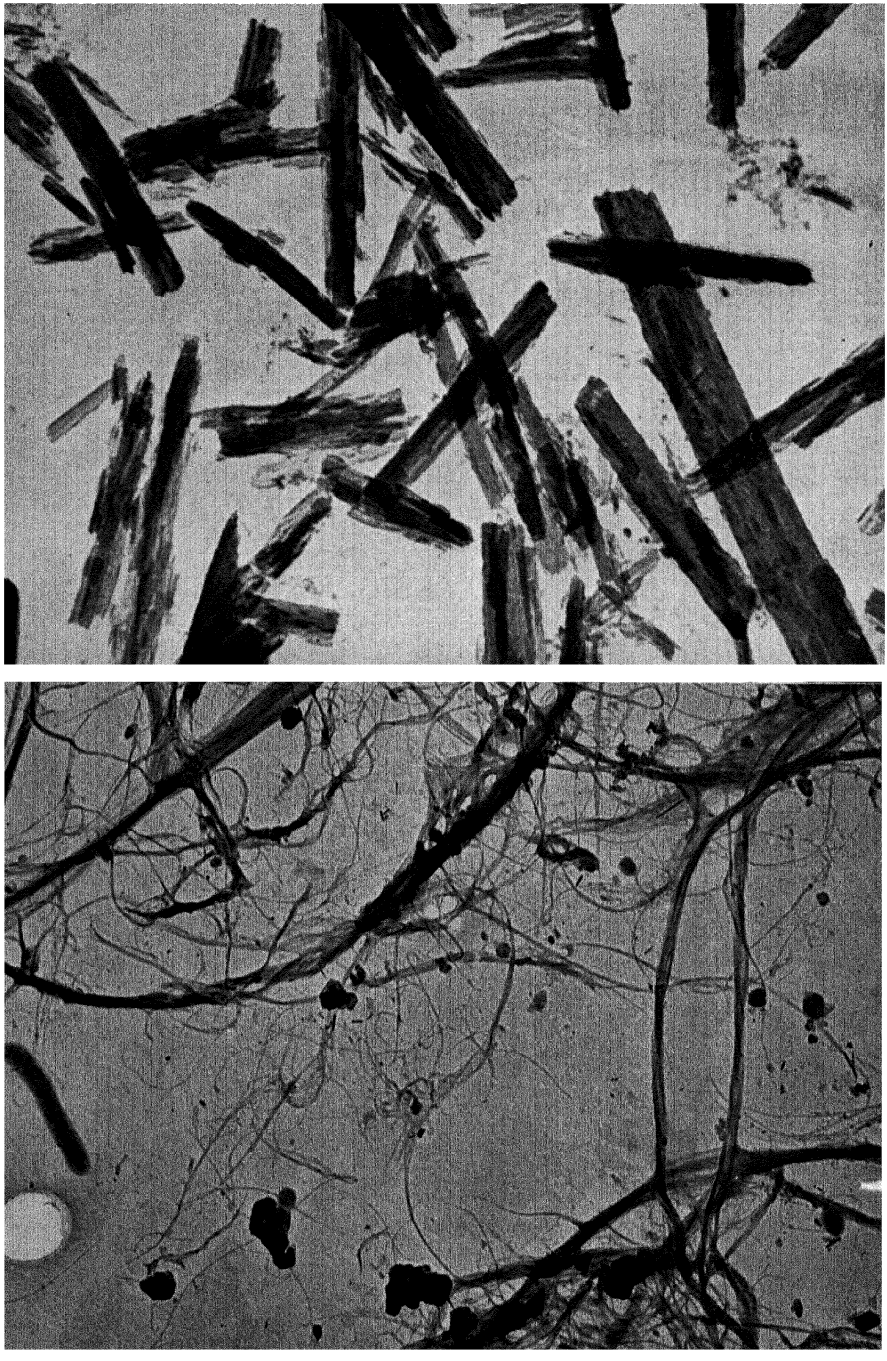
This plate reproduces pictures of various kinds of diatoms.

A is an optical photograph (by Dr. L. T. Newman) of a selected specimen of the type *Synedra delicatissima* kindly supplied by Dr. Paul S. Conger of Washington, D. C. Note that there is an odd circular type of diatom quite foreign to the others. The magnification is ×2,000.

B is a made-up slide showing a random collection of electron microscope pictures of various types of diatoms found in a random sample of diatomaceous earth. The elongated ladder-like structures are similar to those types shown in **A.**

C is an electron microscope picture of the diatom type, *Cyclotella sp.*, magnification ×25,000.

D is an electron microscope picture of the diatom type, *Cyclotella sp.*, magnification, ×5,000.



Courtesy American Cyanamid Co.

(Above) Organic Dye Crystals, ×21,000. The original magnification of the electron micrograph was ×7,000 and it was enlarged to an additional magnification of ×3.

(Below) Kraft Pulp from Paper Beater, ×10,500. The original magnification of the electron micrograph was ×3,500, enlarged ×3.

Chapter 3

WHAT IS LIGHT?

The Meaning of a Scientific Theory

In the preceding chapter we have given some answers to the question, "What does light do?" The present chapter will deal with the more difficult question, "What is light?"

The mere act of formulating these two questions suggests the existence of two phases of scientific development. In the first phase man has learned how to make use of the forces of nature for his own comfort and satisfaction; he may be content with this. But there have always lived some men who have tried to answer the second question, "What *is* the natural force that I am making use of?" So we find in the study of science, on the one hand the engineering trend, and on the other the theorizing and philosophical trend.

The formation of a theory, which is the answer to the latter question, requires a critical review of all known experimental facts relating to the particular natural phenomenon. The acceptability of any theory depends on whether or not we are satisfied in our minds with the picture we form to explain the facts.

However, we should first inquire, "What do we mean by *a scientific theory?*"

We have many natural phenomena to theorize about. What is heat? What is sound? What is light? What is gravitation? In each case we try to conceive in our minds a mechanical model which will produce the observed effect.

What do we mean by a mechanical model? We play around with various machines and gadgets which do things for us. We know the forces involved in springs; we experience the pulls in a tug-of-war; we are familiar with the flow of liquids through pipes; the intricate motions of tennis balls, baseballs, and golf balls

are matters of everyday experience. So when we come to account for such an intangible, nebulous thing as, for example, heat, which we say "flows" from one place to another in material bodies, we try to imagine *what* is flowing. The earliest theory or model of heat was the picture of an imponderable, invisible, elusive fluid, known by the name, *caloric*, which was supposed to flow from a hot body to a colder body. No experiment was ever devised which could really make such a fluid evident to our senses. Of course, everyone now says, "Heat is a mode of motion," by which we mean that we think we have a more satisfactory mechanical model for heat; we say that "heat possessed by a piece of matter is the sum total of the energy of motion of the molecules, and when heat is transferred from one place to another, fast-moving particles are communicating their motion to slower-moving molecules and make the latter move more quickly." In our first rough picture we imagine that these particles act like swarms of minute tennis balls, colliding and bouncing back in a random manner.

Our judgment as to what is a *true theory* is merely our answer to the question, "Which is the most satisfactory mechanical model which will best foretell experimental results?"

We cannot say that any scientific theory is *true* or *false*; we decide merely which mechanical model is experimentally the most satisfactory. This is the sense in which we shall speak of a *theory*.

Theories of Light in Ancient Times

During the earliest period of recorded human speculation about the nature of light very few optical facts were known. People saw with their eyes the things around them and a few inquisitive minds wondered how the process of vision came about. The early Greek philosophers attempted explanations of the phenomenon of light, but their experimental knowledge was confined to three facts (1) transmission of light in straight lines, (2) reflection from smooth polished surfaces, and (3) bending of light by refraction in passing from one medium to another.

Pythagoras (582-497 B.C.) taught that vision was caused by particles continually projected from the surfaces of visible objects

into the pupil of the eye. The teaching of Plato (427-347 B.C.) was rather more elaborate; he held that vision was brought about by the union or interaction of something emitted from the eye itself and something else emanating from the object. Plato's model was threefold; a stream of divine fire emitted by the eye became united with an influence coming from the sun and this combination reacted with a third emanation from the object and so accomplished vision. The simpler Pythagorean idea survives today in what is known as the *corpuscular theory* of light.

Aristotle (384-322 B.C.) discarded these emission theories of light and substituted for them what might be looked upon as a nebulous forecast of the modern *wave theory*; he maintained that light was merely a quality of, or action in, a space-filling medium which he called the *pellucid*—the forerunner of the modern ether.

Modern Theories: Corpuscular Theory and Wave Theory

Little would be gained by trying to unravel the intricacies of the theories regarding light down through the ages. The outburst of experimental science beginning in the sixteenth century revealed in the course of one century many of the fundamental properties of light and laid the foundations of all future work in this field.

In 1608 the first telescope of which there is a published account was constructed by a Belgian spectacle-maker, Hans Lippershey. One year later, using this as a starting point, Galileo built a telescope of such perfection that he was able to see, for the first time in human experience, the satellites of Jupiter; this opened a new field to the astronomer.

In 1621, Willebrod Snell, a Dutch scientist, discovered the laws governing the refraction of light, the phenomenon illustrated in Figs. 2 to 5. These laws enable us to foretell the amount of bending which a light ray undergoes as it passes from one medium to another.

In 1675, Olaf Roemer, a Dane, discovered that light is propagated through space at a finite, though very large, velocity and not instantaneously, as previously supposed. He made this discovery by observing that the times of the eclipses of the satellites

of Jupiter did not show the regularity that one would have expected. He accounted for this irregularity by assuming that the differences were due to the fact that the light took a longer or shorter time to come from Jupiter to the earth as the distance between these two planets changed due to their individual rotations about the sun (Fig. 27). He found that this anomaly was completely accounted for if one assumes that light travels through space at the rate of 192,000 miles per second—the first experimental determination of this important quantity.

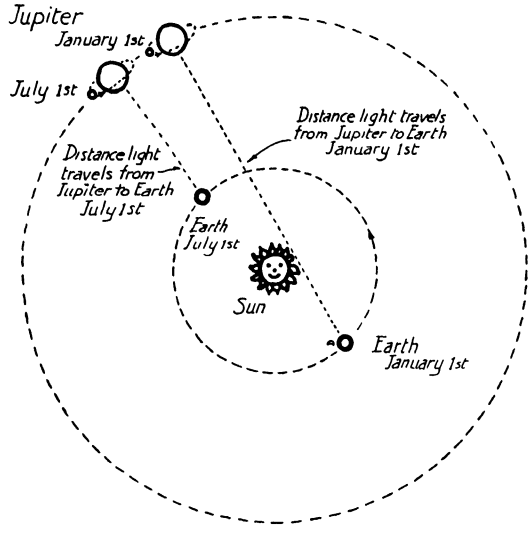


FIG. 27.

Roemer's determination of the velocity of light.

About the same time (1672) Sir Isaac Newton made the remarkable discovery that ordinary white light, such as sunlight or light from an incandescent solid, is broken up by a prism into many colored components, giving the colors of the so-called spectrum—a distribution of colors already familiar in the rainbow; in fact this discovery of Newton's at once offered an explanation of the formation of rainbows.

To complete the contributions of this wonderful century of progress we record that in 1690 Christian Huyghens, a Hollander, observed that the natural crystal, Iceland spar, could break up a single beam of light sent through it into two parts, which travelled through the crystal in different directions. This discovery revealed the phenomenon which we call polarization of light, a property of light which has become a matter of every-

day knowledge since the invention of Polaroid. This material consists of a very thin film of an organic substance made up of long-chain molecules. The film is mounted in a frame on a glass disk. By a special process the molecules are lined up like fibre layers with their long axes parallel to one another. The effect of polarization can be demonstrated by passing light through two of these disks in succession. If the molecules in the first disk are parallel to the molecules in the second, most of the light will pass through both disks. If the second disk is then turned in its own plane through 90° with respect to the first disk, no light will emerge from the second disk. A further rotation of 90° in the same direction will then allow the light to pass through as before.

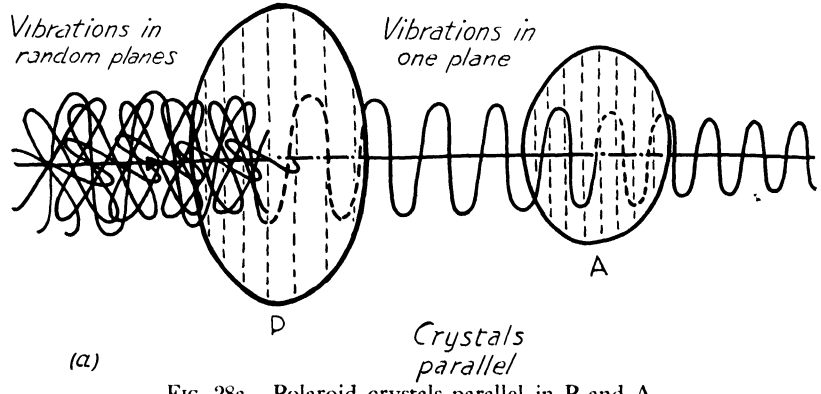


FIG. 28a. Polaroid crystals parallel in P and A.

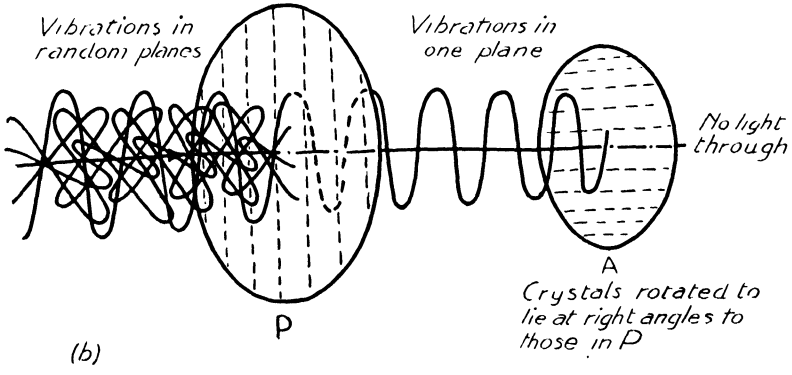


FIG. 28b. Polaroid crystals in A at right angles to those in P.

The construction of a theory which would be able to explain satisfactorily all these phenomena was a much more difficult task

than that which had confronted the Greek philosophers. It is small wonder then that many different theories, upheld by different schools of thought, co-existed for long periods of time.

In Huyghens' and Newton's time two opposing theories existed; these were known as the wave theory of Huyghens and the corpuscular theory of Newton. On close examination of Newton's own statements it will be found that his theory was the more general one and that it left room for both the corpuscular and the wave concept.

In so far as light is a transmission of energy through space we would be justified in accepting a *corpuscular theory*, according to which a light source shoots out in all directions fine particles or corpuscles which enter our eyes and affect the retina (Fig. 29).

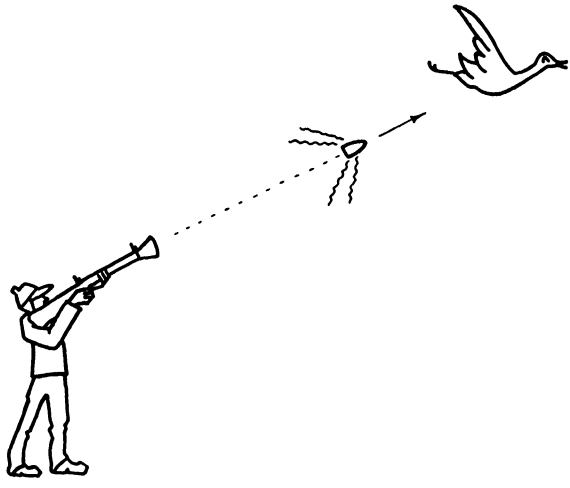


FIG. 29. The transmission of energy through space by a moving mass.

But there is a way in which energy can be transmitted through space without the actual transmission through space of any particles or corpuscles. One of the experiments in physics which almost every child performs illustrates this fact (Fig. 30). A row of dominoes, each standing on end and near its neighbor, can be arranged in any fantastic figure and, when one end domino is toppled over, a pulse of falling dominoes passes along the line. The motion, and therefore the energy, is transmitted through space, but matter is not transferred from the starting

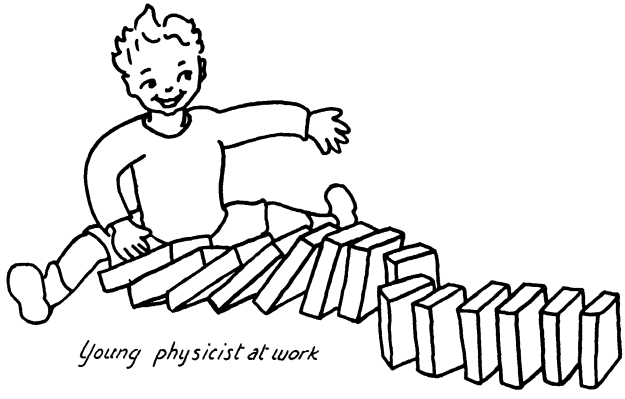
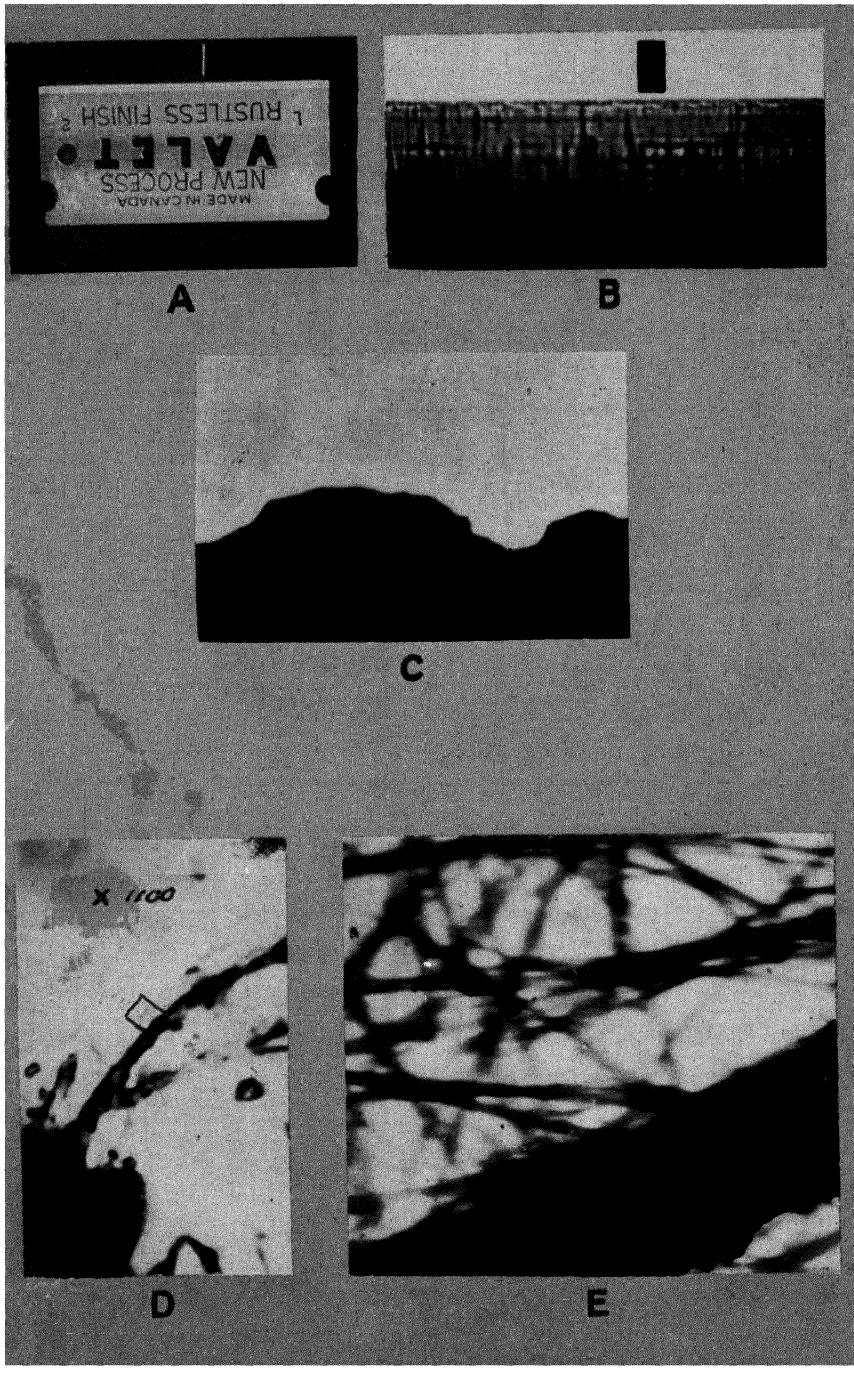


FIG. 30. The transmission of energy through space without the transfer of any mass.

point to the end point. Similar, but more far-reaching, phenomena are observed in the waves on the surface of water. These waves are caused by the winds disturbing the equilibrium of a quiet, flat surface, and we know from the destructiveness of violent storms that these waves carry along enormous amounts of energy. But if we toss a stick on the surface at any point we see that it is not carried along by the wave motion but merely bobs up and down close to the point where it was thrown in. From this we gather that the water itself is not carried along with the wave motion, and that consequently, energy alone must be transmitted.

We may say then that, as far as light is merely a transmission of energy, we would be justified in accepting a *wave theory*: that a light source initiates a vibrational motion in some medium, and that energy is carried along without the passage of material particles along the line of the motion.

Although we have outlined above the approaches to a solution we are still not very convinced that we can answer the question, "What is Light?"


VALET
NEW PROCESS
A
B
C
X 1100
D
E

Explanation of plate on page 50

This plate also shows the comparison between pictures taken with the light microscope and the electron microscope.

A. Normal picture of a new razor blade.

B. Light microscope picture of small portion of the same with magnification $\times 315$.

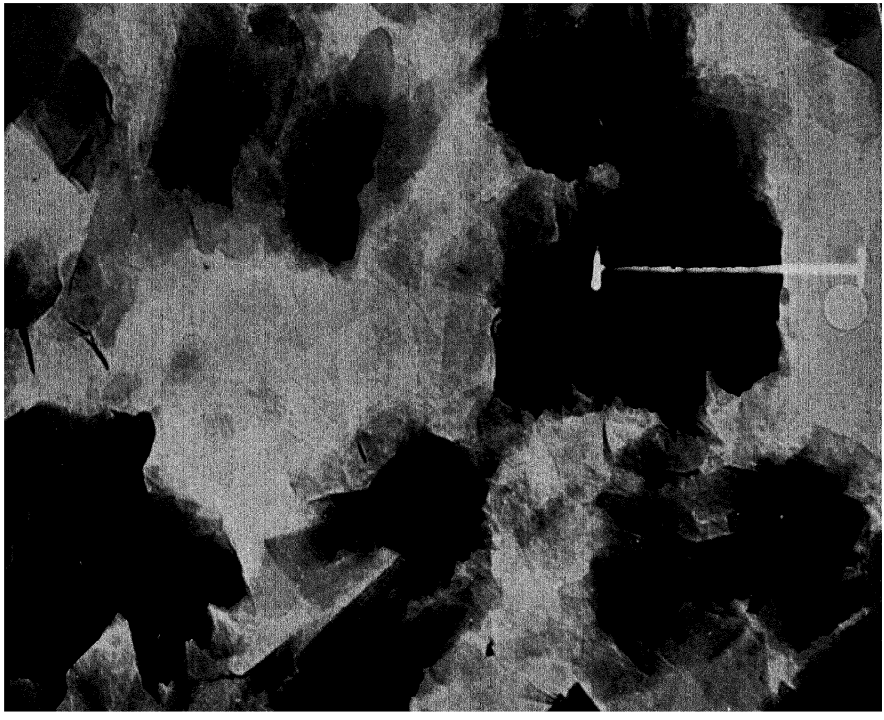
C. Electron microscope picture of a small portion of **B** with total magnification about $\times 5{,}000$.

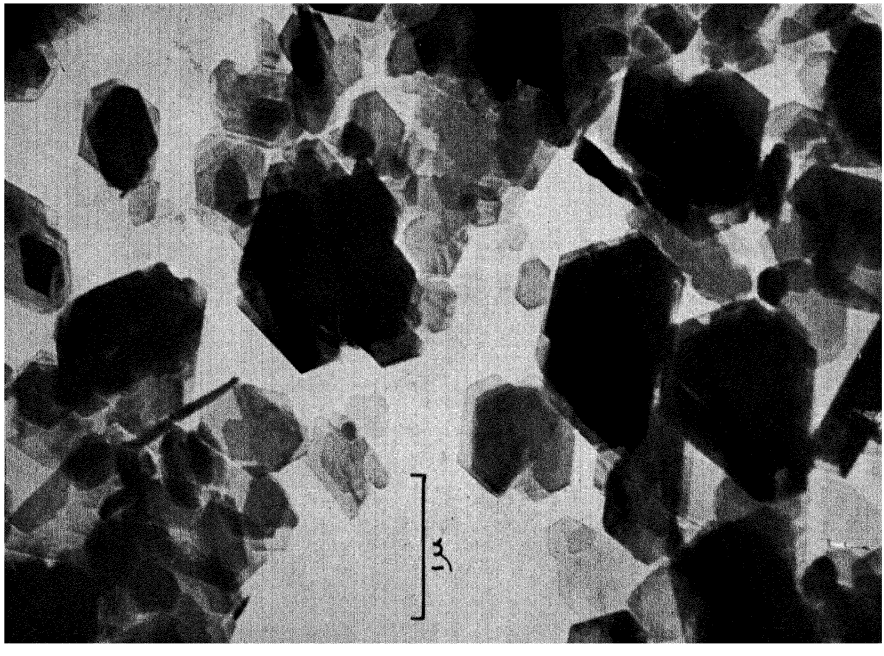
The width of the small line above **A** represents the total section included in **B** and the thick block over **B** represents the total width of the part of B included in C.

D is an optical picture of asbestos powder ($\times 1{,}100$).

E is the electron picture ($\times 18{,}000$) of the portion outlined by the small inked-in square area in **D.** The heavy bar in **E** is the hazy line through the square in **D.**

These are good illustrations of the fact that the electron microscope reveals structures in a sample entirely unseen in the light microscope.





(Above) 2-1μ Fraction of Wyoming Bentonite, ×42,000. *Courtesy A. Prebus, Ohio State University.*

(Below) Kaolin Clay, ×21,000. (7,000× electronic, 3× optical). *Courtesy American Cyanamid Co.*

Chapter 4

WAVE MOTION AND WAVE MOTION MEDIA

Is Light a Wave Motion?

Probably the best way to unfold the present state of the theory of any natural phenomenon is to follow the historical development, proceeding step by step as the human race has done. As for *light*, we have seen that from the earliest times men have been aware of the phenomena of reflection and refraction and have accepted the idea that light travels in straight lines in any homogeneous medium.

The first experimental result which disturbed this concept was the discovery of diffraction, as illustrated in Fig. 24. This effect could not be explained by the corpuscular theory; we cannot conceive of particles, shot off in a straight-line course, bending around the corners of obstacles in their path.

It is natural, when one is confronted with such an apparent deadlock, to review ideas that may have been proposed at an earlier stage and also to re-examine experiments in other domains which might yield a clue to a new approach to the explanation of the nature of the phenomenon in question.

As for light, it had been the dream of natural philosophers, from Aristotle to Newton, that a medium of some sort filled all space. Various properties were assigned to this medium by different dreamers, all aimed at making it a carrier, in some way or other, of light energy from the source to the object finally illuminated. The concept of light corpuscles, to be sure, did not require such a medium, but it failed in the face of the demonstrable facts of diffraction.

Transmission of energy by a wave motion in a material medium suggested itself, since this phenomenon was already familiar to everyone in the action of water waves. The question

then was raised, "Is such a wave concept able to explain diffraction?" Let us therefore study the behavior of water waves and see what can be learned from them that might be usefully applied to a model for light waves.

The Diffraction of Water Waves

The experiment depicted in Fig. 24 for the phenomenon of light can easily be duplicated with water waves. If the bottom of a large flat pan, Fig. 31, is just covered with water and two flat metal bars are placed so as to make a barrier, AB, across the water surface with the exception of a narrow opening at P, the experiment corresponding to Fig. 24 for light can be performed by means of waves upon the surface of the water. Drop a little pebble into the water, say at X; the wavelets will spread out from X as a center and will be reflected back from AB *except* at the opening, P, where some of the motion gets through to the other side. But instead of passing along a narrow path as indicated by the line PQ, the motion that gets through P spreads out all around the surface in the form of little wavelets which seem to emanate from the point P as center.

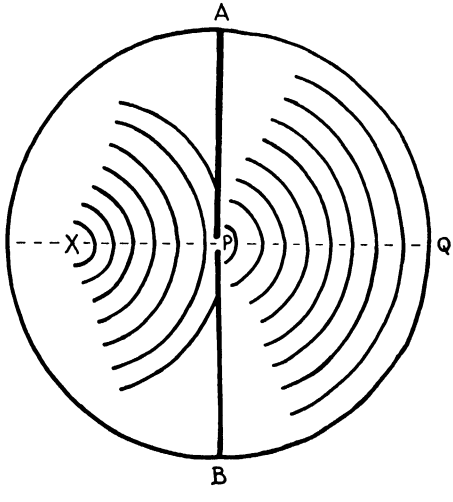


FIG. 31.

How a wave motion spreads on the surface of water after passing through a small opening in a bounding wall.

It is on account of analogies such as this that scientists were constrained to say that light acted as though it had the properties of a *wave motion* in some medium.

The crucial property of wave motion, which is suggested by the phenomenon of diffraction, is that apparently every point on a wave front can be looked upon as being able to act as a new center from which the wave motion can spread anew, as is shown at the point P in both Figs. 24 and 31.

The Elements of Wave Motion

Our fundamental ideas regarding the propagation of energy by wave motion come from the actual motion which we observe in waves on the surface of water. Fig. 32 illustrates what happens when we drop a stone on the smooth surface of still water. As the stone strikes the surface, wavelets spread out in concentric circles from the point of contact as center, and a floating object on the surface at any point will bob up and down. Fig. 32 may be taken to represent graphically two facts about this wave motion. First, if we imagine that the surface could be kept

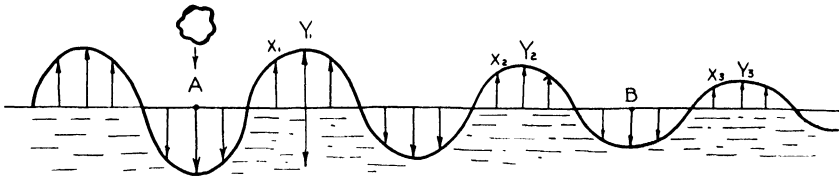


FIG. 32. Graph of water wave showing the meaning of wave length, phase, frequency and velocity for a typical wave motion.

frozen at any given instant, the curve shows the relative position of the surface points at that instant; in the second place, if we imagine the curve travelling along in the direction of A to B, for example, with the velocity of the wave itself, we have a picture of the progress of the motion; and, if we fix our mind on any one point, as Y_1, we get a true idea of the motion of a water particle at this point as the wave sweeps along. Since the actual motion of the particle is at right angles to the direction in which the wave itself is progressing, this is said to be a *transverse wave*.

We can learn from this figure some of the technical language applied to wave motion in general. The distance from crest to crest or from trough to trough is called a *wave length;* two points which are in corresponding positions in the crests or troughs, as

X_1 and X_2 are said to be in the same *phase*. The number of times the particle at a point on the surface bobs up and down in one second, or, as we might say, the number of times a particle completes a cycle in a second, is known as the *frequency* of the wave motion. It is at once apparent that the velocity with which the disturbance moves forward is equal to the number of wave lengths marked out per second, *i.e.*, is equal to the frequency multiplied by the wave length. This is expressed in mathematical shorthand by the relation:

$$v = \nu\lambda$$

where v means velocity, ν frequency and λ wave length.

Fig. 33 represents the same phenomenon as Fig. 32, but shows the concentric circles as we look down on the surface; a curve similar to Fig. 32 is repeated below. This illustration is extended in Fig. 34 to show the interaction of two independent sets of concentric ripples.

If we suppose that two stones are dropped in at the same time at points O′ and O″, two sets of wavelets would develop

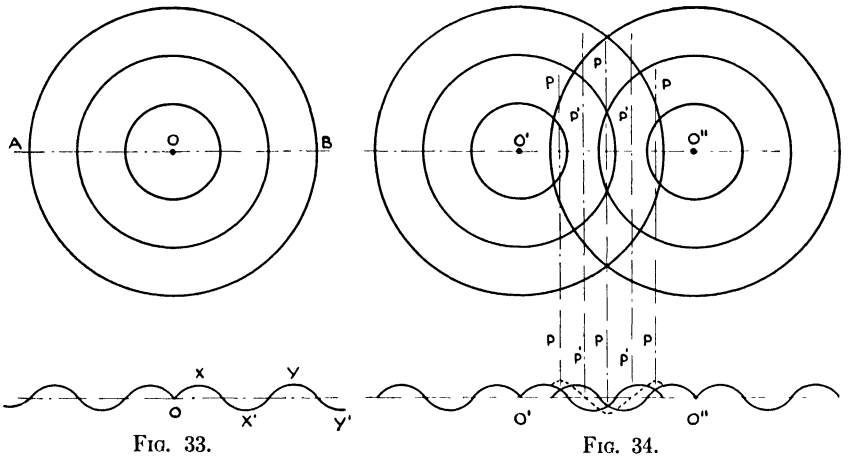


Fig. 33. Fig. 34.

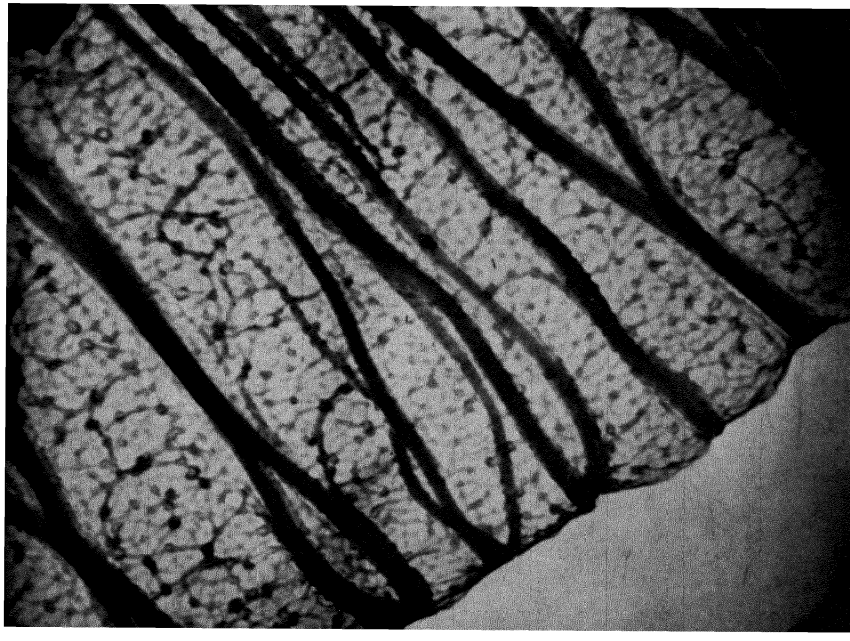
The superposition of two systems of waves on the surface of water.

from these points as centers. These two would overlap as they proceed; Fig. 34 represents an instantaneous picture of a section of the surface through the points O′ and O″. The surface particles at any point, P, will have assumed the displacement due to

the sum of the two motions, and so the real position of the surface points at the particular instant chosen will be that given by the dotted curve. At the position P′, for example, the surface point will be at its original position of rest; that is, at this point the two wave motions combine to give zero displacement. Again, at the position P, there will be an abnormally large displacement due to the two disturbances adding their effects at this particular instant.

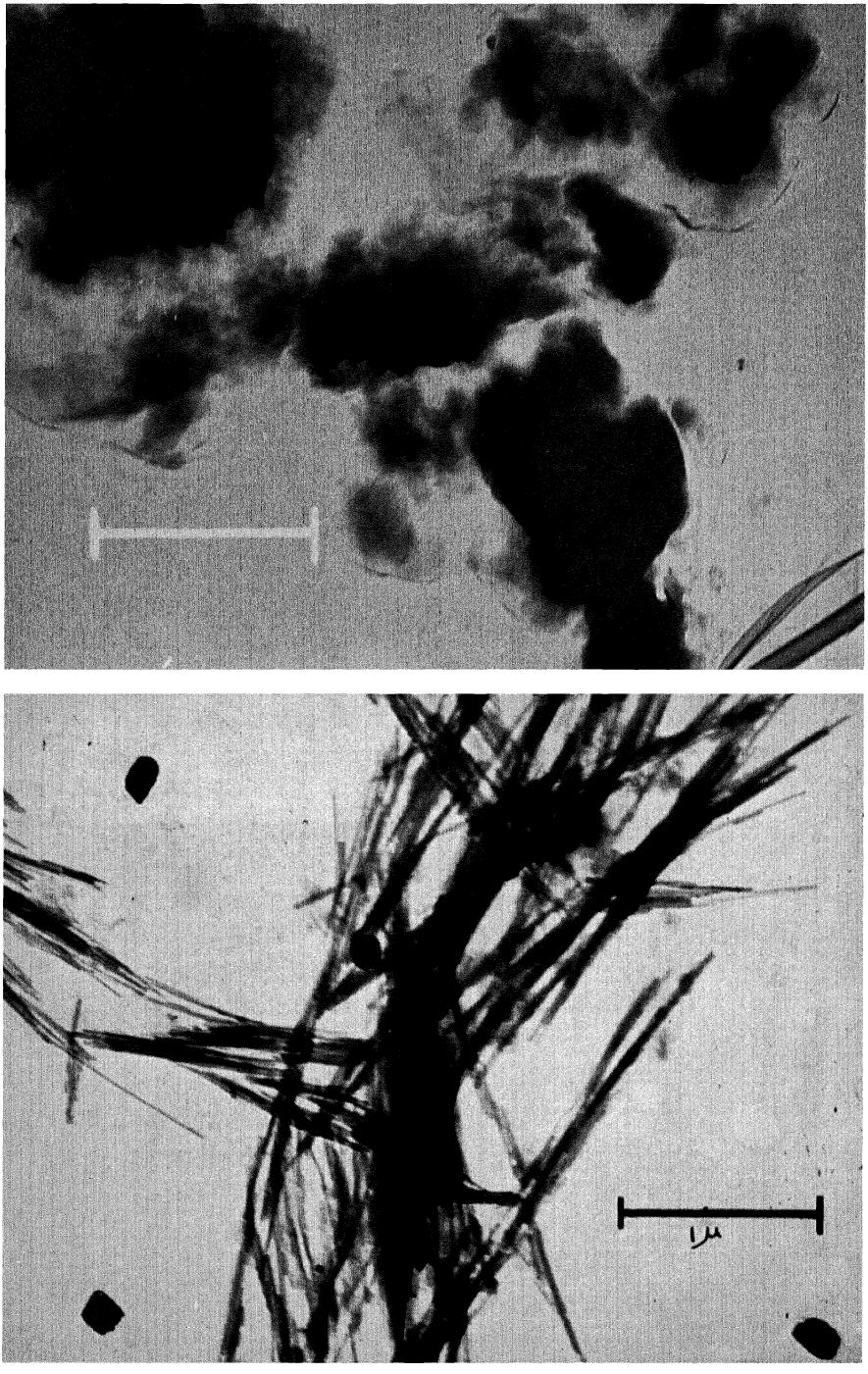
This interaction of two independent wave motions is known technically as interference.

From a study of Fig. 34 it will be apparent that, as the wavelets progress, the resulting (dotted) curve will always cut the axis at the *same* points, *i.e.*, those points at which the lines P′ P′ intersect the axis. That is, at certain places on the surface of the water the two independent waves (from O′ and O″ respectively) will always neutralize each other; in other words, at certain points on the surface there will be no motion at any time.



Courtesy RCA Laboratories

Trachea of honey bee (×15,000).



Courtesy A. Prebus, Ohio State University

(Above) California Montmorillonite, ×38,000.
(Below) Fraction of Attapulgite (200-50μ), ×35,000.

Chapter 5

WAVE MOTION IN ELASTIC MEDIA

Wave Motion in Gases and Liquids

Although we get our simplest example of wave motion from surface water waves, this phenomenon is quite inadequate to serve as a model of wave motions propagated through space in three dimensions. The water wave spreading over a surface is confined to that surface and cannot serve as a model for the motion caused by the explosion of a depth bomb below the surface, which spreads out from the source in all directions in the ocean, nor for the disturbance set up in the air by, say, a firecracker. These two are examples of wave motions in *three* dimensions; but in both cases we have energy being transmitted from one point to another in the form of sound.

For a more detailed description of the phenomenon we illustrate, in Fig. 35 (a, b, c), the propagation of the sound from a gong which has been struck by a drum-stick; this drawing was constructed in accordance with our accepted model of the air, namely, that it is a collection of small spherical particles swarming around in random motion. The metal disk vibrates when struck. As it moves to the right it compresses the air in its immediate vicinity to the right; then it swings back toward the left, making a compression to the left side and leaving a rarefaction on the right side. The air near the disk goes through this succession of oscillations as long as the vibrations of the disk continue.

The events taking place on the right side of the disk are shown diagrammatically in Fig. 35c which represents, as it were, a snapshot exposure of the air particles. The shaded regions are those of compression and the dotted regions are those of rarefaction; the little arrows indicate the direction in which the air

particles have moved just before the snapshot was taken. A moment later the disk will bulge to the left and the state of affairs will be reversed in every respect. We can really measure the pressures along the line CO′ as the sound is travelling, and the curve in Fig. 35b shows graphically the relation between the pressure, d, at a point along CO′ and the distance, s, of the point from the center of the disk at the time of the snapshot. As the direction of motion of the air particle is the same as that in which the sound moves, this form of wave motion is said to be *longitudinal.*

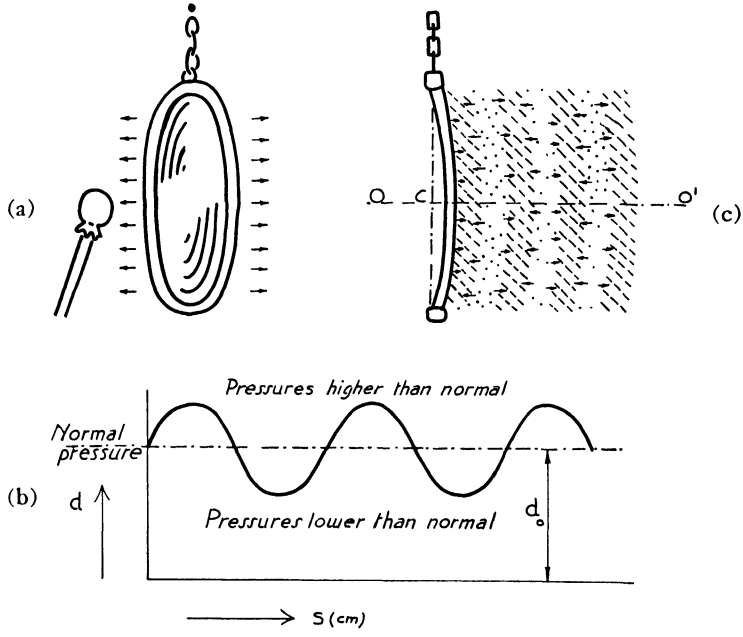


FIG. 35. The motion of air particles in the neighborhood of a vibrating gong. As the sound travels to the right, (b) represents how the pressure (d) varies at any point along CO′, the distance s from the diaphragm.

The human ear, which acts as a receiver, responds to the variations in air pressure, and the sensations produced physiologically are interpreted as sounds of different loudness and pitch. Since sound cannot be transmitted in a vacuum, we must accept the conclusion that the air is the mechanical link between the sound source, the gong, and the receiver, the ear.

That sound is a form of energy is readily understood if one

recalls that windows may be broken by the impact of sound waves resulting from an explosion at some distance. Although the results are not so violent, energy is also necessary to produce the motion of our ear drums as they record sounds falling upon them.

Sound travels not only through air (and other gases) but also through liquids and solids. In every case the origin of the sound is a periodic disturbance which causes a slight displacement of the molecules of a material medium, and the resulting periodic wave motion is due to the action of forces which always come into play to push these disturbed molecules back into their original positions. The velocity with which the disturbance moves through any medium depends on the nature of the medium, and the molecular forces called into play to restore the molecules to their original positions are known as *elastic forces*. We call this property of a medium, *elasticity*; every medium has its own peculiar elastic properties which are indicated by so-called *elastic constants*.

Sound waves in any medium are thus elastic waves. If the frequency of the motion set up in any medium is between 20 cycles and 20,000 cycles per second, the resulting motion affects our ears, causing a sensation in the brain which we call sound. Any disturbance set up in a given medium, whether we can hear it as a sound or not, travels with the same kind of vibratory motion and with the same velocity. In fact, the velocity of any such disturbance in any given medium depends only on the elastic constant of that medium and its density, and not at all on the sound characteristics, such as pitch and intensity.

Consequently, a disturbance caused by an explosion in air travels with the same velocity in still air as the sweetest note of a bird. Again, when a depth charge is set off in the ocean at a considerable distance from the surface, the disturbance travels out from the center of the explosion in spherical waves of compression and rarefaction with a velocity which is the same as the velocity of any ordinary sound in water, or about 4,500 feet per second. The direction of the to and fro motion of the molecules in liquids is always back and forth along the direction of progress of the disturbance, so that here, as in the case of gases, we have *longitudinal* wave motion. This is the only possible kind of wave motion that can exist in liquids and gases.

Wave Motion in Solids

When we come to study how sound travels in solids, we find that two kinds of sound waves are possible. If we pluck a violin string in the ordinary way we obtain a rich, pleasing note: but if, instead of plucking the string, we pull it with a resined cloth along its length, we obtain a screeching, unpleasant note. Both these notes are due to vibrations set up among the molecules of the string; but from the manner in which the disturbance is caused we see that the motion of the molecules, in the first case, must be perpendicular to the length of the string or *transverse*, whereas in the second case the motion will be *longitudinal*, *i.e.*, parallel to the length of the string. So if we could see the motion of the molecules inside the string, we should observe that the disturbance is carried along by a *transverse wave* in one case and in the other by a *longitudinal wave*. Experiment has shown that these two wave motions in solids are regulated by two separate elastic constants, which correspond to two separate elastic properties of the solid of which the string is made.

The Propagation of Waves in Matter

In summarizing our various experiments demonstrating the propagation of different waves in material media we should search for a common criterion that makes the establishment of the waves possible in all cases. To begin with, the equilibrium of the medium in question is in every case disturbed by an external force which imparts to the particles of the medium a displacement in the direction of the force. This displacement is not permanent. The medium offers a resistance which tends to restore the equilibrium position of the particles when the external force is removed. Plastic solids, such as plasticine and dough, which do not possess these strong molecular forces, cannot maintain a wave motion and consequently cannot transmit sound. The motion of the diaphragm of the gong in Fig. 35 sets up longitudinal waves in the air due to the ability of the gong to vibrate for some time after being hit by the drum-stick. In this case we have not only the vibrations in the air but also a wave motion travelling to and fro within the metal of the plate at a definite rate—a wave in the solid itself.

It is to these internal wave motions that we referred in pointing out the existence of wave motions in the material of the violin string. The disturbances which we call earthquakes are wave motions transmitted through the solid crust of the earth, and it is this kind of wave motion in a large volume of homogeneous solid that has really served as the prototype for the wave theory of light.

The Velocity of a Wave Motion in Matter

The interrelation between the elastic constants and the density of solids and the velocity of a wave motion was very fully explored many years ago, beginning with the experiments of Robert Hooke (1635-1703). It was found that the velocity, v, was given by the relation

$$v = \sqrt{E/d}$$

where E is the elastic constant and d the density of the solid.

In Table 2 is collected some information regarding the velocity of sound in some typical media, as deduced from this relation; in every case the numbers obtained for the velocities agree very well with those obtained from experiment. Of course all these quantities change with changing temperature; usually these measurements are taken at a standard room temperature, 20° centigrade or 68° Fahrenheit.

Table 2. Values of the Velocity of Sound.

Substance	Elastic Constant (dynes per sq. cm.)	Density (gram per cc.)	Velocity of Sound* (cm. per sec.)	(ft. per sec.)
Aluminum	7.0×10^{11}	2.70	510,400	16,740
Copper	12.3×10^{11}	8.93	356,000	11,670
Lead	1.6×10^{11}	11.37	122,700	4,026
Steel	20.9×10^{11}	7.8	499,000	16,360
Water (at 20°C)			141,000	4,625
Air (at 0°C)			33,130	1,087
Hydrogen (at 18°C)			130,100	4,268

* From Smithsonian Tables.

A Medium Necessary for Light Wave Motion

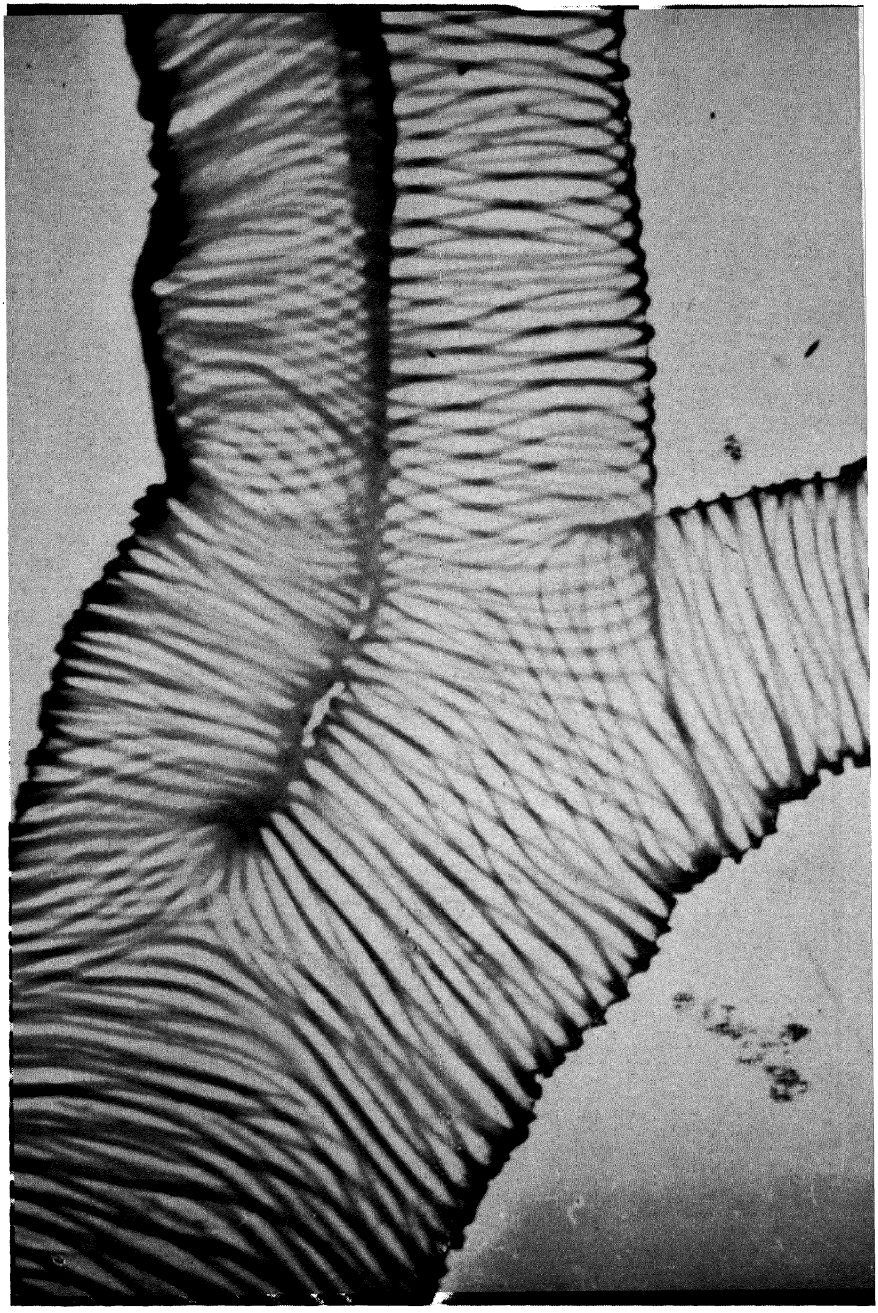
Since the conception of a wave theory of light was based on experimental proofs of the existence of wave motions in material media, it was incumbent on the supporters of this idea to provide a model medium in which such a wave motion could take place. It was postulated that a satisfactory medium did exist throughout all space; this was given the name *ether*—just another of the invisible, imponderable fluids which have often served to satisfy the human longing for an explanation of mysterious natural phenomena.

Manifestly this new medium must have an elastic constant and a density such that the velocity of light would be given by the relation

$$v = \sqrt{E/d}$$

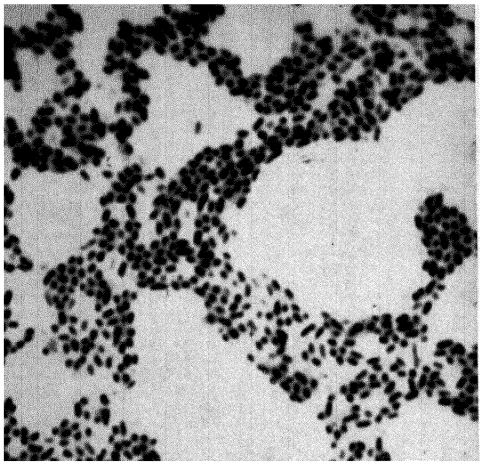
When first suggested, the ether was assumed to be a fluid, *i.e.*, a liquid or a gas, and so the motion of the particles of the ether was supposed to be longitudinal.

Modern determinations of the velocity of light make it 186,000 miles per second (or 30,000,000,000 cms. per sec.)—a perfectly enormous velocity compared with any that had ever been observed for any sound or elastic wave. In order that such a velocity should exist in any medium, the value of the elastic constant, E, would have to be extremely large or the density of the medium would have to be extremely small, or both of these conditions would have to obtain at the same time to a lesser degree. In effect, if the ether were supposed to have an elastic constant, E, equal to that of steel, *i.e.*, if it were as rigid as steel, the density could not be larger than about 1/50th that of the lightest known substance, hydrogen gas; if, on the other hand, the ether were supposed to have a density equal to that of hydrogen, the elastic rigidity would have to be about 50 times that of steel, one of the stiffest materials.

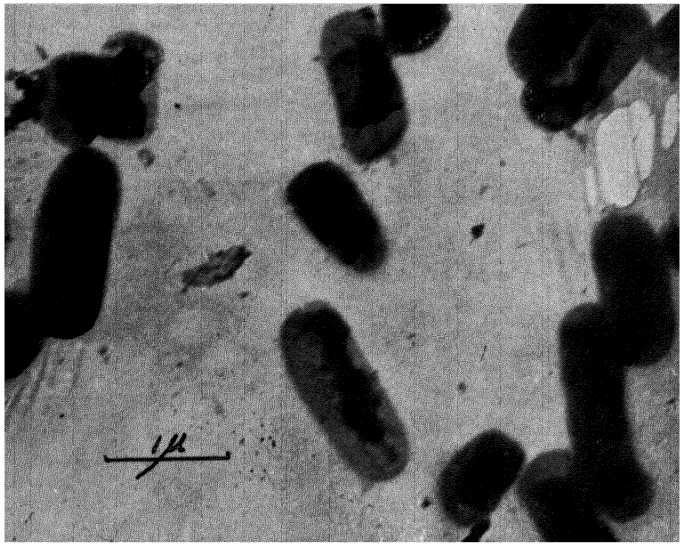


Courtesy RCA Laboratories

Trachea of mosquito larva (×7,500).



Prodigiosus bacillus under optical microscope (×2,000).



Bacillus Prodigiosus under electron microscope. (×16,400.)

This plate is also designed to compare light microscope and electron microscope pictures of the same specimen—the *Bacillus Prodigiosus*. The optical pictures were taken by Dr. J. Craigie of the Department of Hygiene, University of Toronto. The line marked 1μ gives the scale of the electron picture, this length being 1/10,000th of a cm. or 1/25,000th of an inch. It is quite apparent that the electron microscope may be counted on to show structure in such small bodies. It should be said that none of the electron microscope specimens are stained.

Chapter 6

LIGHT WAVES AND THE MICROSCOPE

Interference of Light

Figs. 24 and 25 illustrate actual observations of how light acts and we have seen how the phenomenon presented in Fig. 24 may be exactly reproduced with water waves.

We have now to show that the phenomenon of interference, demonstrated by water waves, is also an essential property of light, and consequently affords additional reasons for looking upon light as a wave motion.

The simplest experiment showing interference of light is illustrated in Fig. 36. Light from a source, S, is shielded by a screen with a narrow slit, P, which acts as a line source for the space to the right of the screen. The light from P spreads out and falls on a second screen which has two slits A and B, symmetrically placed with respect to the center line of the figure. The light passing through the slits, A and B, is allowed to fall on a third screen some distance away, so that the cones of light from A and B will overlap. Now, instead of the last screen being uniformly illuminated, we observe on the screen alternate bands of light and

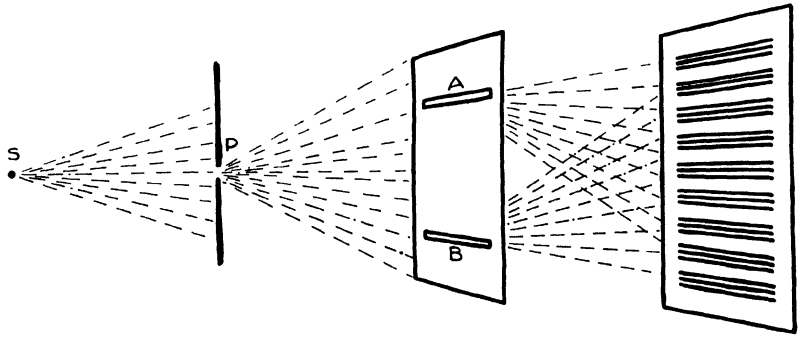


FIG. 36. How two light beams "interfere" with each other. The lines on the last screen are symbolic of darkness.

darkness. That is, we have the curious phenomenon of light from two sources, A and B, travelling independently to a screen and, with no obstacle involved, producing darkness at some points on the screen. By no stretch of the imagination can we convince ourselves that corpuscles travelling along can produce this effect. Fundamentally we must satisfy ourselves that two beams of light, each of which alone would give uniformly bright illumination of a screen, can so interact as to produce bands of light and darkness on the same screen when they are both shining on the screen at the same time.

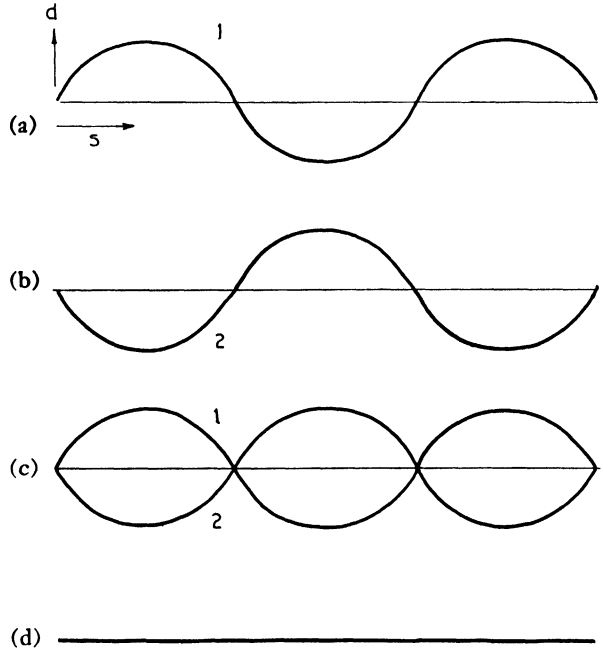


FIG. 37. The interference of two wave motions having a difference in phase of one-half a wave length.

The wave theory gives a very natural forecast of such a result. Suppose we represent the distribution of compressions and rarefactions by curves as (a) in Fig. 37, similar to the wave motion curves of other figures. Let us consider the effects of combining two wave motions represented by Figs. 37a and 37b. If one wave crest tends to produce a compression of the ether and the trough of a second wave tends to produce a rarefaction at the same point

simultaneously, the two forces, if equal in intensity, will cancel each other and the ether will remain undisturbed at that point. If this happens all along the path of two co-existing waves, which thus we describe as opposite in phase, then the ether will remain undisturbed all along the wave path. The effect is the same as if no waves had been propagated at all, or in other words we have two independent waves of light adding up to darkness.

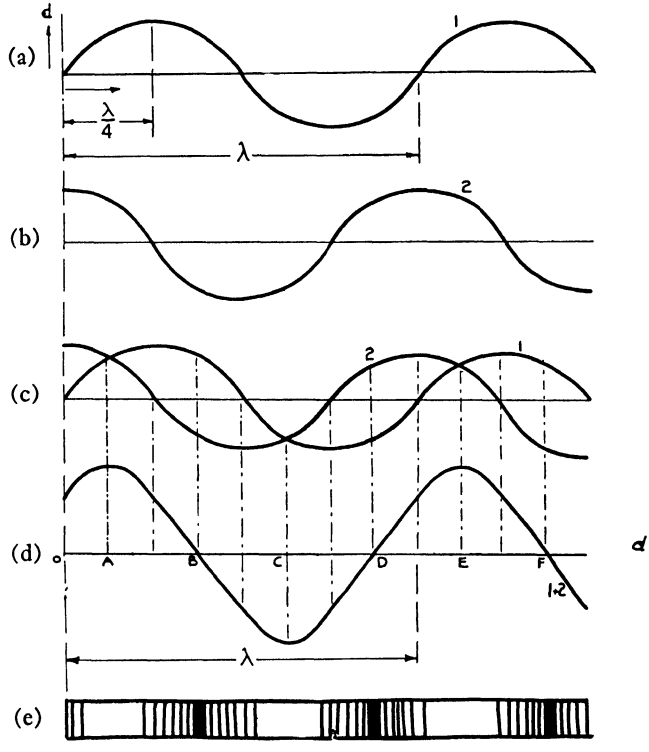


FIG. 38. The interference of two wave motions having a difference in phase of one-quarter of a wave length.

Figures 37a-d are snapshot exposures of the distribution of compressions and rarefactions along the direction, *s*, in which the light is travelling. Wave 1 starts with a compression, wave 2 with a rarefaction, while both have the same wave length. It is apparent that one wave is a half wave length behind the other, or as we say technically, it is out of phase with the other by that amount. This leads to the complete cancellation of the two, if

the two waves are superimposed as in Fig. 37c; the next figure, 37d, gives the graphical result, *i.e.*, no action at any point along the path. As each wave represents an independent light beam of the same intensity in both cases, we must conclude that light plus light adds up to darkness under the particular circumstances that were just described. If, on the other hand, we arrange it so that wave 2 in Fig. 37b is shifted with respect to the first wave by a quarter of a wave length, we produce the conditions illustrated by Fig. 38 (a and b). Both waves have again the same wave length; they are shown superposed in Fig. 38c. When we combine these two so as to represent the distribution of compressions and rarefactions which is the resultant of the two, we obtain Fig. 38d, which is a new wave of different shape but still of the same wave length. Comparing Figs. 38d and 37d we realize that now the two waves do not cancel out all along the path from O to F as before, but only at the points B, D, and F. Between these points the medium is definitely disturbed and energy is propagated. If we were to expose instantaneously a strip of film along OF, this film, when developed, would show the pattern of Fig. 38e, *i.e.*, dark regions at B. D, and F, and light regions between these points with shaded transitions. This example explains how nicely the wave theory accounts for the phenomenon of interference, without any artificial assumptions.

Acceptance of the Wave Theory

By the year 1800 the wave motion theory of light was accepted almost unanimously by scientists. The convincing explanation of many optical effects, such as reflection, refraction, diffraction, and interference, seemed to afford ample justification for accepting the concept of a wave motion of the "ether" as a satisfactory theory. The explanation of the straight line propagation of light based on the wave model left something to be desired, and the nature of the ether itself, with such unique properties as it was found necessary to endow it, remained an enigma.

When the wave theory was first generally accepted, the ether was considered to be of the nature of a gas, and consequently the wave motion in the ether was supposed to resemble the wave

motion in a gas. Now the only kind of wave motion that can exist in a gas (or a liquid) is one where the oscillation of the particles of the medium is longitudinal; that is, the actual to-and-fro motion of the oscillating particles is along the direction of transmission of the disturbance. However, if we refer back to Fig. 28, which illustrates the phenomenon of polarization of light, we realize that polarization can be explained satisfactorily if we imagine the vibrations to be *transverse*. But we cannot imagine the molecular arrangement in the Polaroid able to cut out *longitudinal* vibrations. Now transverse vibrations are possible only in solids; consequently, physicists were forced to look upon the ether as having the properties of a solid. We find a great deal written about the *elastic solid theory of the ether* during the last century.

The Limit of Resolution of the Microscope

With the foregoing background regarding light as a wave motion, we may now return to the question at the close of Chapter 2: "How close together can two object points be and still be distinguishable as two separate points in the image?"

Reference to Fig. 25 will recall that any point source will give an image consisting of a system of dark and light rings, due to the diffraction of light—the so-called spurious disk. This set of rings is due to interference between portions of light which are transmitted by various parts of the lens. As was pointed out previously, if we have two objects, such as P and Q (Fig. 39), we

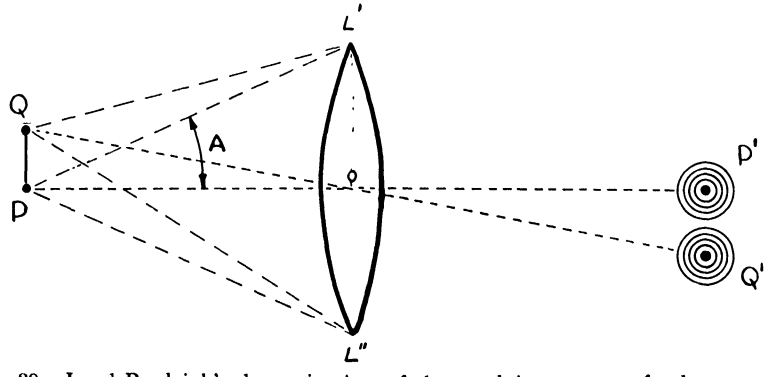


FIG. 39. Lord Rayleigh's determination of the resolving power of a lens system.

cannot separate them in the image if the two spurious disks, P′ and Q′, overlap too much.

Lord Rayleigh used this picture to deduce an answer to the above question. His argument applies also to complex lens combinations, but in Fig. 39 we shall let the single lens, L′L″, represent diagrammatically the objective of a microscope. We shall state Rayleigh's result here and indicate how it is arrived at in a footnote which may be ignored by the non-technical reader.

If d is the smallest value of PQ as defined above, Rayleigh deduced the formula:

$$d = \frac{\lambda}{2\,\text{N.A.}}$$

where λ is the wave length of the light used with the microscope and N.A. is the numerical aperture of the microscope.* The numerical aperture is a very important constant of a microscope setup; it is equal to the product: $n \times \frac{\text{L′O}}{\text{PL′}}$ (Fig. 39), where n is the index of refraction of the medium between the object, PQ, and the first surface of the lens system. In mathematical parlance the fraction $\frac{\text{L′O}}{\text{PL′}}$ is called the *sine* of the angle A, and is written, sin A. It is common practice to write the capital letters, N.A. for n sin A.

* The crux of Rayleigh's argument is that separation of the image points depends on how much light from Q ultimately arrives at the center of P′. (Note that we say P′ here and not Q′.) Whether this light from Q is enough to cause trouble at P′ or not depends on the differences between the distances travelled from Q to the center of P′ by the portions of light from Q which pass through the various parts of the lens, L′L″. The extreme difference of these paths is given by the difference between the paths QL′P′ and QL″P′. Rayleigh assumed that, if this extreme difference of path equalled the wave length, λ, of the light used, the interference of light from Q with the image of P at P′ might be neglected.

Since L′P′=L″P′, the difference QL′P′−QL″P′ will be just the difference QL′−QL″. By a very simple calculation, keeping in mind that the distance PQ is very small and, consequently, that the angles L′PL″ and L′QL″ are almost equal, it follows that 2PQ sin A=λ, the wave length of the light in the region between PQ and the lens. From this we have that:

$$d = \frac{\lambda_0}{2n \sin A}$$

where λ_0 is the value of the wave length of the light in a vacuum and n is the index of refraction of the medium between PQ and the lens surface.

According to this formula, the power to distinguish two points which are very close together in an object is limited in practice by the value of the wave length of the light used and by the value of the quantity N.A. The smaller the wave length of the light used, the smaller the limiting distance PQ may be; the larger the numerical aperture, N.A., the closer together the points P and Q may be. In the plate on page 38 are examples of microphotographs of the same diatom with the following values of N.A.: for B—.5; for A, C and E—.75; for D—.85; for F—1.00; for G—1.25. It is quite apparent that detail is progressively better as the value of N.A. increases.

The maximum value of N.A. for any lens system used in air is slightly less than unity; by using oil immersion objectives, for which n is greater than one, N.A. can be made nearly equal to 1.5. Consequently the best we can do is to have

$$d = \tfrac{1}{3}\lambda_0$$

Thus the actual value of d depends on the wave length of the light used. In Table 3 we give the wave lengths corresponding to the range of colors in the spectrum of white light. These dimensions are usually given in centimeters but, since the numbers turn out to be such small fractions of a centimeter, it has been found convenient to introduce smaller units of measurement. As several of these smaller units are in use it is necessary to keep them carefully differentiated. The basic relations between these other units and the fundamental unit, the centimeter, are as follows:

1 millimeter (mm.) = 0.1 cm.
1 micron (μ) = 0.001 mm. = 10^{-3} mm. = 10^{-4} cm.
1 millimicron (mμ) = 0.001 μ = 10^{-6} mm. = 10^{-7} cm.
1 Angstrom unit (A.U.) = 0.1 mμ = 10^{-7} mm. = 10^{-8} cm.

The range of wave lengths in the visible spectrum extends roughly from 4×10^{-5} cm to 8×10^{-5} cm or, expressed differently from 4000 to 8000 A.U.

If we select for purposes of calculation the wave length 6×10^{-5} cm, the smallest possible distance, d, for visible observa-

Table 3. Wave Lengths of Light of Different Colors.

Color range	In Centimeters	In Angstrom Units
Infrared	Above 7.70×10^{-5}	Above 7700
Red	6.47–7.70 "	6470–7700
Orange	5.88–6.47 "	5880–6470
Yellow	5.50–5.88 "	5500–5880
Green	4.92–5.50 "	4920–5500
Blue	4.55–4.92 "	4550–4920
Violet	3.60–4.55 "	3600–4550
Ultraviolet	Below 3.60 "	Below 3600

tion is approximately 2×10^{-5} cm, *i.e.*, 1/50,000th cm, or 1/125,000th of an inch. This is then also the diameter of the smallest particle that we can see or photograph with the aid of the most powerful microscope, using ordinary visible light.

If we make use of ultraviolet light and photography, we can take pictures of particles about one-half this size and so have visible in the photograph greater detail.

This marks the impasse reached by the year 1900.

Resolving Power and Magnification

The argument presented in the preceding section tells us that, with the help of even the finest microscope, the smallest particle that we can see must have linear dimensions of at least 1/125,000th of an inch. No amount of magnification or re-magnification can reduce this minimum value.

Since the naked eye cannot see differences in dimensions smaller than 1/250th of an inch, it is at once apparent that a dimension of 1/125,000th of an inch must be magnified at least 500 diameters. This is usually written ×500. Though the eye can see very small detail, eye strain and fatigue are avoided by increasing this magnification from 2 to 6 times. This increase in magnification is dependent upon the initial contrast between object and field which, in the case of small transparent particles, is very low. When the contrast is low no increase in magnification will increase the amount of detail, since image contrast decreases with increase in magnification. Magnifications of ×1200

to ×1800 are practical with well-stained materials and a good oil-immersion objective, but higher magnifications up to about ×5000 are possible only with metallurgical materials showing exceptional contrast.

Contrast is a primary requirement in the visual perception of any image. When contrast is low it can be increased optically by the use of suitable filters and photographically by the proper use of emulsions and developers. Enlargement reveals very small detail by bringing it to the size perceptible to the eye. Empty magnifications and low contrast result when the limits already mentioned are exceeded.

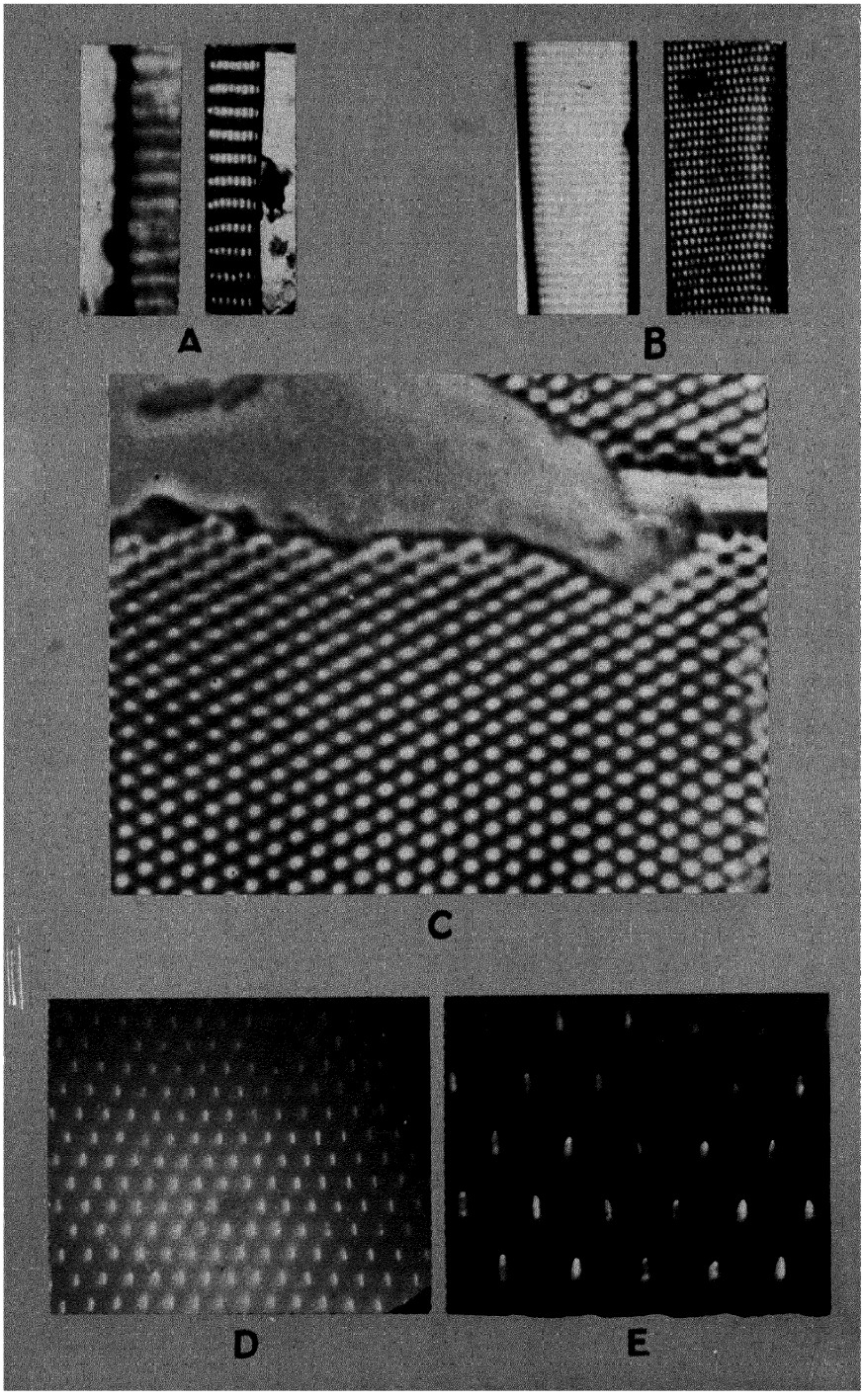
The detail seen in unstained materials, such as cleaned diatoms, can be improved by increasing the contrast with the use of media of higher refractive index than that of cedar oil. Where the use of ultraviolet light is possible with unstained organic materials, such as thin cross-sections of tissues and of bacteria, the peculiarities of differential fluorescence and absorption increase the contrast. While these special techniques have been very successful in revealing detail up to the limits of resolution, in ordinary practice these limits are very seldom attained.

The Ultramicroscope

About 1900 a completely new technique in microscopy was developed by Zsigmondy and Siedentopf of the Zeiss Company. Like many other scientific advances it involved the application of an ordinary well-known experimental fact in a new field.

We are quite well aware that the air of any ordinary room is filled with motes and dust particles which are invisible when the room is well lighted. However, if we darken the room as a whole, admit a narrow beam of sunlight or throw a narrow beam from a projection lantern and view this bright beam from the side, we are made aware of the presence of thousands of motes or dust particles floating in the air. But if we look in and along the beam toward the source, the same dust particles or motes are quite invisible.

The reason for this phenomenon is that the small motes or particles scatter or diffuse or reflect in all directions the light which


A
B
C
D
E

Explanation of plate on page 76

The purpose of these pictures is to show the manner in which the electron microscope contributes to the intepretation of the best optical microscopic pictures.

The objects are diatoms of a type often used for testing first class oil-immersion objectives.

A shows photographs of *Synedra delicatissima.* For the oil-immersion pictures, perfectly symmetrical Köhler illumination and an aperture giving N.A. 1.4 were used. The optical microscope (left) indicates the presence of rows of holes, but the electron microscope (×5,000) (right) goes further than this and shows positively the size and arrangement of these rows and holes. The holes are approximately 0.5μ in diameter, they are separated in the row, center to center, by a distance of 0.20μ; the rows themselves are approximately 0.90μ apart.

B shows corresponding photographs of the diatom, *Amphipleura pellucida.* The optical pictures (left) were taken with the same Köhler illumination and the same N.A. 1.4. The optical microscope shows bars in the valves and hints at the presence of openings within the slots. The electron microscope (×5,000) (right) shows clearly the small holes, approximately 0.14μ in diameter, with centers separated by 0.20μ. The rows are about 0.20μ apart.

C shows a valve fragment of the well-known test diatom *Pleurosigma angulatum* photographed with symmetrical illumination and an aperture of N.A. 1.0. The magnification is enlarged optically to ×5,000.

D is an electron picture of a portion of C with magnification ×5,000. That D itself does not tell the whole story given by the electron microscope is shown by the fact that E, a portion of D with total magnification ×15,000, shows that each individual hole in the shell is really a series of four holes approximately 0.1μ in diameter separated from each other by 0.03μ. The holes appearing at lower magnification are about 0.7μ apart.

The optical pictures were made by Dr. D. H. Hamly of the Department of Botany, University of Toronto.

falls on them. When we view the beam *laterally* our eyes catch the scattered light against a dark background, and so we say we *see* the particles. When the whole room is again illuminated the dark background disappears so that we can no longer distinguish the light scattered by the particles.

Fig. 40 shows diagrammatically the essential features of the Zsigmondy-Siedentopf ultramicroscope. The sample of material containing the small particles—gold ruby glass or some other

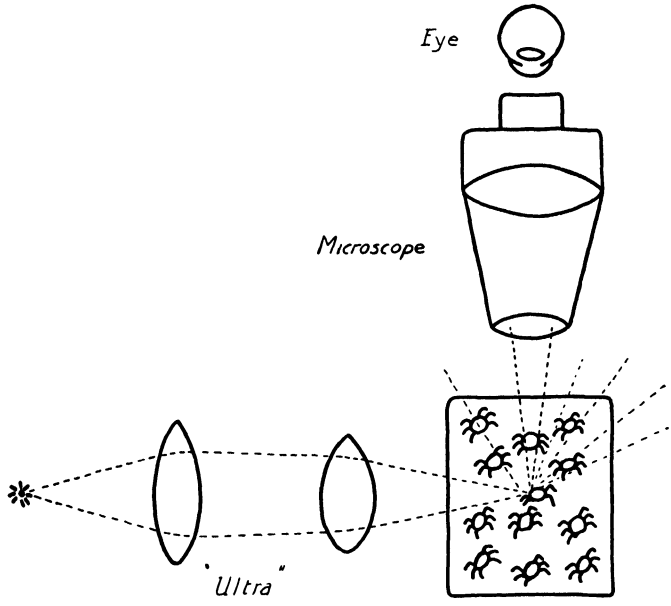


FIG. 40. The principle of the ultramicroscope.

colloidal solution—is illuminated in one direction and viewed at right angles to the illuminating beam by means of an ordinary microscope. The "ultra" part of this instrument is the unique illumination which enables particles to scatter light into the microscope so that they are seen against a dark background.

One deficiency of such a set-up is that we are only made aware of the presence of such particles, but we cannot measure them or tell their shape. On the other hand, we can be made aware of the presence of particles very much smaller than those set by the limits given in the previous sections. The reason for this is that particles of any size will scatter or diffuse some light in all directions, and whether we see such particles or not depends on

whether the amount of scattered light which manages to enter the microscope, and consequently the eye of the observer, is sufficient to affect the retina. This is chiefly determined by the brightness of the illuminating beam. It has been calculated that we should be able to see ordinary molecules with the ultramicroscope if we could illuminate them from a source as bright as the surface of the sun.

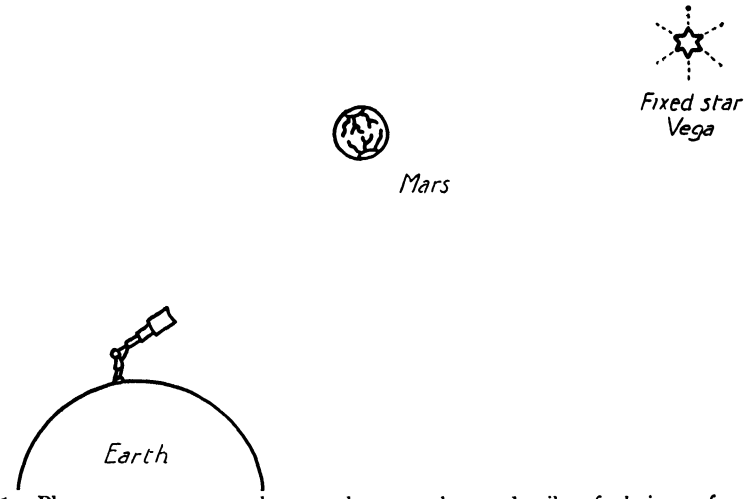
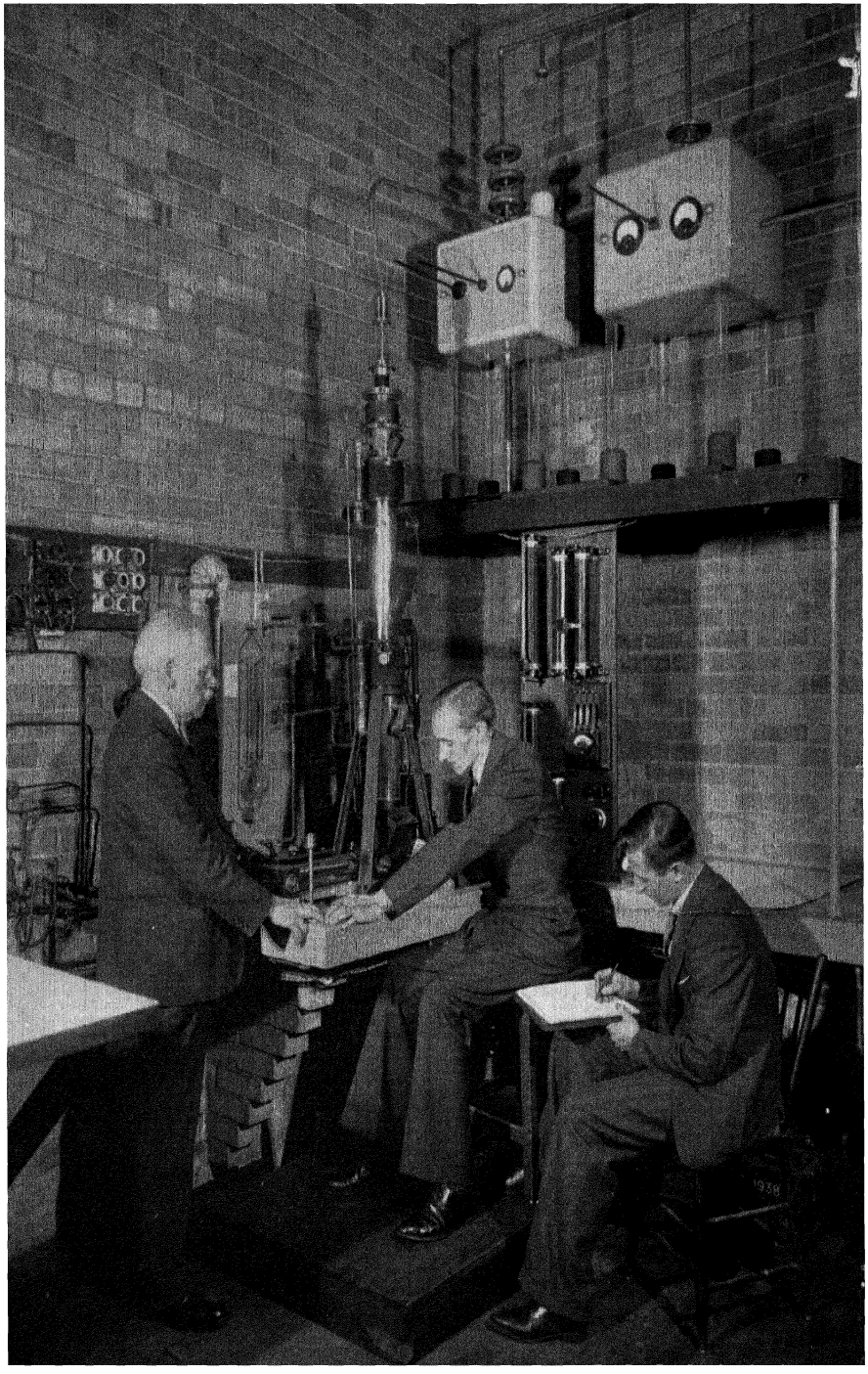


FIG. 41. Planets are so near that a telescope shows details of their surfaces, and gives a distinct measure of their sizes; but fixed stars appear only as points of light, on account of their enormous distances from the earth.

This phenomenon is analogous to one encountered in telescopic vision. The only heavenly bodies for which we can determine the size by direct observation or of which we can see any detail are those belonging to our own solar family, such as planets and their satellites (Fig. 41). But we are made aware of the existence and position of the far-away fixed stars because they are so brightly illuminated that our telescopes gather and transmit to our eyes sufficient light to affect the retina. We are however not able to tell anything about the size and shape of these fixed stars by vision alone, no matter how huge our telescopes.

While the development of the electron microscope has rendered the ultramicroscope outmoded as far as the determination of the size of small particles is concerned, this instrument is still very important as it affords the best method of observing the Brownian movement shown by colloidal particles.



Courtesy Columbian Carbon Co.

The electron microscope at the University of Toronto attacks its first problem in industrial research. Left to right, Professor E. F. Burton, Albert Prebus, and William Ladd.

Chapter 7

THE ELECTROMAGNETIC THEORY OF LIGHT

Faraday's Conception of Fields of Force

Up to the present we have been speaking of light as an isolated phenomenon of nature. It is probably not too much to say that, as far as physical sciences are concerned, the most important discovery of the nineteenth century was that the phenomena of light, electricity and magnetism are intimately related. In fact it has been proven beyond the shadow of a doubt that light is itself an electromagnetic phenomenon. The twentieth century has already gone a great step further by showing that the relation between light and matter is so intimate that it is possible to bring about a transformation of light (radiation) into matter and of matter into light. Indeed, both light and matter present a dualistic aspect—a wave motion and a corpuscular discreteness. In developing this idea we shall have first to recall the discoveries in fields of natural phenomena apart from but paralleling developments regarding light.

During the two hundred years preceding 1800 the fundamental facts regarding electricity and magnetism were known, in so far as the existence of two kinds of electricity and two kinds of magnetic poles is concerned. At this time it was not known that electrical charges and magnets had the slightest connection. Following a suggestion by Benjamin Franklin, the charge assumed by ebonite when it is rubbed with fur was called *negative* electricity, and that assumed by glass when it is rubbed with silk was called *positive* electricity. When two pith balls, one touched to charged ebonite and the other touched to charged glass, were brought close together they attracted each other; but if the two were touched to the same electrically charged body (ebonite or glass) they repelled each other (Fig. 42).

Since there are forces existing between these charged pith balls, energy has been transmitted through space from one body to the other. The question arises, "How does this interaction of forces take place?"

This problem will naturally bring to mind the similar one involved in the propagation of light. There is, however, a difference between the two types of energy transfer. In the case of light, it is only a transfer of energy from a source to the receiver, which may be the human eye or a photoelectric cell or a thermocouple. It is a unidirectional transfer of energy, a flow in one direction, however it comes about. This state of affairs does not prevail in the case of the two pith balls.

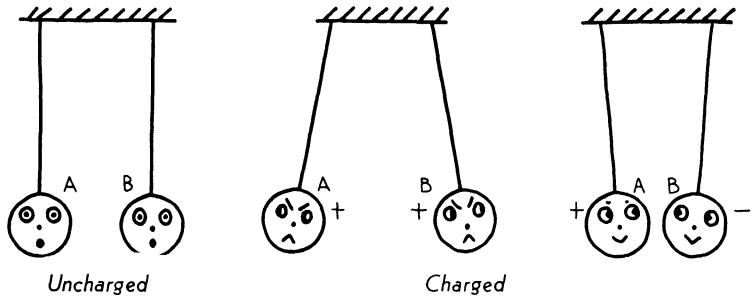


FIG. 42. How charged pith balls attract and repel each other.

The repulsion or attraction in the case of the two balls involves a certain amount of work, so that energy must have been supplied. But we cannot say that ball A is the source and B the receiver of energy or *vice versa*. Again, unlike light, this phenomenon does not involve a continuous transfer of energy from source to receiver, but the setting up of a state of equilibrium in which one pith ball is kept at a certain distance from the other in spite of the effect of gravity, which would make the balls hang vertically.

Most of the early workers were content to cover up their ignorance of this mysterious state of affairs by saying that it was just a case of "action at a distance," quite analogous to the mutual attraction of the sun and the earth.

An exactly similar situation developed with regard to the action of one magnet on another. In the minds of the early scientists, like poles repelled each other and unlike poles attracted each

other because of some innate property of the magnets, not at all dependent on what is in the space between them.

Faraday, whose scientific thinking was dominated by mental pictures of mechanical models of natural phenomena, was constitutionally a vigorous opponent of the ideas involved in the phrase "action at a distance." He believed firmly that the interaction between charged pith balls, as well as that between magnets, could be explained only by assuming that something was happening in the space surrounding the pith balls (or the magnets); Faraday held that there was set up in the *intervening* space a state of strain in some medium filling the space. The space around the reacting bodies thus became the mechanical link causing the repulsion or attraction. This state of affairs is expressed by saying that there is a *field of force* (electrical) around the charged pith balls and another different *field of force* (magnetic) surrounding the magnets.

Media for Electrical and Magnetic Fields of Force

These two media, electrical and magnetic, would have to be imagined to exist coincident with the ether which was assumed for the explanation of the propagation of light.

The whole question was complicated by the discovery by Oersted in 1820 that there existed a magnetic field in the space about a circuit bearing an electric current, and the discovery made later by both Faraday and Henry that currents of electricity could be made to flow in a circuit when the circuit was moved relative to a magnetic field. According to the view held by Faraday all these effects will involve electrical and magnetic media, and the idea grew that both electrical and magnetic effects might be considered to be due to the action of *one* medium, a kind of an electromagnetic ether.

Now to set up strains in a medium in space requires that the medium should have elastic properties, just the same kind of properties as the ether suggested for light. Faraday was brought to the point of considering that *one* ether might suffice for all these purposes and suggested the hypothesis that *light itself was an electromagnetic phenomenon.*

Proof of Relation between Light, Electricity and Magnetism

Under the dominance of this idea, Faraday began to devise experiments which would establish the truth of this supposition. He searched for this evidence for many years and was rewarded for his endurance in the end by the discovery of what is known as the Faraday effect (1845). A beam of polarized light passing through some solids or liquids is affected by a magnetic field in such a way that the plane of polarization of the beam is rotated by an amount depending on the intensity of the magnetic field. Faraday's search for the discovery of a similar influence of an electrostatic field upon light failed, but another British physicist, Kerr, in 1875, discovered that a solid or liquid becomes double-refracting, like Iceland spar, under the influence of an electrostatic field. This is known as the Kerr effect; the Kerr cell, based upon it, has been an important element in early television systems.

Maxwell's Electromagnetic Theory of Light

Faraday's ideas found their most concise expression in mathematical terms in Clerk Maxwell's electromagnetic theory of light (1865). It achieves the fusion of the optical, electrical and magnetic theories, presented earlier, into one new theory that comprises all these phenomena. Faraday's ether, the carrier of electromagnetic energy and Fresnel's ether, the carrier of light, become one and the same; but the new ether is no more an elastic solid ether, but more ethereal in nature. Maxwell maintains that light is propagated as a transverse wave in the ether. The existence of a wave demands that some physical quantity varies periodically along the direction of propagation of the energy transferred. This quantity, which formerly was the density of a material ether, now is the electric and magnetic field in free space. To speak of light as a transverse electromagnetic wave, then, means that along the beam electric and magnetic fields exist which are directed at right angles to the direction of propagation and which periodically rise and fall in intensity from zero to a maximum to zero and a minimum and to zero again. Since Faraday's electric and magnetic fields are made the variable quantities of

the light wave, Maxwell's theory demands that electric and magnetic disturbances of the ether will show the same properties as light and will be propagated with the same velocity, i.e., with the speed of light.

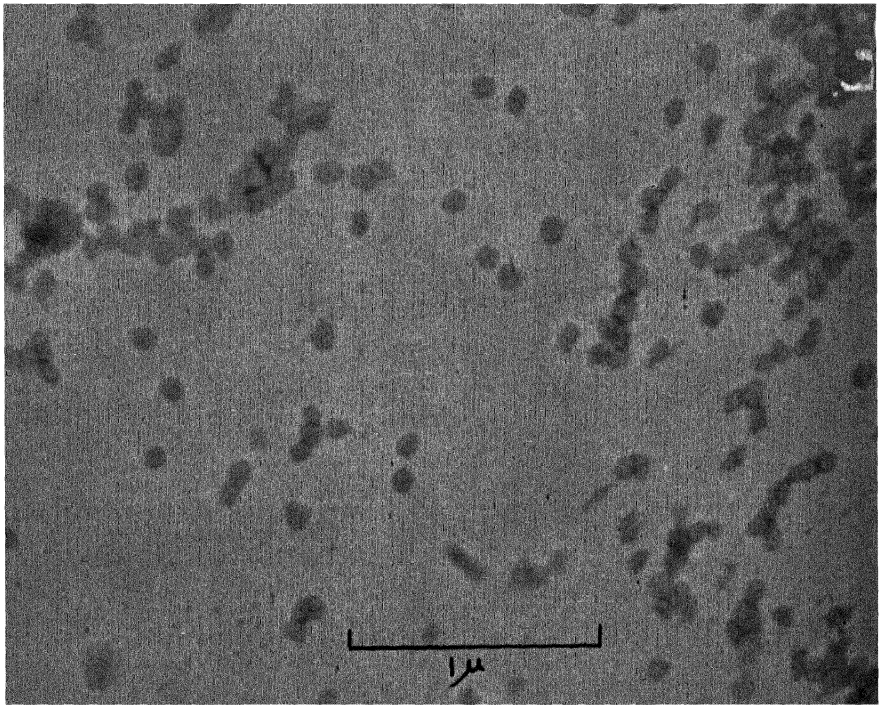
This theoretical conclusion was verified experimentally by Heinrich Hertz in 1887. He found that electromagnetic waves were produced by a spark gap and could be reflected, refracted, diffracted, and focussed in the same manner as light waves and

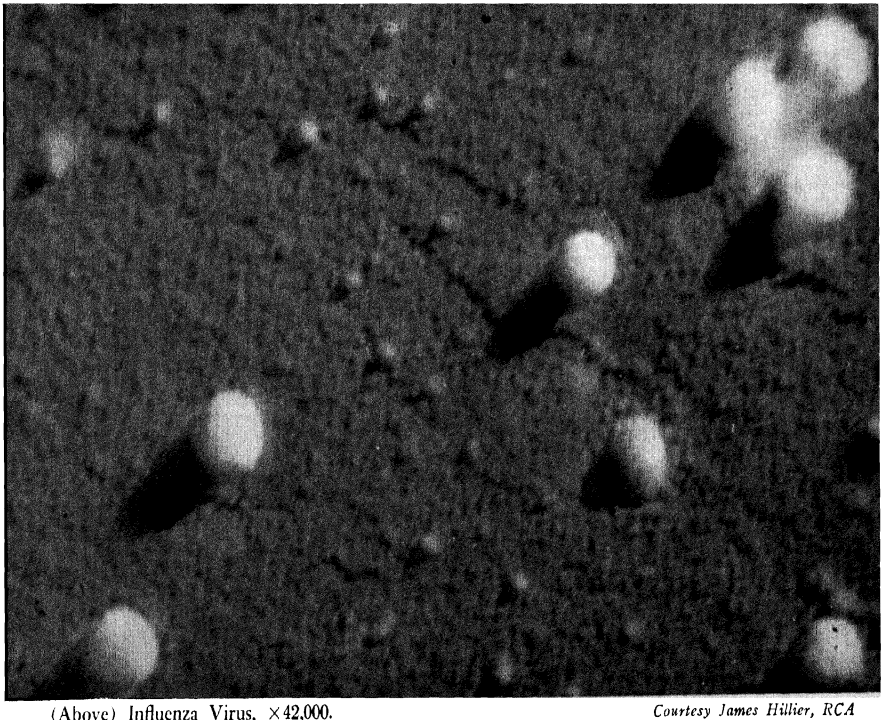
Table 4. Classification of Electromagnetic Waves and Values of the Wave Lengths.

Designation of Wave	Limits of Wave Lengths From	To
Long radio	10000 m	1000 m
Broadcast band	1000 m	100 m
Short	100 m	10 m
Ultra-short	10 m	0.5 m
Micro-waves	50 cm	0.1 mm
Infrared or heat	0.1 mm	0.001 mm
Visible light	8×10^{-5} cm	4×10^{-5} cm
Ultraviolet light	4×10^{-5} cm	ca 10^{-6} cm
X-rays	ca 10^{-6} cm	ca 10^{-9} cm
Gamma rays (radium)	ca 10^{-8} cm	ca 10^{-11} cm
Secondary Cosmic rays	10^{-11} cm	
Wave length to be associated with electron beams	From 10^{-8} cm up	

that they were indeed propagated with the same velocity. These epoch-making experiments thus confirmed Maxwell's electromagnetic theory in the most beautiful manner and everybody was very happy indeed. The mystery of light seemed to have been solved once and for all.

It is quite beyond the scope of this book to trace the development of the study of electromagnetic waves since Maxwell's time, but the above table shows the extent of its ramifications. We have recorded here the whole gamut of electromagnetic wave lengths, almost all of which have been measured experimentally by some satisfactory procedure.





(Above) Influenza Virus, ×42,000. *Courtesy James Hillier, RCA*
(Below) Type A, Influenza Virus, Shadow Technique, ×95,000. *Courtesy University of Michigan*

Chapter 8

THE ELECTRON

The Discovery of the Electron

In spite of the success of the electromagnetic theory, there were minor uncertainties to be cleared up. It was not clear, for instance, how dispersion of light in a refracting body came about. In order to develop a satisfactory explanation for these phenomena. L. Lorenz (1880) postulated, in all material bodies, the existence of small, electrically charged particles, which were supposed to have the property of vibrating with a natural frequency when disturbed by a light wave. The creation of light at the source, *i.e.*, the excitation of the ether, also was ascribed to such vibrating charged particles. They were, as yet, of an entirely fictitious nature from an experimental point of view, but their existence was demanded by a brilliantly conceived and well-founded theory.

It was not long before the physical reality of these charged particles was established. Early in the second half of the nineteenth century several outstanding physicists in various countries devoted a good deal of their time to the study of gaseous discharges, *i.e.*, the passage of electricity through a partially evacuated glass envelope. Tubes known as Geissler tubes on the continent and Crookes tubes in England were the earliest examples of these experiments, and our neon signs are an end product of this chain. During this period we meet men like Johann Wilhelm Hittorf, Sir William Crookes, Eugene Goldstein, Sir J. J. Thomson, and F. Braun. Their work led to the discovery of the electron by Sir J. J. Thomson in 1897. All the workers which we have just mentioned had found that a certain radiation is given off by the cathode, the negative pole, when a voltage is applied through the partially evacuated tube by connecting its sealed-in

terminal wires to a Wimshurst machine, a battery of galvanic cells or an induction coil. This radiation came to be known as the cathode stream or cathode rays.

Fig. 43a shows the diagram of a Geissler tube and the striations visible at a pressure of about 7.6 mm. of mercury.* Fig 43b

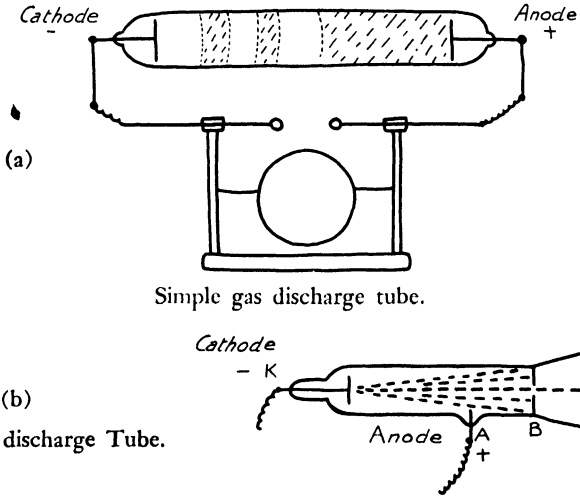


FIG. 43.

shows the familiar Braun tube, a sample of which is in almost every physics laboratory. It is generally about one and a half feet long. At K an aluminum disc is sealed into the neck of the tube to serve as cathode and at A a wire is sealed into the side of the neck to serve as anode. A disc with aperture at B permits passage of the central section of the cathode stream which emanates from the cathode, K. This fine beam then strikes a mica disc, S, which is covered with some luminscent powder that gives off light when struck by the cathode stream.

The Braun tube contains the essential elements which are present in a modern cathode ray tube, *i.e.*, cathode, anode, and fluorescent screen. If the disc, B, were made the anode and the terminal at A left out altogether the similarity to modern tubes would be more evident. It is only because Braun tubes still con-

* Low pressure in evacuated tubes is expressed in terms of "Millimeters Mercury" (mm. Hg.). The normal pressure of the atmosphere at sea level is equal to 760 mm. Hg. 7.6 mm. Hg. is then equal to $\frac{1}{100}$ atmosphere. Modern radio tubes are exhausted to about $\frac{1}{100,000}$ mm. Hg. or less.

tain a lot of air that the position and shape of the anode does not matter. The very simple type of cathode shown in Fig. 43b is operative for the same reason. These gas discharge tubes lent themselves to a variety of interesting experiments. Sir William Crookes, E. Goldstein and others were untiring in their efforts to glean the true nature of the emanation from the cathode which Goldstein first called by the now familiar name of cathode rays. These scientists produced hundreds of tubes, many of which have been preserved to our day. By changing the shape of the electrodes and that of the envelopes, by varying the pressure of the remaining gas content and by other modifications, they unfolded a story which challenged the imagination of many researchers of their time.

The Properties of the Cathode Stream

There were many ways in which the cathode stream resembled ordinary light. When the stream was allowed to fall on the surface of various minerals placed inside the vacuum tube, the minerals would be made to fluoresce, often with brilliant colors. Sir William Crookes observed the phenomenon on such minerals as zincblende, fluorspar, willemite and diamond. When the highest vacuum was reached, the glass of the tube itself gave a brilliant fluorescence wherever the cathode stream struck it; the color was usually of a greenish hue, but the color was found to depend on the nature of the glass.

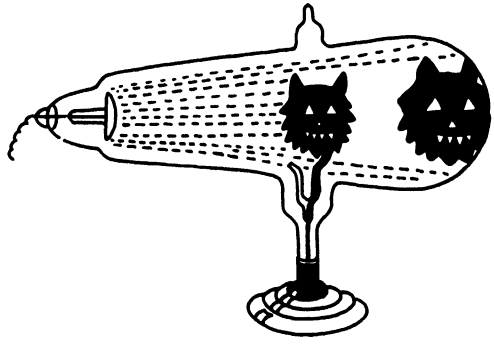


FIG. 44.

The shadow of a metal obstacle cast by cathode stream.

If an opaque object were placed in the path of the stream a very sharp shadow was cast (Fig. 44). This experiment suggests

that the cathode stream travels in straight lines as in the case of ordinary light.

Goldstein found that when a coin was used as the metal cathode, instead of a plain smooth disc of metal, the imprint of the embossed figure on the coin, heads or tails, became visible on the fluorescent screen. This phenomenon suggests some kind of focussing effect on the screen due to the structure of the surface of the cathode.

But there were two very important respects in which the cathode stream differed definitely from light. The stream was repelled from a negatively charged plate and attracted toward a positively charged plate—which suggested that in some way the stream bore a negative charge. Again, if an ordinary small bar magnet were brought near the discharge, the stream was deflected at right angles to the direction in which the magnet was pointed. If the north pole of the magnet were brought near the stream, the deflection would be in one direction; for the south pole, the deflection would be in the opposite direction. These experiments are easily shown with the Braun tube (Fig. 43b) as the motion of the beam is indicated distinctly by the movement of the fluorescent spot on the screen. No experiment was known which would show that ordinary light would be acted upon by either an electrostatic field or a magnetic field in such a simple manner.

The last experiment was epoch-making, because from it Sir J. J. Thomson deduced that the deflection was such as would happen if the cathode stream really consisted of a stream of *negatively charged particles*; these were afterwards called *electrons*.

In addition to the properties already ascribed to the cathode stream, such as producing fluorescence, casting shadows and therefore travelling in straight lines, there are other properties of an electron stream which are of great interest.

We believe that we do not see the electrons or the electron stream; what was seen and was given the name of *cathode stream* was a visible *path* which the electrons produce in knocking against air molecules. The end of the electron beam is indicated by the fluorescence on a luminescent screen placed in the tube. It is by

he use of these screens that actual measurements of the motion of electron beams can be made.

When the metal cathode was formed in the shape of a concave cup, the cathode stream was brought to a focus in the tube; if a piece of platinum foil is placed at this focus it soon becomes red hot—a fact first demonstrated by Crookes. The electrons give up their kinetic energy to produce heat.

When electrons impinge upon a photographic plate they set free the silver from the silver bromide film in the same way as light does. The amount of blackening thus produced by electrons on a film indicates the intensity of the beam. This effect is utilized in high-energy cathode ray tubes in order to obtain a permanent record of very fast-moving beams. The pictures produced by the electron microscope are obtained in the same manner.

The Charge and Mass of an Electron

If one conceives that electrons are material, charged particles the question at once arises, "What is their mass and their charge?" Among the early experiments on the nature of the cathode stream, one offered an almost insuperable difficulty to the "material particle" theory.

Lenard removed the fluorescent screen from the Braun tube and bored a very small hole in the large end of the tube where the cathode stream could be made to strike the tube. Over this hole he cemented a very thin metal foil window; this window sufficed to prevent gas molecules, even the smallest molecules, hydrogen, from entering the tube. In other words the vacuum could readily be maintained. Lenard got the curious result that the cathode stream came out through this window and gave a light spot on a fluorescent screen held outside the tube. Ordinary light can go through such thin foil; but if the cathode stream consisted of particles, these particles would have to be much smaller than the smallest gas molecule. To find the mass of the electron was then of prime importance.

J. J. Thomson faced this dilemma and set about finding definite values for the mass, usually denoted simply by m and the

charge, written *e*. The scope of this book does not allow us to develop this work in detail: suffice it to say that his experiments made use of the deflection of electrons in electric and magnetic fields. We shall refer only to the deflection in an electric field—that caused by inserting two metal plates in the Braun tube and providing means of keeping them at a difference of potential (Fig. 45b).

The manner in which *m* and *e* came to be related in the experimental results can be illustrated by referring to a simple problem in ordinary elementary physics.

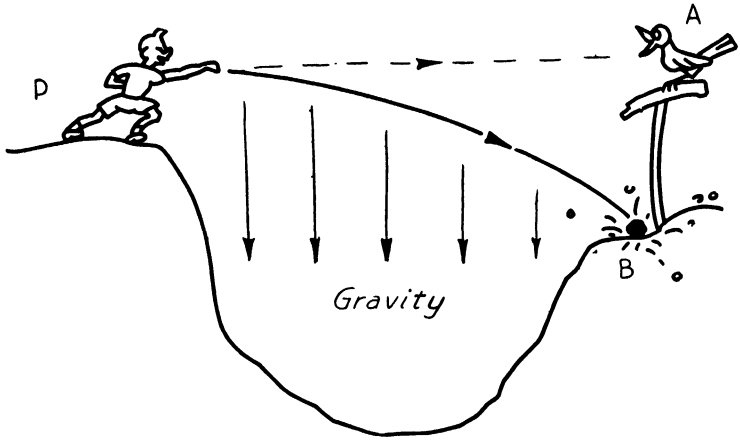


FIG. 45a. Gravity tends to pull the stone downwards during its flight.

Suppose a boy standing on the edge of a steep bank is throwing stones at a sign board across a creek and aiming at a bird at A which is on his own level (Fig. 45a). He soon finds by experiment that if he is to hit A he must give an upward direction to the stone at first. If the stone is thrown horizontally it will always strike at a lower level than A, such as the point B. The physicist expresses the relation between the mass, *m*, of the stone and the force of gravity acting on the stone by a simple statement that the force is given by the product of the mass and the acceleration, *a*, (the rate of gain of the velocity in the vertical direction). In our mathematical shorthand, we express this: $f=m\times a$. The value of the acceleration can be easily determined if we know the time it takes the stone to travel from P to B and the distance AB.

In the Braun tube (Fig. 45b) we suppose that the electron is shot in a horizontal direction from P′. For the part of its journey that lies between the charged plates, the electron is exposed to the action of the electrical force acting between the charged plates, as a consequence of which it travels over the path, P′B′. The speed of the electron under the circumstances outlined is so great that the action of gravity on the electron may be neglected; in the arrangement indicated in the figures, the electrical force in Fig. 45b deflects the electron from a straight-line course just as the force of gravity in Fig. 45a deflects the stone from a straight line. We have, then, an electron of mass, m, acted on by a force,

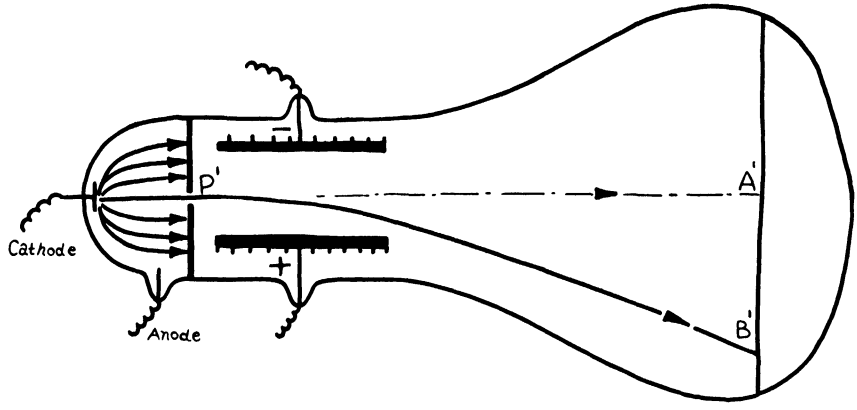


Fig. 45b. Deflection of electron beam in an electric field. The part of the path between the plates is curved.

say f, and given thereby an acceleration, say a. We may then write: $f = m \times a$.

In the case of the electron the force, f, depends directly on the size of the charge, e, and the expression for the acceleration involves the velocity of the electron and the distance A′B′. As we shall see later, the force, f, on the charge, e, is given by the relation: $f = F \times e$, where F is the strength of the electrical field acting between the plates, which in turn is very simply determined in the experimental arrangement here used. So in the relation, $f = m \times a$, we may substitute $(F \times e)$ for f which gives the expression $m \times a = F \times e$. By a simple transformation we may write this in the form

$$\frac{e}{m} = \frac{a}{F}$$

Since both a and F can be measured experimentally, we thus arrive at an experimental value of the ratio $e:m$.

The foregoing indicates roughly the manner in which J. J. Thomson approached the problem. The upshot was that these early experiments gave a definite value to the ratio of the quantities e and m, but did not settle the definite value of either of them separately. Historically the next step in the development was to assume a definite value for *one* of them. This choice fell on the the value for the charge e.

Faraday's early experiments on the conduction of electricity by liquids, known as electrolysis, seemed to indicate that there existed a small ultimate unit of electrical charge—an atom of electricity, one might say. The magnitude of this unit was equal to the charge on a hydrogen ion (which is positively charged) or to the charge on a chlorine ion (which bears an equal negative charge); the numerical value of this ionic charge had been satisfactorily determined long before 1897. Using this value for e, the value for the mass of the electron came out to be about 1/2000th of the mass of an atom of hydrogen. It required a great flight of the imagination and a considerable amount of intellectual bravery on the part of J. J. Thomson to announce his belief in the existence of a material particle of such unheard-of minuteness. In the years that followed everyone came to regard this strange conclusion as a fact.

The value of the charge on an electron is now accepted to be 4.804×10^{-10} electrostatic unit, or 1.603×10^{-19} coulombs. This value is, of course, also the value of the charge on a univalent electrolytic ion, such as that of hydrogen or chlorine.

The deduced value of the mass, m, of the electron then turns out to be 9.1×10^{-28} gram. The mass of the hydrogen atom is 1.675×10^{-24} gram, from which we see that the ratio of these two masses is approximately 1:1838.

The Electron as a Fundamental Particle

It is to be noted that electrons are produced in many different ways, and experiments similar to J. J. Thomson's were carried out to determine the value of the ratio e/m for electrons produced

in a great variety of ways. The amazing result of all these investigations, carried out by many workers in different countries, was that, no matter how the electrons were produced, they always gave the same value of the ratio e/m. Moreover, although Braun tubes were made with a number of different metals for the cathode, all these metals gave off electrons having the same e/m ratio. It is true that some metals will give off their electrons more readily than others, but there is no doubt that all metals contain a copious supply of electrons.

Later experiments have disclosed that insulators also contain electrons, but they are not nearly as readily released from the confines of these materials, be they glass, ebonite, sulfur or any other insulating substance, as in the case of metals.

We may then look upon the electron as a building stone of matter in general. Even organic materials, such as plastics, wood, cotton, and plant tissue contain electrons in their basic atomic units.

The Building Stones of Matter

It would be misleading to say that all matter is made of electrons only. It is true that all matter contains electrons, but they are not the only fundamental building stones. Since the value of e adopted for the electronic charge was equal in magnitude to the charge on a hydrogen ion, and so related to the hydrogen atom, it was thus postulated that the hydrogen atom was tied up in some way with *one* electron. Now it was known already from earlier experiments that atoms (or even molecules) are not, of themselves, charged either positively or negatively. Consequently, if we assume *one electron* to be a constituent of a hydrogen atom, we must assume that there will be another part of the hydrogen atom which possesses, of itself, a positive charge equal in magnitude to e. This assumed second part of a hydrogen atom has been given the name of *proton.*

Since a hydrogen atom consists of *one* electron and *one* proton, and since the mass of *one* electron contributes only about $\frac{1}{2000}$th of the total mass of the hydrogen atom, we are led to say

that the mass of the proton is about $\frac{1999}{2000}$ths of the mass of the hydrogen atom.

Early in the last century there was propounded the theory that all other atoms were made up of hydrogen atoms. In place of this we now say that atoms—all atoms—are made up fundamentally of electrons and protons, in equal numbers. The electrons contribute little to the mass. Elemental substances differ from one another only in the number of electrons and protons per atom.

There is very definite experimental evidence that when strong electrical forces from external sources are exerted on a group of atoms, some of the atoms are broken up, giving rise to positively charged and negatively charged remnants. Since the electron has such a small mass, the idea was suggested that this breakup of atoms was due to the expulsion of one or more electrons from the atom. Some atoms thus lose one or more of their units of negative charge and are then left with a net positive charge equal in magnitude to that of the negative charge carried by the escaping electrons. An atom thus deprived of one or more of the normal number of its electrons is called an *ion*, and the process is known as *ionization*.

This illustrates the beginning of the construction of a *model of an atom.* It should be apparent to all that the whole development is built up on step-by-step assumptions suggested by our everyday experience with things which we handle.

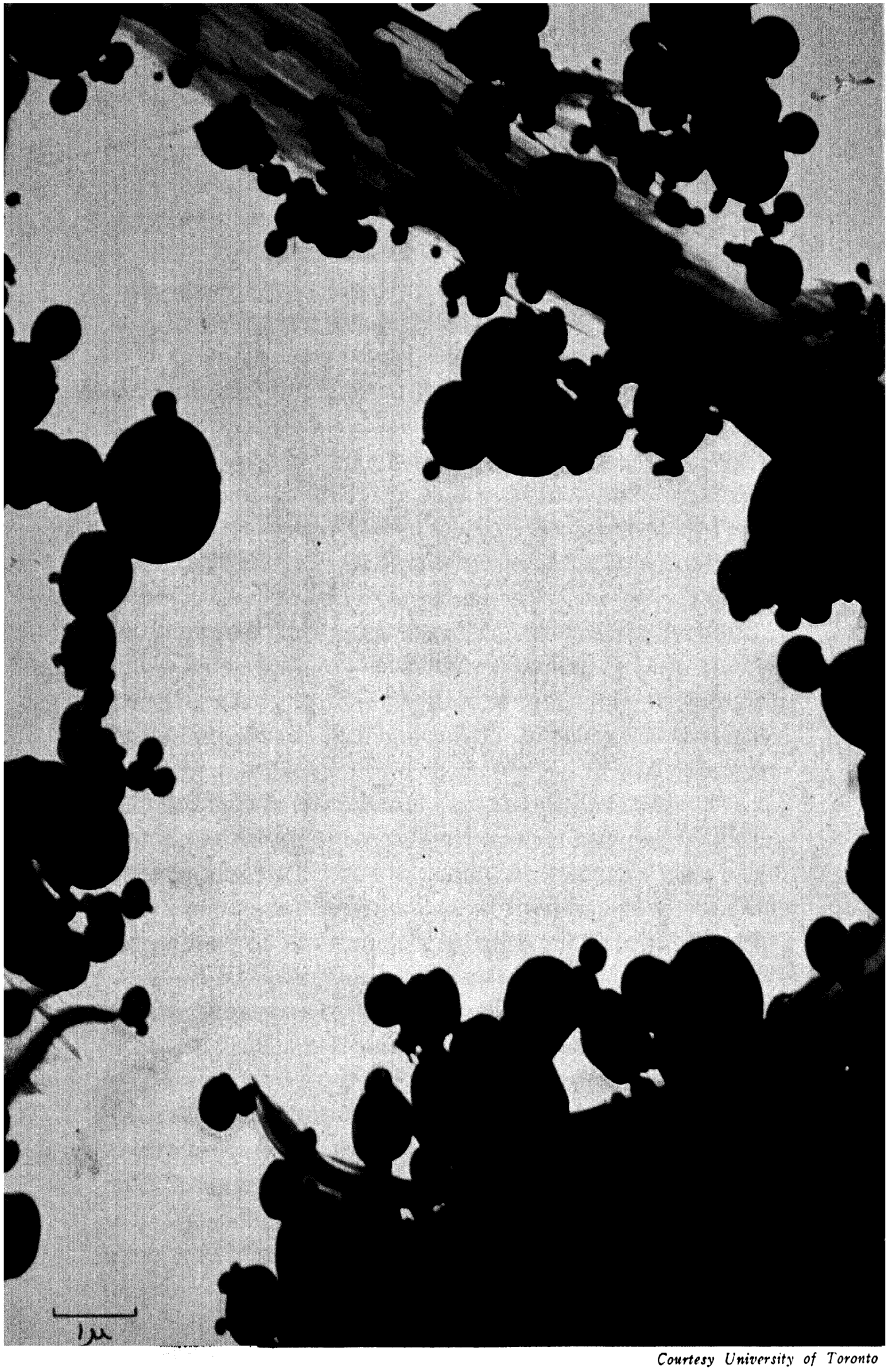
Electron Emission in the Braun Tube

We are now in a position to say a few words about the origin of the electrons in the Braun tube and the mechanism by which they are produced. The pressure in this tube, as first constructed by F. Braun in 1897, is about 5 millionths of one atmosphere or, in terms of millimeters of mercury, between 1/100 and 1/1000 mm. At this pressure one cubic centimeter contains millions of molecules made up of some of each of the constituents of air, namely oxygen, nitrogen, carbon dioxide, hydrogen, carbon

monoxide and the rare gases argon, neon, krypton, xenon and radon to a very small degree. The molecules of most of the gases consist of two or more atoms that normally associate in groups and they are almost always electrically neutral.

Ordinarily some of these gas molecules are ionized, since cosmic rays and rays from radioactive materials traverse all space and even penetrate the glass of the tube. These rays have a great content of energy which they can impart to the gas molecules with the result that, in the space between the cathode and the anode, some electrons are set free and positively charged gas ions are created. The electrons will move toward the anode and the positive ions toward the cathode. It is a peculiarity of gas-discharge tubes that the strongest electric force exists in the region close to the cathode. The fairly heavy positively charged ions drift toward the cathode, due to the electrostatic attraction, and they are finally given a great acceleration toward the cathode disk and impinge on it with great energy. This energy sets free electrons from the metal of the cathode and these electrons in turn are now driven away from the cathode by the electrostatic repulsion. They shoot like bullets out of a gun and travel in approximately straight lines toward the fluorescent screen. If such an electron should strike a gas molecule during its travel it will give up some of its energy and ionize this molecule, creating new electrons and ions, so that in the end a regular avalanche of positive ions strikes the cathode, producing more electrons. The bombardment of the cathode by positive ions can be so severe that some of the metal is sputtered away and deposits as a thin film on the glass wall of the tube.

It is readily appreciated from this somewhat sketchy description that the Braun tube operates by virtue of its imperfect vacuum. If there were no gas left in the tube the avalanche could not get started and no electrons would be obtained. On the other hand, we have all complained about gassy radio tubes in our sets at one time or another and so have an appreciation of the undesirability of gas-filled tubes. There must be other ways to get electrons out of cathodes. Let us find out how.



Courtesy University of Toronto

Lens paper and methylene blue. A solution of methylene blue was blown through an atomizer into air and the air was then drawn through lens paper. The bare parts are holes in the paper. The bar across the middle is a very fine fibre of the paper. Note the spherical shape of the methylene blue particles and the strange way in which they cling to one another. ×14,200.

Chapter 9

ELECTRON EMISSION

Thermionic Emission from Metals

It has been mentioned above that all matter contains electrons. Among the solid substances, metals in particular show an abundance of electrons, and it is because of this fact that metals "conduct electricity." This latter statement simply implies that some of the electrons contained in the metal are free to move under the influence of an electric field established within the metal by the application of an electric force. The flow of electrons within metallic conductors drives our motors, lights our lamps and heats our kitchen ranges.

The flow of electrons through empty space in a vacuum tube actuates radio tubes, photocells, cathode ray tubes, television camera tubes and electron microscopes. Evidently in these cases, some means must be found always to get the electrons out of the metal and make them travel through the vacuum along predetermined paths.

The most commonly employed method by which electron emission is obtained from a metal is that of heating the metal to a high temperature. That electrons are emitted from an incandescent wire in the presence of an external electrical field was discovered by Thomas Edison in 1881, though not described in our present-day language. Broadcasting transmitting tubes utilize incandescent tungsten filaments as a source of electrons. Wehnelt discovered in 1904 that the oxides of such metals as calcium, strontium and barium emit electrons more copiously at much lower temperatures than metals do. These "dull emitters," operating at a dull red heat, are used nowadays in all our radio receiving tubes. They consume less power than a bright emitter and

consequently are more economical in operation. Dull emitters yield more electrons per dollar.

Electron emission obtained from metals by heat is described in technical language by the term *thermionic emission.* This name was coined at a time when the nature of the emitted particles was still in doubt and it does not describe thermal electron emission clearly. To be sure, there always takes place a definite, though negligible, amount of *ion* emission when electrons are emitted, but the term *thermionic emission* is now used with the meaning of thermal electron emission, *i.e.*, emission of electrons by heat.

The emission of electrons from a metal surface has, at times, been compared to the evaporation of water vapor or steam from a water surface. At reasonably low temperatures, the water particles cannot escape very easily from the bulk of the liquid since they are held in subjection by the attraction of their fellows. When the water is heated to higher and higher temperatures, some individual water molecules gain enough kinetic energy to escape from the surface. When the temperature has risen to the boiling point, all the energy put into the water as heat is used to provide escape energy for the molecules at the water surface until all water has evaporated. We picture this process as a mechanical model for thermionic emission. In this case also heat must be provided in order to overcome forces at the surface of the metal which tend to restrain the electrons.

Electron Emission from Oxide-coated Cathodes

Thermionic emission from oxide-coated cathodes has been utilized technically for over thirty-five years, but a clear understanding of the mechanism of thermionic emission has been gained only recently. It has been established by innumerable experiments and investigations during the past few decades that the copious emission of electrons from an oxide-coated cathode is due to the existence of a very thin film of metal on the surface of the oxide layer.

The oxide layer itself is produced by a chemical reaction that takes place when the cathode is first heated *in vacuo.* It

is probably the most general practice in America to spray onto the cathode surface a mixture of barium carbonate ($BaCO_3$) and strontium carbonate ($SrCO_3$), to which calcium carbonate ($CaCO_3$) is added in some cases. These carbonates are prepared in the form of a suspension in amylacetate, with some nitroglycerin as binder. Mixtures of this type are commercially available from chemical supply houses. The cathode material consists of pure nickel or nickel with a fraction of a per cent of titanium, aluminum or magnesium added. During the process of exhausting the tube the cathode is heated in steps up to a temperature of about 1350° K.* The alkaline-earth carbonates (or nitrates, or hydroxides as the case may be, depending on the compound that was originally sprayed onto the cathode) break down at about 1100° K into oxides and carbon dioxide (or nitrous oxide or hyrogen in the case of the nitrates and hydroxides, respectively). The gas is pumped away, leaving the oxide layer on the cathode. In the presence of small amounts of reducing agents such as carbon, titanium, aluminum or magnesium, about 0.5 per cent of the oxide molecules are reduced to free barium (or strontium or calcium), with the release of oxygen. Confining our description to the case of barium, we may say that the barium atoms in the bulk of the oxide coating find their way to its surface by diffusion and form a monatomic layer which, for optimum emission, need not cover the oxide surface completely. Partial reduction of the oxide takes place at the "sinter temperature" of about 1350° K. During its use the cathode is operated at about 1000° K and diffusion of the atoms to the surface may continue during its life. This thermal activation in the absence of externally applied voltages, which we have just described, is possible only in the presence of reducing agents. It is a reliable technique for mass production and does not require any prolonged ageing of the cathode after the tube has been exhausted although ageing is generally applied in order to stabilize the emission.

* 1350° K is read "1350 degrees Kelvin" or "1350 degrees absolute" and refers to the absolute temperature scale introduced by Lord Kelvin. This scale is widely used in the scientific literature and can be translated into centigrade by subtracting 273.18 degrees; thus 1350° K equals 1076.82° C. Or, the other way around, °K is obtained from °C by adding 273.18. Thus, water boils at 373.18° K under normal pressure.

Aside from this purely thermal activation, another activation procedure may be followed which is characterized by the application of anode voltage during the high-temperature treatment of the cathode while the tube is being evacuated. It may then be assumed that the oxide is separated into barium ions and oxygen ions which will migrate under the influence of the applied field according to Faraday's laws of electrolysis. The direction of the field is such that the positive barium ions drift through the oxide toward the core metal, where they give up their charge, while the negative oxygen ions migrate toward the surface of the coating and escape. The neutral barium atoms will then again diffuse through the oxide coating from the core metal to the surface and form the active surface layer, which is the origin of the electron emission under normal operating conditions. This electrolysis activation does not require any reducing agents and can thus be applied to materials of extreme purity.

The existence of the thin barium film, the way in which it is produced, and the seat of the electron emission, have been subjects of lively controversy for many years. However, very conclusive experiments have been carried out that prove the existence of the barium film at the cathode surface and show that without its presence the copious electron emission ceases; the barium film evaporates at 1600° K. The electron microscope has added greatly to a better understanding of thermionic emission, since it not only permits visual observation of the intensity distribution of the electron emission over the cathode surface during operation, but also reveals minute changes in emission from point to point, at the surface of the coating.

Comparison of the Electron Yields of Emitters

Pure metals, such as nickel, tungsten, molybdenum and platinum, do not emit electrons unless they are heated to very high temperatures. Only tungsten and molybdenum are used as "bright emitters" in practical cases. To give an example, an oxide-coated cathode will emit 100 ma. per square centimenter of its surface when at a temperature of 1000° K. It will require a certain number of watts to reach and maintain this temperature.

If we divide the total emission obtained from a cathode by the number of watts supplied to the cathode heater, we arrive at the emission yield, which is about 20 milliamperes per watt for an oxide-coated cathode. A tungsten filament operating at 2300° K will give about the same emission per sq. cm as the oxide cathode at 1000° K, *i.e.*, 100 milliamperes per sq. cm, but the emission yield will be less than one milliampere per watt.

In order to produce an electron current between cathode and anode it is necessary to apply a positive voltage to the anode. We shall explain very shortly (p.135) that an accelerating field must exist at the cathode surface in order to send the electrons on their way toward the anode after they have been released from the bulk of the cathode by the thermal energy imparted to them from the heater unit.

The ease with which a cathode surface is able to emit electrons is expressed by a term called "work function," the symbol for which is ϕ. It stands for the amount of work which the electrons have to perform in escaping from the cathode against the restricting forces exerted by the atomic lattice of the cathode and the induced electrical forces immediately after their escape.

The lower the value of ϕ, the more copious will be the emission under any given conditions, and the lower will be the operating temperature of the cathode necessary to obtain a certain required emission current. Table 5 gives the value of the work function, ϕ, in electron volts for a number of different cathode materials and also the common operating temperature in absolute degrees (°K), the melting point in °K, the emission yield in milliamperes per watt and the electron emissivity in milliamperes per sq cm of active surface.

Secondary Electron Emission

We have so far described two mechanisms by which electrons may be released from the confines of a metal. In each case it was necessary to add energy to the cathode. The "cold" cathode of a gas-discharge tube was bombarded by positive ions which imparted their kinetic energy to the cathode; the "hot" cathode of Wehnelt received energy in the form of heat. In both cases

this imparted energy was transformed into kinetic energy gained by the "free" or "conduction" electrons of the cathode, which were thus enabled to "escape" from the cathode into the vacuum. This "escape energy" can be provided in still different ways, as we shall see presently.

We may well utilize again the model introduced above which established an analogy between the evaporation of water molecules and thermionic emission of electrons. Small masses of water can be forcibly separated from any large body of water, even at low temperatures, when a foreign body, for instance a stone, is thrown into the water and a splash is produced. The splashing water spray derives its escape energy from the kinetic

Table 5

Emitter	Symbol	Melting Point (°K)	Operating Temperature (°K)	ϕ (electron volts)	Emission Yield ma/watt	Electron Emissivity ma/cm^2
Barium	Ba	1123		2.52		
Strontium	Sr	1030		2.1		
Calcium	Ca	1083		3.2		
Barium oxide	BaO	2196	1000	1.1	20.	100.
Strontium oxide	SrO	2703	1000	1.4		10.
Calcium oxide	CaO	2845	1000	1.9		1.
Tungsten	W	3643	2300	4.52	1.	100.
Molybdenum	Mo	2890	2200	4.15		100.
Platinum	Pt	2047		5.32		
Nickel	Ni	1725		5.03		
Thoriated tungsten	W-Th		1900	3.15	40.	1200

energy of the stone that has been thrown in. When particles much larger than electrons, such as positive ions, are directed toward a metal surface with sufficient velocity, their impact will "splash" electrons from the metal. Likewise, if electrons of sufficient velocity, obtained from another source, are directed toward a metal surface they will impart their energy to the free electrons of the metal and thus knock them out of the metal. Electrons emitted by the bombardment of a surface with charged or uncharged particles are called *secondary* electrons, and this

type of emission is termed *secondary emission.* The bombarding particles, if they are electrons, are called *primary* electrons.

If we carry our analogy a little farther we may gain greater insight into the mechanism of secondary emission. The splash of water is noticeably more pronounced when the stone is thrown into the water at an oblique angle than when it is simply dropped vertically. Similarly, the secondary electron yield is greater when a primary electron strikes a metal surface at an oblique angle rather than at a right angle. Two, three, indeed as many as eight secondary electrons may leave the surface for each impinging primary electron; and finally, as the stone may skip after its first contact with the water, the primary electron itself may be "reflected" by the metal after a very slight penetration into it and be re-emitted as a reflected secondary electron.

All these effects have a great practical importance. During the early stages of the development of electronics, the science dealing with electronic tubes and devices, secondary electrons had none but nuisance value. They were most unwelcome, since they interfered with the controlled electron stream emitted by the cathode; they had to be suppressed and the introduction of the "suppressor grid" into the radio tube which promoted the triode to the tetrode was a distinct advance. In later years, ways and means were found, however, to utilize secondary electron emission to advantage so that today secondary emission amplifiers are available which have made possible great advances in television. One may well say that without secondary electron emission present-day cathode ray television systems would not be possible.

Photoelectric Emission

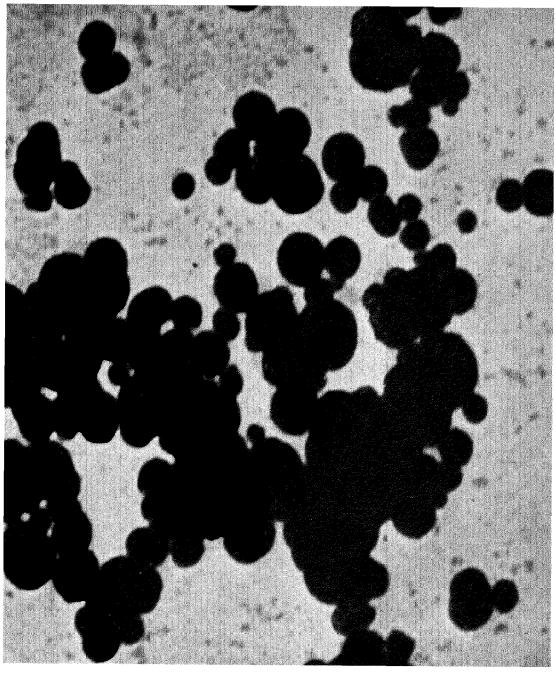
Photoelectric emission of electrons is another example of cold-cathode emission. Electrons are released from a metal surface by the incidence of light. This effect was discovered by Wilhelm Hallwachs in 1888. Since we used the splashing of water for the explanation of cold-cathode emission by bombardment with positive ions or electrons, we may well extend it to photoelectric emission. The stone or foreign body which produced

the splash of droplets when dropped or thrown into the water was the model for positive ions in one case and for primary electrons in the other. We shall now let it stand for Newton's light particles and thus find no difficulty in forming a picture of the photoelectric effect. In all three cases we transfer the kinetic energy of a particle to the free electrons of the metal and thus provide the necessary escape energy for their release.

By reinstating Newton's light particles we apparently nullify our earlier statement that these could not stand the test of experimental facts discovered later. It is quite true that the particle concept did not fit the effects of diffraction, interference and polarization, all of which were discovered long before 1888. The photoelectric effect, on the other hand, presented an entirely new problem, as we shall show presently. It can be explained satisfactorily only on the basis of the particle concept, and the extension of our analogy above is therefore quite justified.

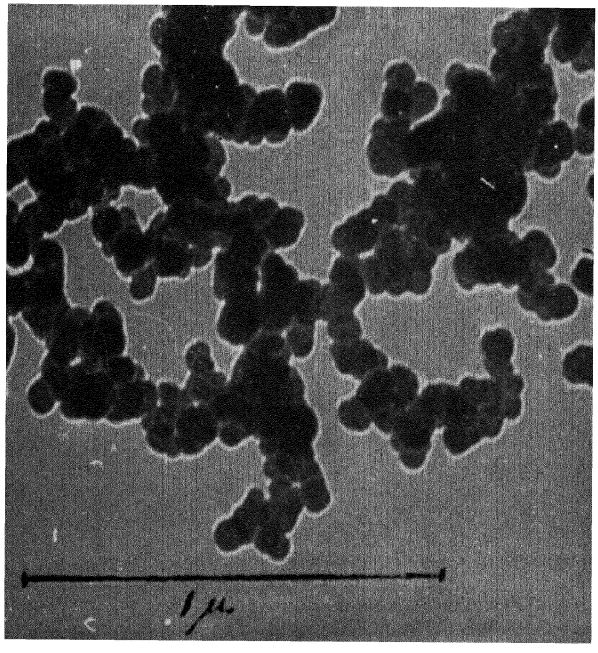
Luminescence and X-rays

We have just learned that a beam of light can release electrons from a solid body. Sir William Crookes demonstrated unknowingly that a beam of electrons can release light from certain minerals when these are bombarded by electrons. The luminescent screen of willemite in the Braun tube is based on this effect. Very fast electrons will release an invisible light from metals when they impinge upon them. This was discovered by Roentgen in 1895, and the invisible radiation emitted by the metal is now known under the name of x-rays. It was established by experiments in later years that x-rays have the same fundamental properties as ordinary light; their energy content is, however, very much greater. They are thus not so readily absorbed by any material bodies that stand in their path. They penetrate the glass wall of the tube envelope within which they are produced and are stopped only by fairly dense substances, such as bone structures or metals. When the x-rays impinge upon a photographic plate they reduce the silver bromide film in the same way as light does and thus produce a shadowgram of the objects in their path.



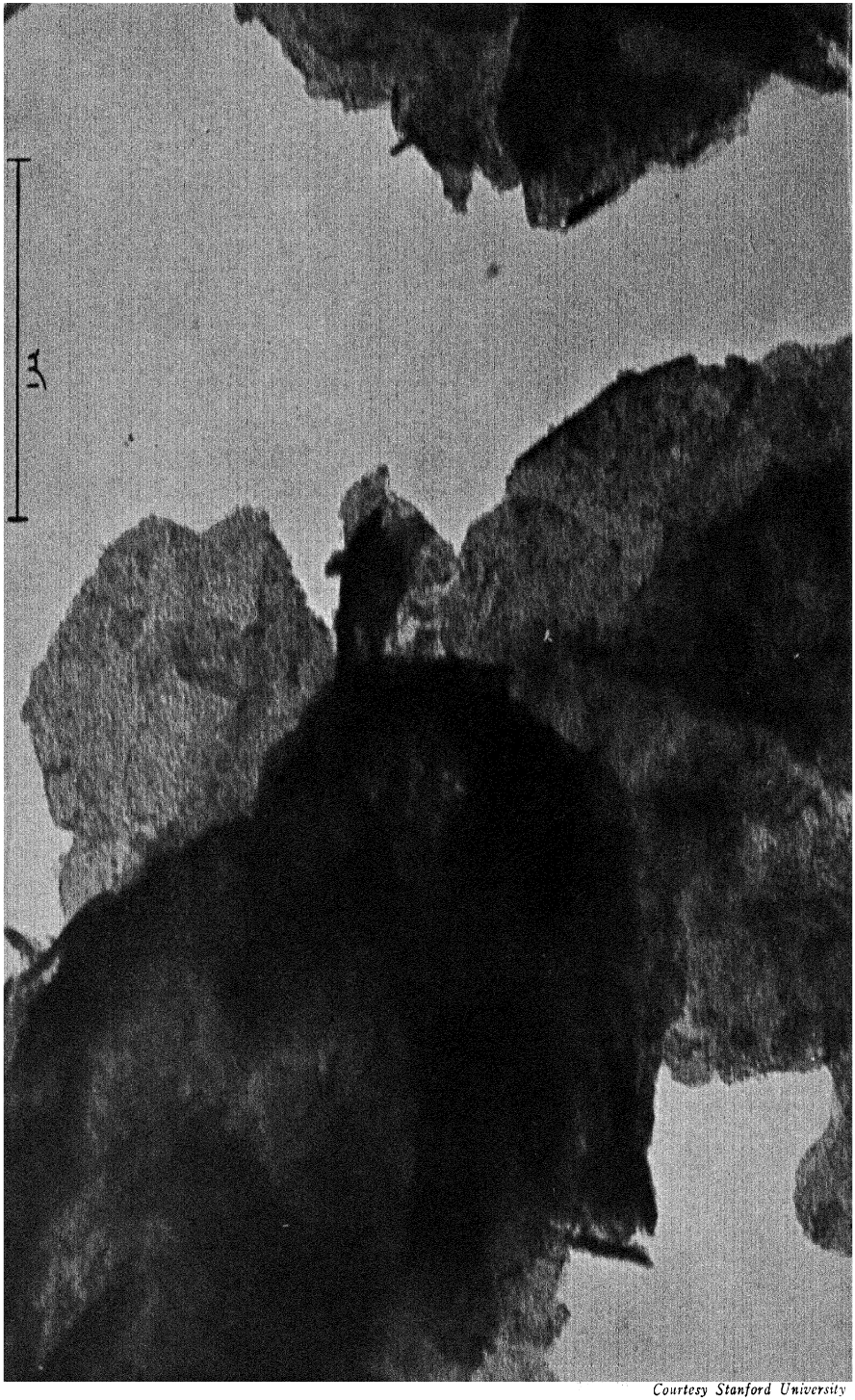
P-33 Carbon Black Particles; note smooth surface and spherical form.

Courtesy Columbian Carbon Co.



Micronex Carbon Black Particles.

Courtesy RCA Laboratories



Courtesy Stanford University

"Extra Light" Magnesia, 70 kv. original magnification ×8200.

Chapter 10

THE DUAL THEORY OF LIGHT

The Photoelectric Effect

During his experiments on the creation of short radio waves from an electric spark, Heinrich Hertz observed in 1887 that a spark would pass the gap more easily if ultraviolet light fell on the negative pole of the gap. Stimulated by this observation, Wilhelm Hallwachs, a year later, found that a negatively charged body loses its charge under the influence of ultraviolet light; this is the so-called Hallwachs effect. In later years, it was shown that a great number of substances, solid, liquid and gaseous, emit electrons under the influence of light. This phenomenon is called the *photoelectric effect*. It is the basis of the modern "magic eye" or photocell. Television pickup cameras are based on the photoelectric effect and so are sound films. Innumerable industrial devices utilize photoelectric cells which are now being manufactured in large quantities. Aside from its practical importance, the discovery of this effect marks a milestone in the history of physical science. It led to the establishment of the dual theory of light. Since this subject is our main concern in this chapter, we must of necessity take pains to study the laws that govern this photoelectric effect.

Let us first become familiar with the physical appearance of a photocell and its operation. Fig. 46 shows the diagram of such a cell in its simplest form. A spherical glass envelope with a tubular neck, St, is mounted in a base, B, which carries a base pin, P. This pin is connected with a straight wire, A, (or a loop), that is supported in the center of the sphere on a glass stem. The inside of the glass sphere, with the exception of a window, W, is silvered and electrical connection with the silver film is made through a fine wire which is sealed into the glass and

soldered to the terminal, K; this film serves as the cathode and A as the anode. During the process of manufacture the cell is connected to an exhaust system through a tube attached at T. The silver layer is oxidized by passing a glow discharge in an oxygen atmosphere and then cesium (or some other alkali metal) is deposited on the silver oxide. A carefully controlled baking process permits a reduction of the silver oxide and the formation of cesium oxide with some excess of cesium at the inner surface. This complex surface, the photo-cathode, has been found to yield a large supply of electrons when it is exposed to a light source, L, sending its rays through the clear window, W. In order to facilitate the flow of electrons through the cell, a positive voltage, E, from a battery is applied to the anode, A; a current, *i*, indicated by a micro-ammeter, M, will flow through the circuit as soon as the cell is exposed to light. When the light is shut off, or the window covered, the current falls to zero immediately.

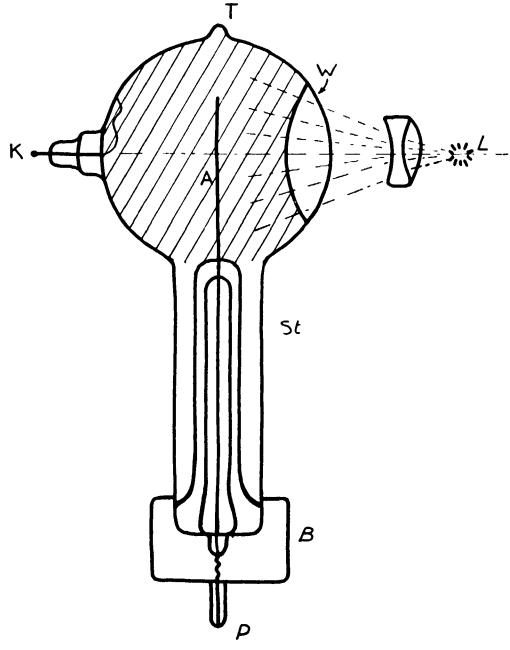


FIG. 46. A photoelectric cell.

Fig. 47 gives the circuit diagram. A load resistance, R, is included in the circuit. This may take the form of a sensitive relay, which operates any desired device, or the voltage drop across the resistance, R, created by the photo current, *i*, may be fed to the input stage of an amplifier so that a less sensitive relay may be used in the output circuit of the amplifier tube.

The following facts can now be observed:

(1) The photo-electrons are emitted by the cathode, without any measurable delay in time, as soon as the light reaches it.

(2) The number of electrons emitted increases with an increase in the intensity of the light source; *i.e.*, the stronger the illumination of the cathode the greater the number of electrons emitted per unit area of the cathode and the greater will be the deflection of the ammeter.

(3) The frequency of the light source, or, in other words, the color of the light or the wave length of the light, has a decisive effect on the operation of the cell. The *velocity* with which the electrons leave the cathode, or, in other words, the *energy of the electrons* at the moment they leave the cathode, increases with the *frequency* of the light. The intensity of the light has no effect on the value of this initial energy of the electrons. Furthermore,

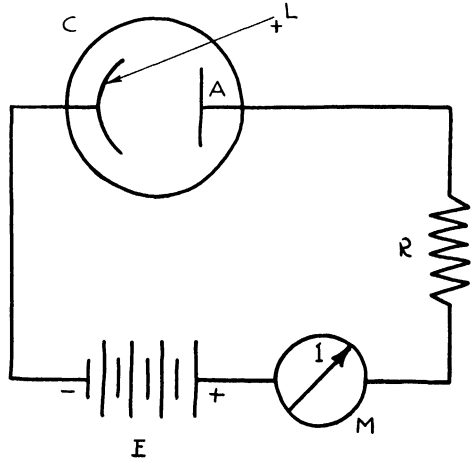


Fig. 47. A photoelectric cell circuit.

the frequency of the light source must exceed a certain characteristic minimum value before any electrons are emitted at all. This threshold frequency, ν_0, or threshold wave length, λ_0, depends on the type of cathode that is used in the cell. It is thus possible to make cells that are particularly sensitive to red light, others that respond to blue or ultraviolet light, and again others that have their maximum sensitivity coincide with that of the human eye at 5,500 A. U. (yellowish green).

The laws governing the photoelectric effect are illustrated by graphs in Figs. 48, 49, and 50. In Fig. 48 the current, i_e, carried by the number of electrons, n, emitted per second per unit

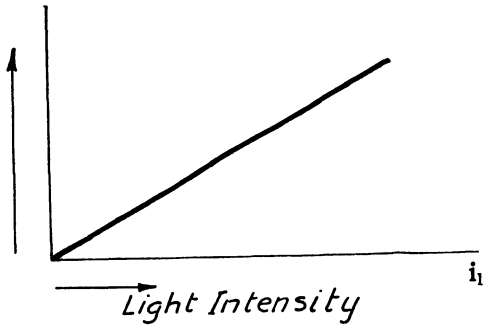


FIG. 48.

Relation between the photoelectric current, i_e, and the intensity of the light causing this current.

of cathode area is plotted as ordinate and the incident light intensity, i_1, as abscissa. We find that i_e is directly proportional to i_1. Fig. 49 shows how the energy, E, of the emitted electrons increases uniformly as the frequency, ν, of the light from a constant-energy light source is gradually increased. It is to be noted that a certain definite theshold frequency, ν_0, must be reached before any energy is emitted. Fig. 50 gives the response of a cell to the various wave lengths of the spectrum. The photocurrent per unit of area which results from a unit of light energy of a given wave length is plotted for the whole spectrum of wave lengths. When the wave length is longer than λ_0 in the infrared region, corresponding to ν_0 in Fig. 49 ($\nu = v/\lambda$), no more electrons are emitted. This random example, Fig. 50, discloses a strong maximum photo-current in the blue region of the spectrum and a lesser second maximum in the red.

The Inadequacy of the Wave Theory

We shall now try to explain these facts on the basis of Maxwell's electromagnetic wave theory of light. Without losing ourselves in too many details, we may apply the familiar concept of any wave theory to the problems at hand. It is, for instance, readily observed in everyday occurrence that a radiating source gives off energy uniformly in all directions. Thus, a light source can be seen from all directions, a bell on a church tower can

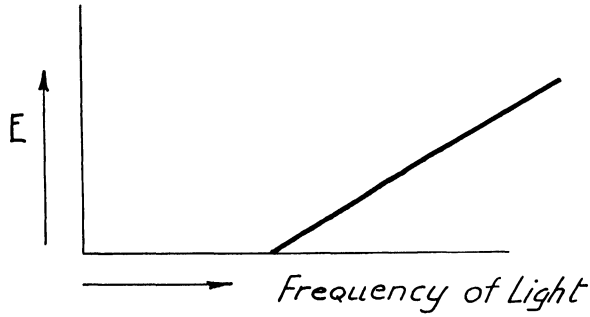


FIG. 49.

Dependence of the energy of the emitted electrons, E, and the frequency of the incident light. The frequency ν_0 is the point where the graph leaves the axis.

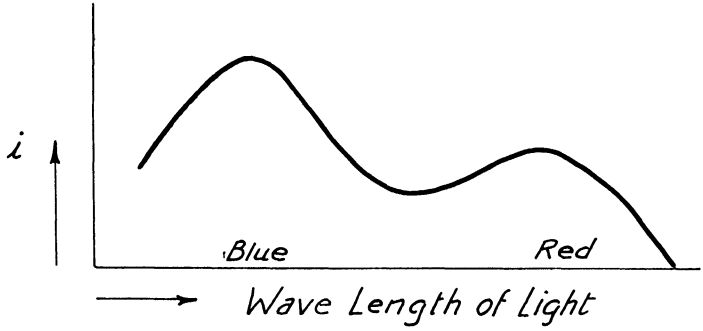


FIG. 50. How the current, i, of a typical photoelectric cell varies as the wave length of the incident light increases.

be heard from all directions, as long as no obstacle intervenes. The intensity of the light received or of the sound heard will decrease with the distance from the source according to a definite law. It turns out that the received energy falls to one-quarter of its original value when the distance is doubled or to one-ninth when the distance is trebled, and so on: in other words, the received energies are coupled with the distance from the source by the inverse square law. If we keep the distance from the

source constant, the received energy at that distance will be the same per unit of time, no matter in which direction from the source the receiver is located. If an airplane flies in a circle around a transmitting tower, the light at its top will appear of a certain constant brightness to the pilot. He could fly on the surface of a sphere with the light source as center and still observe the same brightness; this sphere is indicated in Fig. 51. If the pilot then should fly further away, say, on a sphere twice as large, the beacon would appear to be only one-quarter as bright. If we

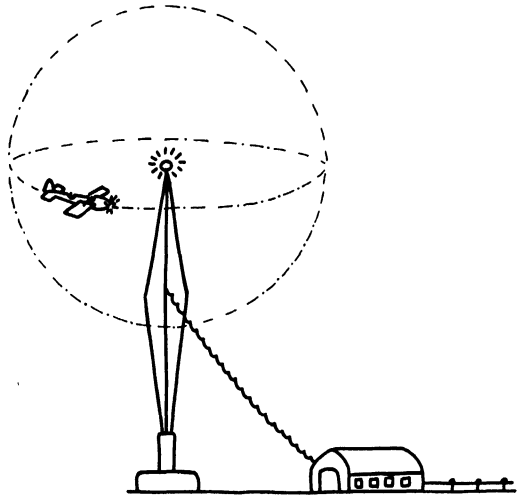


FIG. 51.

How energy received from a point source varies with the distance from the source.

were to follow the light energy that is sent out by the beacon at a particular instant and trace its propagation through space, we would have to visualize something like a soap bubble that first snugly fits the light bulb and then expands continuously to enormous proportions. It would of necessity become thinner and thinner as its size increased; the thickness of the film may be taken to measure the energy contained in a unit area of the surface. Since the fixed amount of energy that started to peel itself off from the bulb is spread over a larger area when the size of the sphere has increased, the energy per unit area must of necessity decrease.

When our light energy, or soap bubble—to continue the analogy—reaches a photo-cathode, the surface element of the bubble, say one square centimeter, will impinge on the corresponding surface element of the cathode and so transfer its energy to it. The electrons emitted from this small area by the light energy striking it should then share this energy among themselves and, according to the principle of the conservation of energy, the combined energy of the electrons could not exceed the energy content of the surface element of the light wave. Careful measurements disclose that this condition is not fulfilled. The electrons are actually emitted with a far greater energy than could be conveyed to them by a uniformly expanding spherical wave. It might be suggested that the cathode stores up the energy of a number of successive waves until the required amount is obtained to account for the observed electron energies. This would take considerable time, of the order of hundreds of hours, before the figures would agree. Actually, as has been stated above, no measurable time delay between the arrival of the light wave and the emission of the electrons can be observed.

Our discussion has been based on two assumptions. First, the validity of the principle of the conservation of energy and second the wave nature of light. Since our deductions cannot explain the observed effects one of the assumptions must be wrong. The law of the conservation of energy has been found to be quite consistently true and serves as one of the pillars on which the science of natural phenomena seems to rest. We must then, once again, call into question the wave nature of light.

The Quantum Theory

The nineteenth century complacency regarding the sufficiency of the wave theory of light received its first shock in 1900 through the work of Professor Max Planck of Berlin. He found it impossible to explain the experimental relations between the absorption and emission of radiant energy by hot bodies and their temperatures by any wave motion model. The classical concept, accepted at this time, was that the continuous flow of energy through space in the form of electromagnetic waves required that

both absorption and emission of such energy by hot bodies should also be continuous. But this theory of absorption and emission could not be made to agree with experimental facts. So Planck made the exceedingly bold assumption that, no matter how the energy is transmitted, absorption and emission at material bodies takes place in very small but definite units, *i.e.*, discontinuously. Each small unit bundle of energy, Planck called a *quantum*; he suggested that there would exist an "atom of mechanical action," which came to be represented by the letter h, now known as Planck's constant.

Now, when the curious results given by the photoelectric experiments were considered, it was apparent that they could be explained if one assumed a corpuscular theory for light. Einstein, in 1905, extended Planck's theory to say that not only are absorption and emission discontinuous but even the energy of a light beam travels through space in quanta. This brings us back to the corpuscular theory of light—Newton's theory!

A light corpuscle, a *quantum* or a *photon*, as it is called, would carry its energy undiminished from the source to the greatest distance and would be able to hand its energy to an electron when it strikes a photo-cathode so that the electron can be emitted instantly. The more intense the light source, the more corpuscles are emitted and the greater the number of electrons set free. This satisfies actual observations.

In order to explain the relation between the electron energy and the frequency of the light in the photoelectric effect (Fig. 49) it becomes necessary to assume that the various corpuscles of light have different energy contents depending on the frequency of the light. Thus a corpuscle, or quantum, or photon, of blue light contains more energy than one of red light; the electrons set free by blue light move faster than those set free by red light.

Einstein suggested that, as the energy is proportional to the frequency, it might be expressed by the relation:

$$E(\text{the energy}) = (\text{a constant}) \times \nu(\text{the frequency})$$

He further suggested that the constant be put equal to Planck's constant. This leads us to the fundamental equation for a quantum:

$$E = h\nu$$

We now find ourselves in a great predicament. All the arguments raised against Newton's corpuscular theory of light must of necessity come up again. We know that a corpuscular theory cannot explain diffraction, interference, or polarization. We may recall that Newton himself hesitated to be tied down to the corpuscular theory exclusively and made use of periodic states which imply nothing else but a wave character. This intuitive hesitation of his to accept a one-sided theory is now raised to a basic principle in physics. *Light is neither wave nor corpuscle: it is both.* This is what we mean by a *Dual Theory of Light.*

One should not be frightened at this seemingly contradictory statement. The fact is that we cannot bend nature to suit the niceties of our old-fashioned ideas. Things evidently are not as clear-cut as we would like them to be. We should furthermore bear in mind that the light corpuscle or photon, $h\nu$, is defined by a *frequency*, and thereby is closely tied in with the wave concept. Frequency is a derived term; it means the number of times that a wave recurs per second. To find the value of the frequency, we measure the wave length and then divide it into the velocity of light. We might say that the path of the photon is guided by the wave that is associated with it (Fig. 52). It simply helps our mind to visualize what may be going on. A transverse



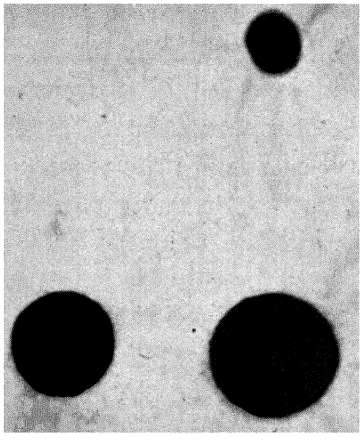
FIG. 52. An electron and its associated wave.

wave is drawn that weaves itself around the direction of propagation indicated by the axis. Wherever the wave intersects the axis the heavy dot represents a photon traveling in a straight line.

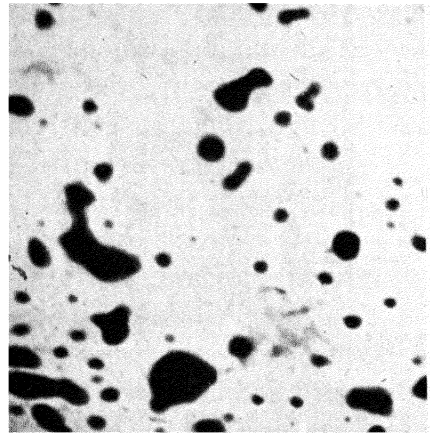
In disclosing this dual nature of light, not by the choice of their fancy but driven by irrefutable facts, physicists now think of the wave concept when describing phenomena that are evidence of the wave nature of light, and of the photon concept when dealing with the photoelectric effect and radiation problems. In the words of Sir William Bragg: "We teach the wave theory on

Mondays, Wednesdays and Fridays and the corpuscular theory on Tuesdays, Thursdays and Saturdays."

When we review the changes that the concepts of the nature of light have undergone during the course of the years and realize the fruitfulness of the concept of duality, we may well turn to the electron and question whether it has an exclusively corpuscular nature. It will be shown in the following chapter that for the electron also a dual theory has been firmly established. The wave nature of the electron is indeed the basis upon which the electron microscope rests.

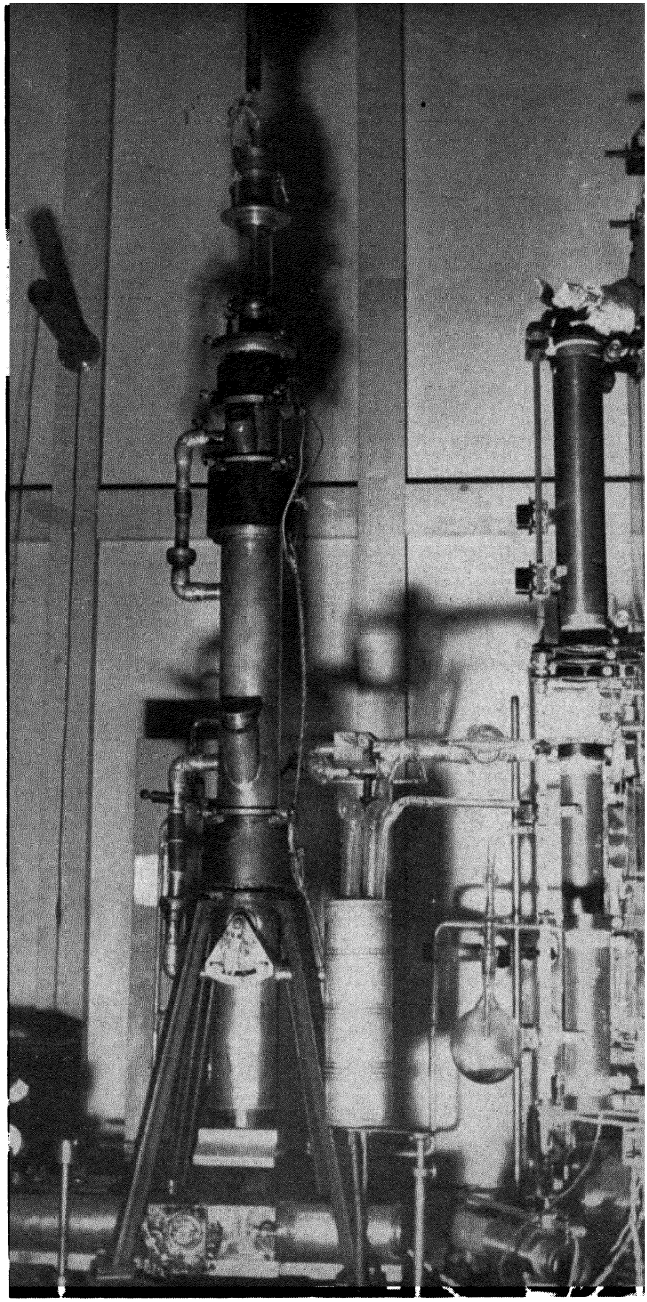


Particles of rubber in natural latex, magnified 25,000 times.



Courtesy Columbian Carbon Co.

Particles in synthetic-rubber latex (Buna-S) magnified 25,000 times.



The first magnetic electron microscope constructed in America at the University of Toronto. At the right is shown part of the evacuating system and rheostats used to regulate the magnetic fields of the lenses. The overall height is about six feet. The first picture was taken in June, 1938.



Courtesy R.C.A. Laboratories

Aluminum Oxide (×44,000).

Chapter 11

THE DUAL THEORY OF THE ELECTRON

Waves and Matter: de Broglie's Theory

Although the dual theory of light was impressed on the physicist rather early in this century, the far-reaching consequences of the fundamental experimental facts on which it was based were not fully recognized until de Broglie of Paris announced his new views in 1923. We have seen how light must be looked upon as having both a wave nature and a corpuscular nature, in order that we may have a satisfactory model simulating the action found in the various light experiments. In the photoelectric effect we find the energy of light directly inducing motion in electrons. Some time after the discovery of this effect, A. H. Compton (1922) showed that certain experiments could be explained satisfactorily only by saying that the action of the radiation of light in the form of x-rays upon an isolated electron was the same as though there were an ordinary mechanical collision between two corpuscles; the two corpuscles Compton suggested were the photon and the electron.

It was at this point that de Broglie suggested a new concept which is best expressed in his own words:

> "A consideration of these problems led me, in 1923, to the conviction that in the *Theory of Matter* as in the *Theory of Radiation*, it was essential to consider corpuscles and waves simultaneously, if it were desired to reach a single theory, permitting of the *simultaneous* interpretation of the properties of *Light* and those of *Matter*. It then becomes clear at once that, in order to predict the motion of a corpuscle, it is necessary to construct a *new mechanics*, a theory closely related to that dealing with wave phenomena, and one in which the motion of a corpuscle is inferred from the

motion in space of a wave. In this way there will be, for example, *light corpuscles*, *photons*, but their motion will be connected with that of Fresnel's *waves*, and will provide an explanation of the phenomena of interference and diffraction. Meanwhile it will no longer be possible to consider the material corpuscles or electrons as discrete isolated entities; it will, on the contrary, have to be assumed in each case that they are accompanied by a wave which is bound up with their own motion. I have even been able to state in advance the wave length of the associated wave belonging to an electron having a given velocity."

We recall that in talking about sound waves, we found a simple relation ($v = \nu\lambda$) between the velocity, v, the wave length, λ, and the frequency, ν. Now, if the energy of the electron is also directly proportional to the frequency, we should expect a simple relation between the velocity of the electron and the wave length to be ascribed to it. This relation is expressed by: The wave length, $\lambda = \dfrac{\text{Planck's constant, } h}{\text{Mass of electron } (m) \times \text{its velocity, } (v)}$

or $$\lambda = \frac{h}{mv}$$

Experimental Confirmation of de Broglie's Theory

The theory outlined in the last section was *mere theory*. The important question then was: "Would electrons, or a beam of electrons, exhibit experimentally that there really is a wave motion associated with an electron, or, in other words, would a beam of electrons show the phenomena of interference and diffraction, the *sine qua non* of wave motion?"

After de Broglie's announcement, this question was investigated and soon answered in the affirmative by two groups of workers, quite independently: by Davisson and Germer (1927) in the research laboratories of the Bell Telephone Company, New York, and by G. P. Thomson in work done at Aberdeen (1928). We do not need to go into the details of these experiments, but it will suffice to say that they answered the question decisively. A moving electron has a wave associated with it.

The Wave Length Possessed by an Electron

As noted above, the theoretical value of the wave length that de Broglie worked out for an electron is

$$\lambda = \frac{h}{mv'}$$

The value of m, the mass of the electron, a constant for all electrons, was determined first by Sir J. J. Thomson and many times since, so both h and m are well determined constants.

As we shall see later, the velocity of an electron can be easily determined if we know the accelerating voltage (V). Substituting the various experimentally determined values in the above expression, it has been found that

$$\lambda = \frac{12.24}{\sqrt{V}} \times 10^{-8} \text{ cm.}$$

where V is expressed in volts. If the voltage is of the order of hundreds of volts, the wave length is of the order of 10^{-8}cm or less.

In view of this fact, scientists interested in the microscope at once asked: "Can the electron waves be used in any kind of microscope?" Because, if they could, there would be promise of increasing the resolving power a thousand times or more.

We know that the light microscope permits us to see particles 1/125,000th of an inch in diameter. Smaller ones we cannot see. (Chap. 6.) We are limited by the wave length of the light. Using electron light, which has very much smaller wave lengths, we should be able to photograph very much smaller particles and also to reveal much greater detail in an object.

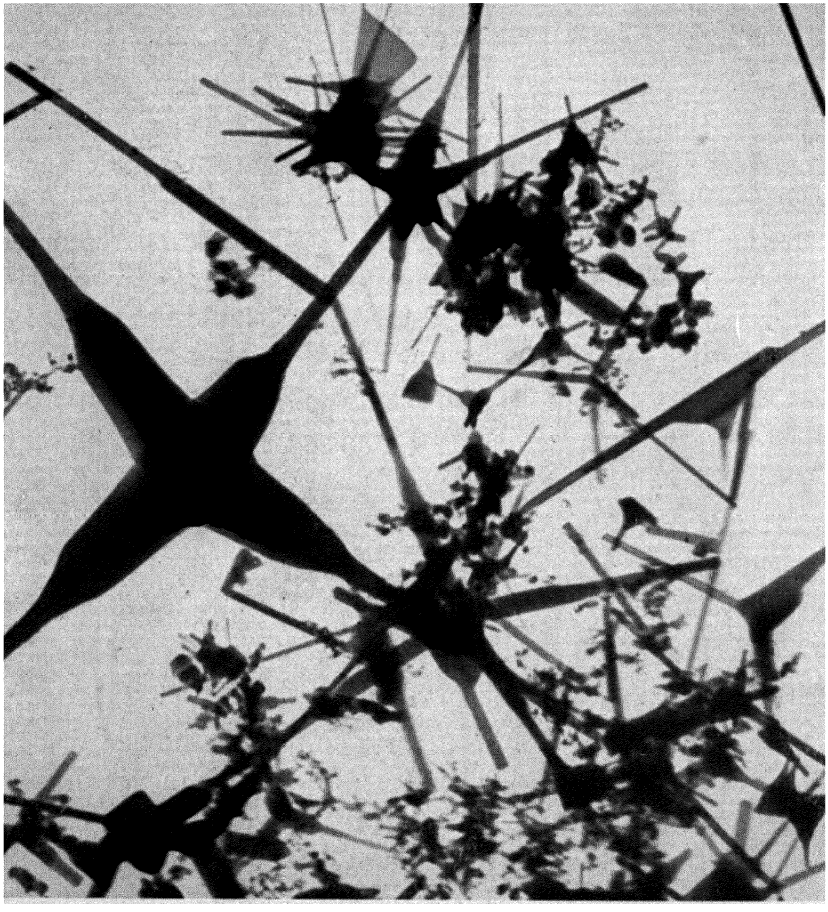
This the *electron microscope* has accomplished.

Electron Waves and Electron Rays

In the development of his theory, de Broglie showed that the path of an electron, its so-called *trajectory*, as it moves through space bears much the same relation to its wave property as the *ray of light*, which we have used in our early figures, does to the wave property of light. In de Broglie's words, "the possible trajectories of the corpuscle are identical with the possible rays

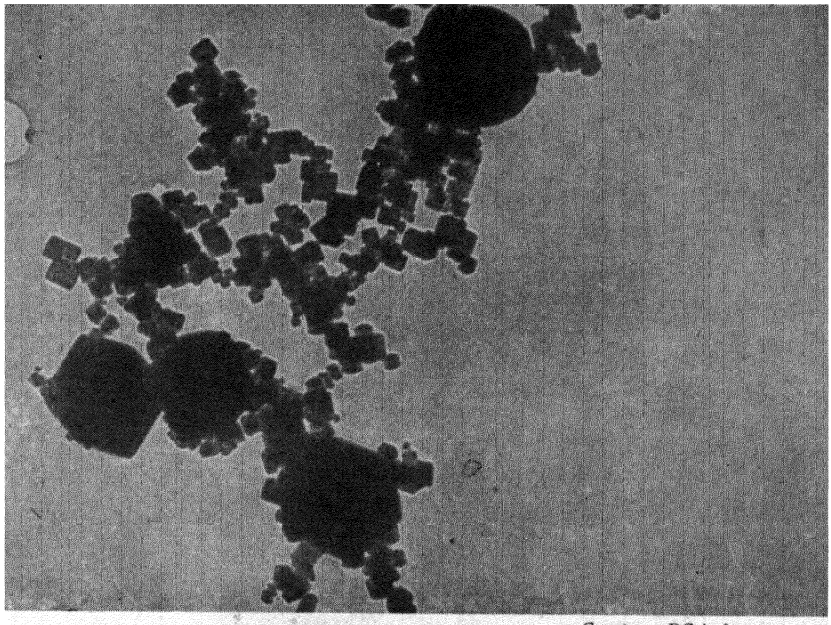
of its wave." Therefore, if we could determine these electron paths and treat them as "light rays," we might find out something about the possibility of focussing such rays.

There are two ways in which the paths of electrons may be affected: (a) by electrical fields of force and (b) by magnetic fields of force. Of course, these electron beams cannot pass through material lenses, and so if we wish to produce the refraction of electron-waves, we shall have to construct electrostatic or magnetic fields of force, which may serve as *electrostatic lenses* or *magnetic lenses*. All these operations must be carried out in a good vacuum.



Courtesy American Cyanamid Co.

Zinc oxide smoke (×30,000).



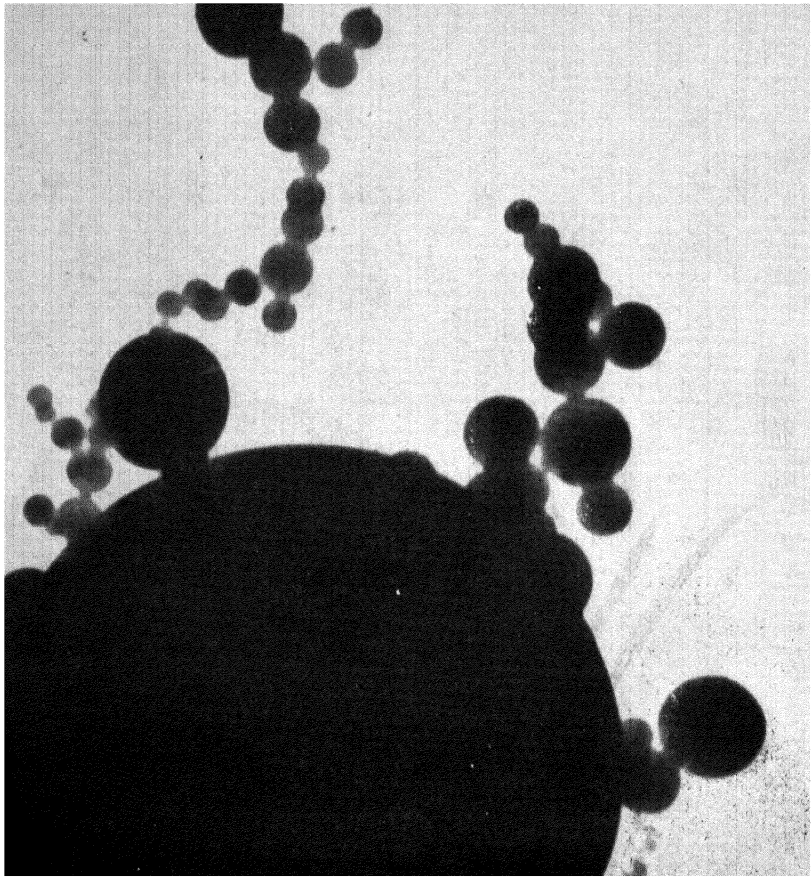
Courtesy RCA Laboratories

Magnesium oxide smoke (×50,000).



Courtesy American Cyanamid Co.

Tungsten oxide smoke (×30,000).



Courtesy American Cyanamid Co.

Aluminum oxide smoke (×30,000).

Chapter 12

THE MOTION OF ELECTRONS IN ELECTRICAL FIELDS

Work, Force and Power

We come now to a stage in the development of the subject where we shall have to be rather more precise in our language and to introduce some technical terms, which may need some elucidation. Some of these technical terms are simple words in everyday use, which, when used in a strictly scientific sense, need special definition. Such words are *force*, *work* and *power*. In our colloquial use of these terms, we may say a man is "a man of great force" or "a man of great power" and mean the same thing, and probably about the same as to describe the individual as "one who does an enormous amount of work." But when we come to use the term *work*, for example, in the scientific sense, we think of such a thing as carrying a load up a hill; this is exerting a force against the force of gravity.

For example, suppose a crate weighing a ton has to be delivered at a factory platform (Fig. 53). It may be hauled up by a block and tackle or dragged up an inclined plane on rollers. It is almost self-evident that the work done or effort expended will be proportional to the pull one has to exert and also to the distance through which we have to pull the crate. It is a matter of common knowledge that we do not have to exert as large a pull if we make use of the inclined plane as we do if we pull the weight straight up. When we make exact measurements of the pull and the distance in the two cases, it comes out that the product of the pull and the distance over which the object pulled moves is always the same for the same height of platform. If we use different lengths of inclines, *i.e.*, inclines making different angles with the ground, we still get the constant value when we multiply pull by distance.

This measure of the work done is just the weight (2000 lbs) multiplied by the height (20 feet). What we called the *pull* is, in technical terms, called the *force* exerted; we then have the relation: work done equals force exerted times distance through which the force acts, or in mathematical shorthand simply:

$$W = f \times d$$

In Fig. 53, $f_1 \times d_1 = f_2 \times d_2 = 2000 \times 20 = 40{,}000$ units.

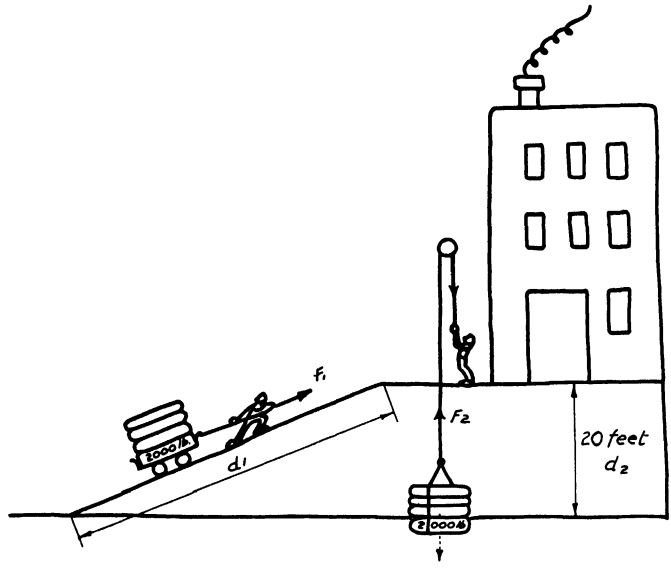


FIG. 53. The work done in pulling the load from the ground to the platform is the same no matter how the work is performed.

We have mentioned also *power*; technically this is just the *rate* at which work is done. The relation is:

$$\text{Power } (P) = \frac{\text{Work done}}{\text{Time taken to do it}} \text{ or } P = \frac{W}{t}.$$

If in Fig. 53 we pull the rope of the block and tackle by hand, we take a long time to pull the weight up, but if we use a donkey engine of a few horsepower, we can haul up the heavy load in seconds, simply because the power of the engine is greater than the power of one man.

Man's first ideas about electrical charges were that when bodies such as glass or ebonite were put in a state defined by saying they were charged, such bodies exerted a force on each other. As soon as we begin to talk about one charged body exerting a force on another, which is indicated by the bodies being pulled toward or repelled from each other (Fig. 42, p. 82), we think of gravitational forces—the attraction of the earth for bodies free to fall. However, with the electrical forces, we have not only attraction but repulsion. In any case we come to the ideas of forces moving masses, or masses being moved against forces, *i.e.*, work being done; and in the end we have the relations between force, work and power

$$W = f \times d, \text{ and } P = \frac{W}{t}$$

as in the ordinary experiences in the lifting of weights.

In these days we are all familiar with the development of "electrical power," as we say, by harnessing huge waterfalls. When the engineer wishes to calculate the rate of production of energy he uses just the same relation.

Work done in any time equals the weight of the water fallen, f, times distance fallen, d, i.e., $W = f \times d$, since the total weight of the water is just the force of gravity on the water. If the unit of time taken is one second, then the power, P, available at the falls will be:

$$P = \frac{W}{t} = \frac{f \times d}{t}$$

where t is the interval of time in seconds.

Difference of Level and Difference of Potential

When an engineer discovers a new falls or creates a difference of level by a dam, he knows that the power available depends on two things, the quantity of water falling down per second and the height of the falls (or dam). Of course, fundamentally, he measures the height directly by the use of a yardstick or steel tape measure. *But there is another perfectly good way to determine the height, namely, by measuring the work done in hauling up*

from the level of the bottom of the falls to the level of the top of the falls a given weight of water, say a pailful.

Here we have just the concept of *difference of level* between two points, say A and B, on the earth; there are two things that a given difference of level between the points A and B will tell us: (1) in what direction water will flow, whether from A to B or from B to A, *i.e.*, we must know which point is at the higher level; and (2) how much work is done in lifting a definite weight from one point to the other. All of these terms have been adopted in the language applied to electricity.

If we have two points, A and B, either in space or on a conductor, say a wire, and there are electrically charged bodies around, which, of course, give rise to electrical forces, then there will be an electrical force acting between A and B and electricity will be moved from A to B (or B to A). This case is more complicated because we have two kinds of electrical charge to talk about, positive and negative, and any electrical forces will tend to make positive electricity move in one direction and negative electricity move in the opposite direction. So we have to choose one or the other as a reference term; a certain charge of *positive electricity* has been chosen as the standard test quantity; that is, it takes the place of the pail of water used to measure differences of level.

What we call *difference of level* in dealing with water falls is called in electrical language *difference of potential*; this is measured in volts. If we know the difference of potential between two points, A and B, we know which way positive (as well as negative) electricity will move, whether from A to B or B to A, and we know how much work will be done in taking a unit positive charge from one point to the other.

How are we to measure difference of potential? We have no yardstick or measuring tape for it. The only way it is measured is by finding the work done in taking a certain unit quantity of electricity from one point to the other. In fact, *the difference of potential between two points is defined as the work done in taking a unit of positive electricity from one point to the other.*

In the case of lifting weights, as in Fig. 53, the work done in lifting a given weight depends *only on the difference of level* between the ground and the platform and not on the path by which the weight is pulled (*i.e.*, straight up or up along an incline); so the work done in moving a quantity of electricity from one point to another depends *only on the difference of potential* between the two points and not on the path along which the electricity is moved.

Lines of Force and Equipotential Lines

Fig. 54 illustrates a specific experiment in which the electrical terms introduced above are used. Two parallel metal plates, A and B, are connected to the ends of a battery so that A bears a positive charge and B a negative charge. If we put our unit positive test charge on a small pith ball, P, it will be pushed away from A and attracted toward B. If we have the experiment carefully arranged, P will move in the direction from A to B along lines perpendicular to A and B, no matter where it is placed originally in the space between A and B. These lines then indicate at any point the direction in which the electrical forces are acting. They are called *lines of force.*

Now mark off on these lines points corresponding to equal divisions of the total work done in taking P from A to B along any one of the lines of force reaching from A to B. Four such divisions are indicated by the dots. If we join the corresponding

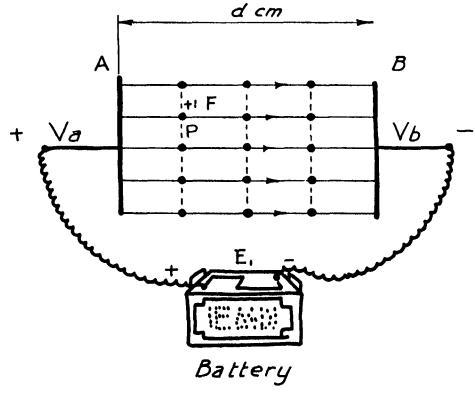


FIG. 54. Lines of force and lines of equipotential.

dots on the various horizontal lines by broken lines, we get a series of lines which mark off regions of equal work done in going out from A; these vertical lines are known as *equipotential lines*. This is a simple case, and it is apparent that the lines of force are perpendicular to the equipotential lines wherever they cross one another.

From the symmetry of the lay-out in Fig. 54, we would easily agree to the statement that the force, f, acting on the small charged pith ball, P, will be the same at every point between A and B. From the expression giving the relation between work, force and distance, we can then say that:

$$W \text{ (Work done in taking P from A to B)} = f \times d.$$

But the definition of the difference of potential between A and B is just this work if the charge on P is a unit charge. So if we put the potential of A equal to V_A and that of B equal to V_B and indicate the force on unit charge by F, we obtain:

$$W = V_A - V_B, \text{ and so } V_A - V_B = F \times d$$

From this equation, we get a very useful relation $F = \frac{V_A - V_B}{d}$.

Now if everything is symmetrical as in Fig. 54, $\frac{V_A - V_B}{d}$ is the fall of potential per cm., which is consequently called the potential gradient from A to B. We then arrive at the statement that the electric force per unit charge at any point is equal to the potential gradient, sometimes called the gradient of the potential. This quantity—the force per unit charge at any point—is also called the *intensity of the electrical field* and is usually denoted by the capital letter, F; this is sometimes called the field strength. It is the difference of potential between A and B divided by the distance between the two plates.

Again, since by definition the difference of potential between two points is the work done in moving a unit positive charge from A to B, we can readily deduce that twice as much work will be done in moving two units of positive charge from A to B and 9 times the original work when a charge of 9 units is moved from

A to B. We can express this in a general way by the relation:

$$W = q \times (V_A - V_B), \text{ if the charge is } q \text{ units.}$$

Since $W = f \times d$ where f is the electrical force acting on the charge, q, we may write

$$f \times d = q \times (V_A - V_B).$$

Since $\dfrac{V_A - V_B}{d} = F$, it follows that $f = q \times F$, or force equals charge times field intensity.

If a positive charge q moves from the positive plate A to the negative plate B in Fig. 54, it moves in the direction of the electric field F, and we say that the field does the amount of work, W, on the charge q. This work appears as the kinetic energy, $\frac{1}{2}mv^2$, which the charged particle of mass, m, possesses when it arrives with the velocity v, at the plate B.

On the other hand, if we were to move a positive charge q from plate B to plate A, the charged particle would have the work W spent upon it. Either we must push the particle along against the force of the field or the particle must possess an initial energy equal to W in order to be able to sacrifice that much on its way from B to A. This can be realized by the following experiment (Fig. 55).

We arrange a third plate, C, behind the plate B at the same distance, d, which separates A and B and connect another battery, E_2, of the same voltage as E_1, so that plate C is positive with respect to plate B by the same amount that plate A is positive with

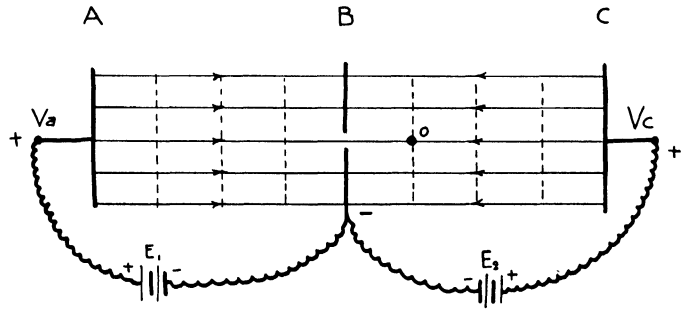


FIG. 55. Gain and loss of energy of a charge in an electric field.

respect to B. The fields F_1, F_2, in the space to the left of B and the right of B will then be equal and opposite. If we provide a small hole in B and let the positive charge originate at C, it will acquire the energy W while traveling from C to B and then lose it while travelling from B to A. It will arrive with zero velocity at A.

The same reasoning applies naturally to negative charges. If e stands for the negative charge of an electron, the work done on the electron by moving it from plate B to plate A in Fig. 54 is

$$W = e \times (V_A - V_B)$$

and if it were to be moved from A to B, it must have this initial energy in order to be able to overcome the opposing field force. That could be realized by an experiment similar to that illustrated in Fig. 55. When a field does work on the electron and thus accelerates it, the energy gained by the electron is expressed frequently in terms of *electron-volts*. Thus an electron, which, starting from rest, has been accelerated by moving between two plates having a difference of potential of 50 volts, is said to gain a final kinetic energy of 50 electron-volts of energy. It is also sometimes said to have a final velocity of 50 electron-volts. There are then unfortunately two kinds of *electron-volts* in use, one referring to the energy of an electron, the other to its velocity.

Fig. 56 represents a more general case of lines of force and corresponding lines of equipotential.

We have now to deal with the motions of electrons in vacuum tubes under the influence of electrical forces brought into action by maintaining two metal plates in the vacuum tube at a difference of potential.

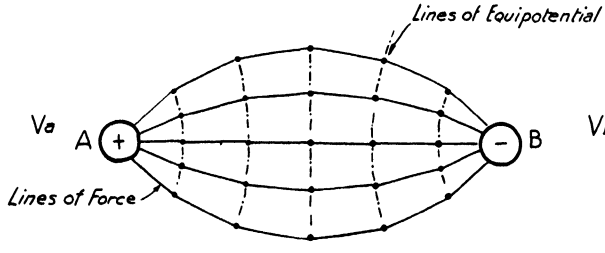


FIG. 56.

The field of force between two spherical conductors at a difference of potential.

The Motion of Electrons in a Uniform Field

The electron stream observed in the earliest experimental tubes, such as the Crookes tube and the Braun tube, shown diagrammatically in Fig. 57, was produced by the impact of positive ions on the negative electrode.

As we have noted above (p. 97), these impacts of the positive ion masses will knock electrons out of the plate, C, really in great profusion, and these electrons will be forced away from C toward A along one of the lines of force.

The resulting motion of the electron will be quite similar to the motion of a stone when we drop it to earth. We know that as soon as the stone is released it begins to fall with a velocity which becomes greater and greater the longer the stone is falling. This is what is called technically "accelerated motion."

Using this analogy we might say that the electron, P, (Fig. 57) "falls" from C to A with a uniformly accelerated motion. As the final velocity with which the stone reaches the earth depends on the height from which it has fallen, so the final velocity of the electron depends on the difference of potential through which it has fallen. The greater the potential difference $V_A - V_C$, the greater is the final velocity.

From what has preceded we see that we always use the term, difference of potential between points, and do not speak of the actual value of anything called potential at any point without referring to an assumed reference potential. This is quite in keeping with what the engineer talks about when he is calculating the power that he can get out of a waterfall. Niagara Falls has a height of 190 feet and the available power is fixed by this *difference of level* but the engineer in making his calculation does not

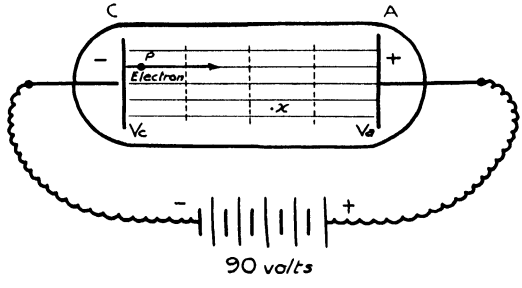


FIG. 57.

The motion of an electron in a uniform field in a vacuum tube.

need to know how far the bottom or top of Niagara Falls is above sea level. In fact, sea level is just an adopted level from which heights of individual stations may be measured. Similarly, in electrical measurements, the earth, which is a huge conductor, is said to be at zero potential, and this fixes our reference point.

Thus the potential of a conductor joined electrically to the earth, or as we say, to ground, is said to be zero. With this definition of a standard potential, called zero potential, a positively charged body is said to have a potential above the earth, because positive electricity will flow from such a body to the earth; a negatively charged body is one which is said to be below the potential of the earth, or at a negative potential, because positive electricity will flow from the earth to such a body.

Referring to Fig. 57, we may say that the plate A is 90 volts above ground (or +90V) when it is connected with the positive terminal of the battery, the negative terminal of which is connected to a water main, giving good electrical connection with the ground (the earth). If the positive terminal of the battery is grounded, then the plate, C, is said to be 90 volts below ground (or −90V). The essential point to remember is that we use the term potential only in the sense of difference of potential.

Once more referring to Fig. 57, we may speak of the potential at a point in free space, such as X. This can be found by measuring the amount of work that must be done in order to bring a unit positive charge from plate C to X. If the point X were to lie on the plate C, we would not have to perform any work, since the potential V_C is the same at any point of C. If the point X, on the other hand, were to lie on the plate A, we would have to move a unit positive charge from C through space to A and overcome the repelling electrostatic force all the way until we reach the potential of +90 volts on A. By actually measuring the amount of work performed, it can be shown that it rises linearly all the way from C to A. If the point X lies half way between A and C, the potential at X is then 45 volts above C.

The Paths of Electrons in Non-Uniform Electric Fields

We shall now consider a case where the equipotential areas in space between cathode and anode are not plane but curved, at

least in part. This may be realized by giving the cathode a spherical shape. We know that the surface of a conductor is everywhere at the same potential. If the cathode is grounded, the zero-potential area then must of necessity follow the contour of the cathode (Fig. 58). The other electrode is again connected to a 90-volt battery and the potential values at the various equipotential areas are indicated. Since the anode is a plane, the equipotential planes gradually straighten out the nearer we approach the anode A.

We now assume that electrons are emitted with zero initial velocity all over the cathode surface, as indicated by the small dots. From each such electron, a line is drawn toward the anode in such a way that it intersects all equipotential planes at right angles. We know that this is the path the electrons must follow according to rule. The result is that all electrons meet at a small circle at the anode just as if they had been focussed.

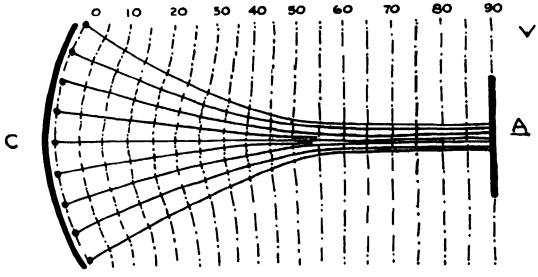
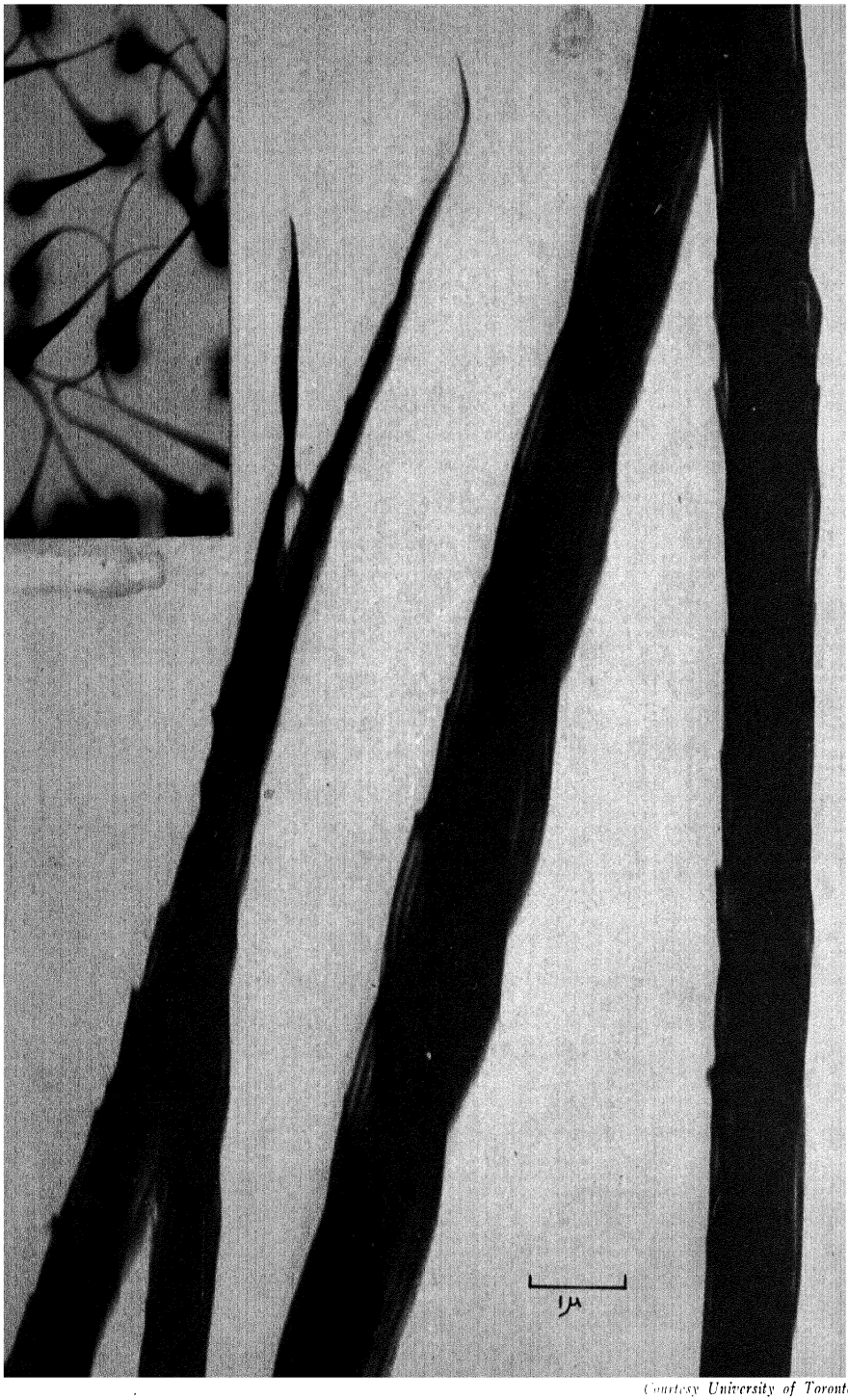


FIG. 58.

Lines of force and lines of equipotential in a non-uniform electric field.

This sort of thing had been observed by Crookes, Hittorf, Goldstein and others during their early experiments, and they contrived many different shapes for cathodes and anodes in order to learn more about the paths. We must remember, however, that these scientists did not yet know that they were dealing with electrons and they also had no clear conception of potential distribution and its importance for the determination of the paths or trajectories of the emitted particles.

We notice in Fig. 58 that the electrons do not travel in straight lines when the equipotential areas are curved, *i.e.*, when the field is not uniform. In analogy with the reflection of light at a concave mirror one is tempted to speak of an electron focus.



Courtesy University of Toronto

Hairs on edge of midge's wing (*Chironomidae*) (×20,000). Insert: Hairs on surface.

Chapter 13

THE MOTION OF ELECTRONS IN MAGNETIC FIELDS

Magnets and Magnetic Fields

It has been mentioned on a few occasions in the preceding text that the paths of electrons may be influenced by the proximity of magnets. Thus, the fluorescent spot on the willemite screen of a Braun tube can be shifted at will when a small bar magnet is brought near the tube and moved into different positions. Whenever a mass, no matter how small, is deflected from its original path, a force must be acting upon it; the force is the cause of such a deflection. We know of mechanical forces, gravitational forces, and electrical forces. Now we must add magnetic forces to this list and learn something about their interaction with electron beams, since this interplay is important in the operation of the electron microscope.

Everyone is familiar with the ordinary magnetic compass—a small piece of steel pivoted so as to move in a horizontal plane. Its usefulness depends on the fact that one particular end always points toward the north, when the compass is kept at rest and

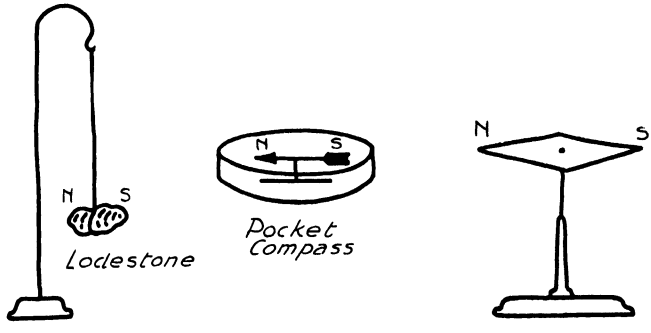


FIG. 59. Lodestone and compass needles.

level. The end which points to the north is called the north pole, that pointing to the south, the south pole (Fig. 59).

It is really not known exactly when compasses were first used, but the earliest forms use a magnetic substance which occurs naturally on the earth's surface. This substance called lodestone (leading-stone) is made up of oxides of iron. If an irregular piece of this mineral is suspended by a thread so as to be balanced horizontally, the longest dimension will always set so as to point in a north-south direction—one definite end always pointing to the north.

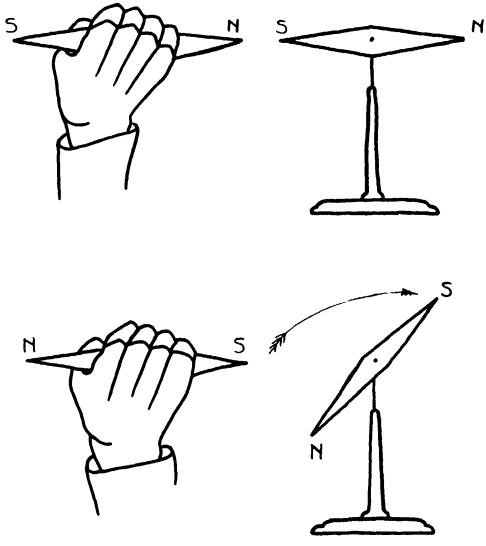


FIG. 60.

The laws of magnets; unlike poles attract each other, like poles repel each other.

The question may be asked, "How did the modern small steel magnet develop from the lodestone?" This leads us to speak of a very important property of lodestone, *i.e.*, that it is able to attract to itself pieces of iron or substances containing iron. Not only will the lodestone attract iron, but if it comes in contact with a piece of iron, it will impart its own power to the iron and so convert it into a magnet. Every boy who owns a jack-knife knows that he can magnetize it by rubbing it on a magnet. All our magnets are made of steel, because steel will retain this curious magnetic property longer than soft iron.

When people began to experiment with these magnetic needles, they discovered a very curious property which has to do with the interaction of one magnet on another. If we have two magnetic needles and pick one up and bring one end up to the end of a second magnet, we find that two poles which are different (N and S) always attract each other, but that two poles of the same kind (N and N, or S and S) always will repel each other (Fig. 60.) This last fact recalls to us something similar regarding electrical charges—like charges repel, unlike charges attract each other—but this does not prove any real connection between magnets and electrical charges.

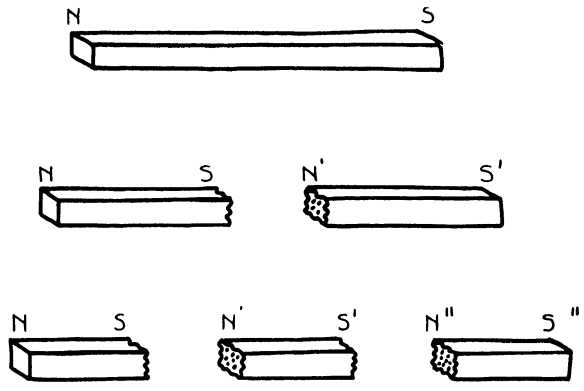


FIG. 61. Breaking up a magnet into many parts always makes a complete magnet out of each part.

One very remarkable difference is apparent at once. We may impart to a body a positive or a negative charge and detect its presence by simple tests. But we cannot detect both a negative and a positive charge on an isolated conducting surface, since the two charges neutralize each other. For magnets, the opposite condition exists. Each magnet always has a north pole and a south pole and we can never get any separate portion of a magnetic substance with only one kind of pole, north or south. If we have a piece of steel which is magnetized and break it into any number of parts, all the parts are still perfect magnets with both north and south poles (Fig. 61).

Since one magnet will exert a directive force on another, and since any magnet always sets itself in a north-south direction when free to do so, we decide that the earth itself must have a directive action on a magnet. From this we conclude that the earth itself is a huge magnet also having two poles, *i.e.*, points toward which the north and the south poles of magnets are directed. The magnetic pole in the northern hemisphere is in

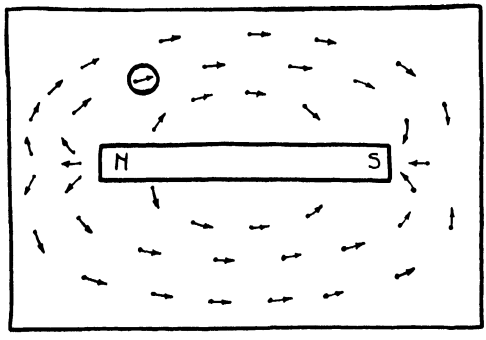


FIG. 62.

The magnetic lines of force about a bar magnet.

northern Canada near Hudson Bay; this point is known as the *north magnetic pole*. Neither of the earth's magnetic poles are in the same place as the geographical north and south poles.

Just as in the case of the attractions and repulsions between electrical charges, so we have here the remarkable fact that one body affects another apparently "at a distance." In this case also Faraday ascribed this interaction to something going on in the space round about the magnets. We speak, then, of the region round about a magnet as a *magnetic field of force*, and also of magnetic *lines of force* which show us graphically the direction of the magnetic force at any point round about any magnet. These magnetic lines of force can be easily found in a plane by moving a small compass around on a piece of cardboard placed over the magnet and marking at every point the direction in which the compass needle sets itself.

Fig. 62 shows the distribution of lines of force about a bar magnet and Fig. 63 that between the poles of a horseshoe magnet; the remarkable and, as we shall find later, useful property of the field of the horseshoe magnet is that the most intense force is in

the region between the poles and that in the central part of this region the field is uniform, *i.e.*, the force on a certain specially defined unit pole is the same at every point.

It has been agreed to define the direction of the magnetic line of force as the direction in which a north pole tends to point. This is the direction indicated by the arrows in Fig. 62.

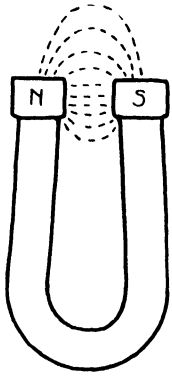


FIG. 63.

The magnetic lines of force for a horseshoe magnet.

The Magnetic Field about a Conductor bearing a Current of Electricity: The Electromagnet

What has a magnet to do with an electron? The answer to this question goes back to an accidental discovery in 1820 by a Danish scientist, Oersted, that an electric current flowing through a wire exerted a magnetic effect in the region round about the wire. In other words, the current through the wire set up a magnetic field. This is illustrated in Fig. 64, where a horizontal wire, which is part of an electrical circuit, is shown with magnetic compass needles pivoted above and below the wire. As represented, the horizontal wire is placed so as to lie in a north-south direction; when no current is flowing (Fig. 64 A), the needles both point due north. When the switch is closed and the current flows in the wire in the direction determined by the position of the plus and minus signs on the battery, the north poles of the needles move in the directions indicated by the arrows. If we follow the movement of the poles of the magnet in its various positions, we are led to the conclusion that the magnetic

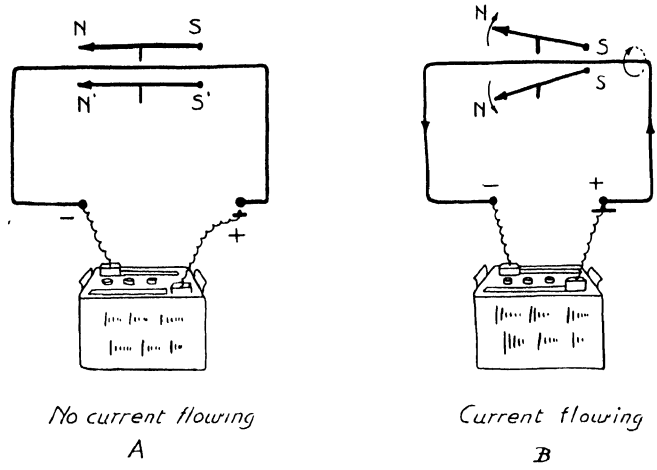


FIG. 64. The direction of the magnetic lines of force about a conductor through which a current is flowing.

lines of force about the wire are circles in planes at right angles to the wire and with their centers in the wire. The relation between the direction of the current and the direction of the magnetic lines of force is given by a very simple rule (Fig. 65). If we are using a screwdriver to drive in a screw, and let the direction of progress of the screw represent the direction of the current, the direction of rotation of the thumb represents the direction of the magnetic lines of force.

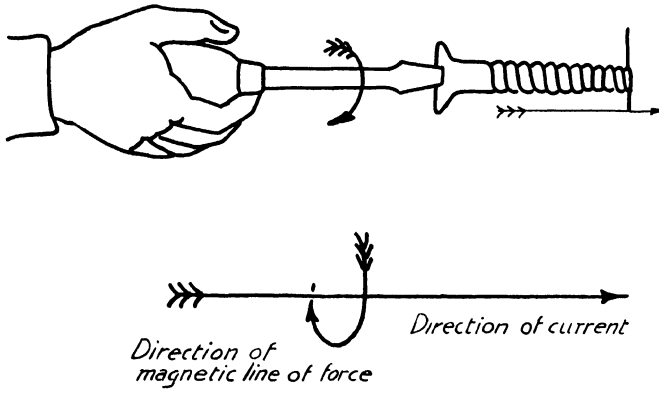


FIG. 65. A simple rule for remembering the relation between the direction in which a current is flowing in a conductor and the direction of the magnetic field set up.

Now if we bend the wire of Fig. 64 into a circle, as in Fig. 66a, the lines of force, if we could see them, would appear to come out of the inner plane of the circle, bend around the wire and re-enter the other face of the circle of wire. This is shown more clearly by viewing the circle of wire edgewise from the left, as in Fig. 66b. In fact this figure suggests that the circle of wire acts as though it were a very thin flat magnet, such as we might get if we sliced out a very thin section of the bar magnet shown in Fig. 62.

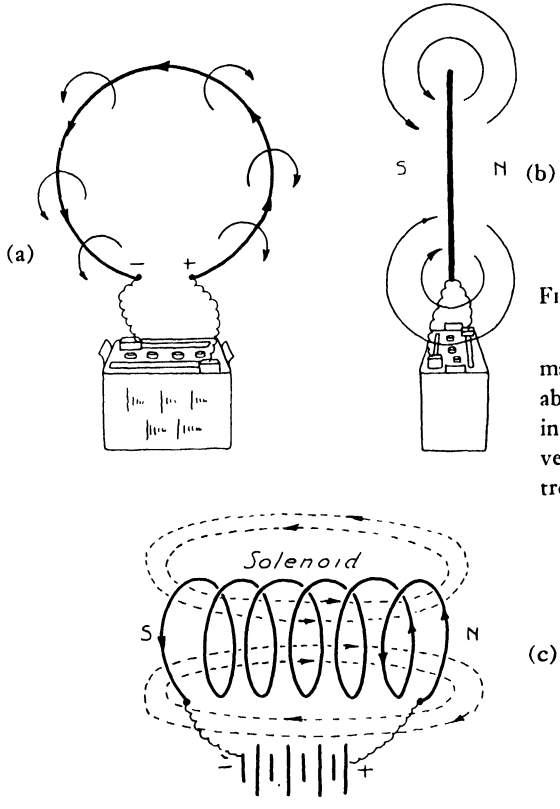


FIG. 66.

The direction of the magnetic lines of force about a conductor bent in a circle and the development of the electromagnet.

If, instead of a circle of one turn, we have a long wire coiled up in what is called a *solenoid* (Fig. 66c), we have an exact parallel of a long bar magnet; such a solenoid is known as an electromagnet. One end of the solenoid is a north pole and the other end a south pole, the polarity of either end depending on the direction of the current through the coil.

In this case we have produced the equivalent of a bar magnet without the use of any lodestone, iron or any other magnetic substance. One very important property of such an electromagnet is that the strength of the magnetic field within the coil of wire is *uniform* (see Fig. 67). However, we can get a much

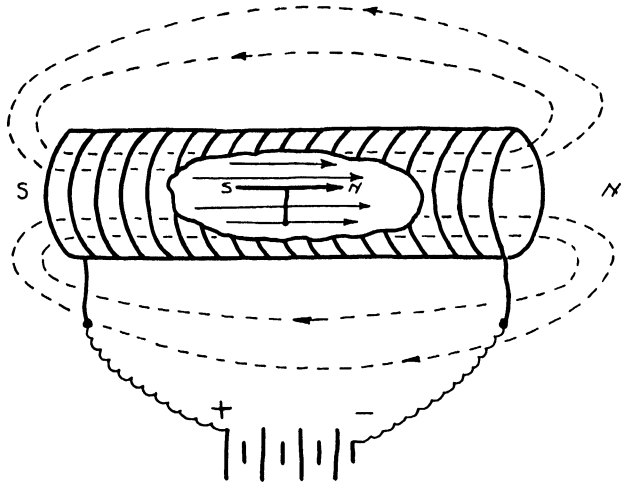


FIG. 67. The magnetic field at the center of a long solenoid is uniform.

stronger magnetic field about the electromagnet if we insert a core of iron or steel in the solenoid.

The great usefulness of the electromagnet is due partly to the fact that by increasing the value of the current through the wire, we can increase the strength of the magnetic field over a great range of values. Again, by employing an alternating current, it is possible to cause a corresponding alternation in the direction of the magnetic force.

The Action of a Magnet on a Conductor Bearing a Current

Oersted's discovery showed that a current in a conductor can move a magnetic needle: that is, a fixed conductor bearing a current affects a movable magnet. The converse of this is that a fixed magnet ought to produce motion of a movable conductor which is bearing a current. This can be shown to take place by a simple experiment (Fig. 68). A battery sends a current through

a wire, AB, which is suspended from a metal hook, A, and dips into a pool of mercury, M; a bar magnet is supported through a cork at the bottom of the tube. When the current is sent through AB, the lower end rotates about the pole of the magnet as long as the current flows. Here the motion of the conductor is perpendicular to both the direction of the current and the direction of the magnetic lines of force.

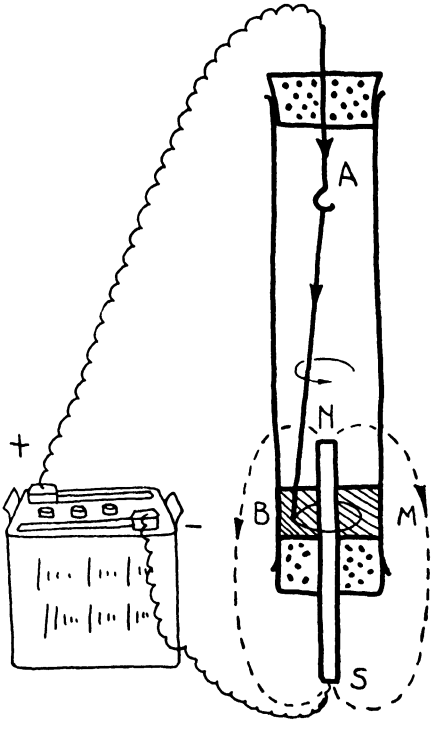


FIG. 68.

A stationary magnet can produce motion in a conductor bearing a current; the converse of the action shown in Fig. 64.

Now if electrons are negatively charged particles, a stream of electrons moving along a straight line should be equivalent to a flow of negative electricity in that direction. Consequently, if the stream of electrons is sent through a magnetic field, the magnetic force should move the electrons in the stream in a direction at right angles to both the direction of the electron stream and the direction of the magnetic field (Fig. 69).

It was just this observation which led Sir J. J. Thomson to conclude that the electron stream acted as though it were a

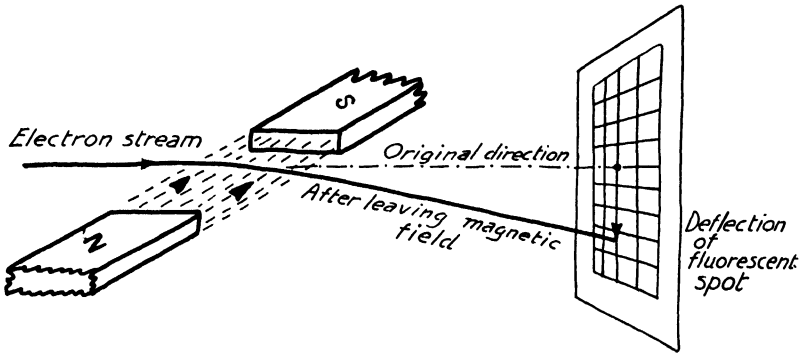


FIG. 69. The deflection produced in the path of an electron passing through a magnetic field.

stream of negative electricity and to announce that electrons were small particles of matter charged negatively.

Experiments show that the electron is affected by a magnetic field only when it is moving. If the electron is at rest, there is no action whatever.

Comparison of the Action of Electric and Magnetic Fields on Electrons

We find then that the flight of electrons is affected by the presence of a magnetic field as well as by the presence of an electrical field. It is important to contrast the effects of these fields.

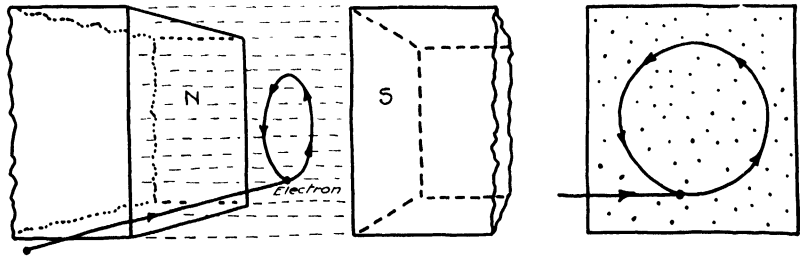
An Electrical Field

1. Acts on an electron which is initially at rest and causes it to move along the lines of force in a direction opposite to the motion of a positive charge.
2. Acts on moving electrons in such a way as to bend the beam into regions of higher potential (Fig. 58). This refraction of the electron beam at the equipotential boundary layers is accompanied by a variation in the speed of the electrons.

A Magnetic Field

1. Has no effect whatever on an electron which is at rest.
2. (*a*) Has no effect on a moving electron as long as the direction of motion is along the lines of force of the magnetic field.
   (*b*) Moves the electron in a circular path, if the direction of motion of the electron is at right angles to the lines of force of the magnetic field. This circular path is still perpendicular to the magnetic lines and the speed of the electron is not altered.

Fig. 70a illustrates what will happen to a moving electron entering a uniform magnetic field in a direction at right angles to the lines of force. Immediately the electrons enter the magnetic field, a force is exerted on them which tends to bend the



(a) (b)

FIG. 70. The path of an electron entering a magnetic field in a direction at right angles to the lines of force is changed to a circle. Fig. 70b gives an end-on view of the circular path; the dots represent the sections of the lines of force.

electron beam into a circle of definite radius; this circular motion persists as long as the electron remains in the field. The value of this radius, R, varies directly as the velocity of the electrons, and inversely as the intensity of the magnetic field. The technical expression is $R=\frac{mv}{eH}$, where m is the mass of an electron, v its velocity, e its charge, and H the value of the magnetic field; these values must be expressed in terms of definite units in order to get the value of R in centimeters.

If the magnetic field occupies a small space, the electron may escape from the region of the field before it completes the circular path; this is illustrated in Fig. 71. The electron beam enters the field at A and escapes at B; while moving in the field, the electrons follow the path AB, which is an arc of a circle with the radius given by the above relation. That is, AB is a part of the dotted circle, which would really be the path of the electron if the uniform magnetic field extended farther in space.

At the point B, where the electrons leave the magnetic field, the action of the magnetic force ceases and the electrons continue their flight in a straight line along the tangent of the circle at B. The circle which is indicated by the dotted line in Fig. 71

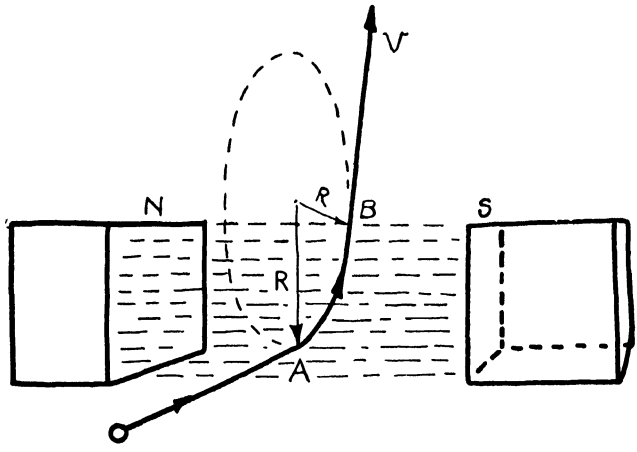


FIG. 71. The path of an electron which escapes from the magnetic field.

appears as an ellipse since it is drawn in perspective. Figs. 70b and 72 give the electron trajectories which an observer would see while facing the magnetic field. The dots indicate the field arrows. This principle of magnetic deflection of electron beams in the manner just described is used very generally in cathode-ray tubes and television tubes for scanning.

Fig. 73 illustrates this application of magnetic deflection in its simplest form. Two solenoids, C_1 and C_2, are placed, as shown, at right angles to the axis of the cathode ray tube. This is a modern Braun tube in which an oxide-coated cathode is used as the source of electrons; many other refinements have been incorporated. A sharp spot of light is formed on the luminescent

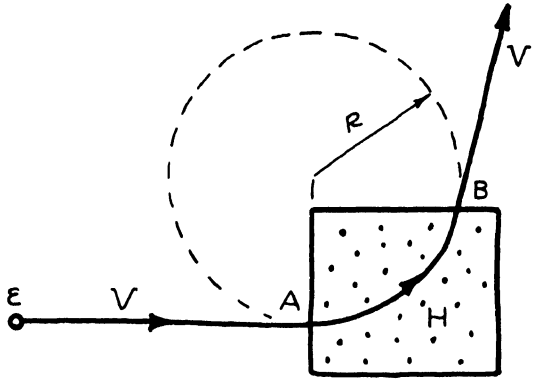


FIG. 72.

End-on view of Fig. 72. The dots represent sections of the magnetic lines of force.

screen, S, at the end of the tube. When the coils are activated by an alternating current, an oscillating magnetic field will be established along the axis A-B of the coils. Since the field, H, is proportional to the current flowing through the coils of the solenoids, it will reverse its direction continuously according to the alternations of the current, *i.e.*, H will be directed from A to B at one moment and from B to A 1/60th of a second later, if 60-cycle current is used. The effect of this alternating field, H, will be that the fluorescent spot on the screen, S, describes a vertical line flitting back and forth between P_1 and P_2.

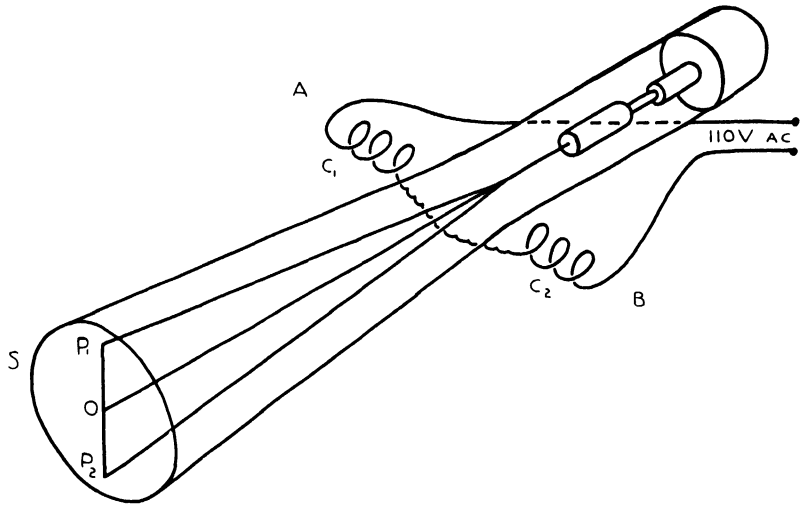


FIG. 73. The magnetic deflection of an electron stream due to an alternating field.

Path of an Electron Moving in any Given Direction on Entering a Magnetic Field: Vectors

Let us now investigate what takes place when the magnetic field and the electron beam do not happen to be at right angles, as in the previous examples, but are inclined to each other at a smaller angle.

For this purpose we need to say a few words about directed quantities in physics, which are called vector quantities. As examples we mention force, velocity, field strength; each of these quantities is determined by a numerical value and a direction.

The velocity, or speed, of a moving object for instance, may be 50 miles per hour where 50 is the numerical quantity. In order to describe the movement fully, we must also indicate the direction in relation to some reference point. Thus we say, a car is travelling north on a highway with a speed of 50 miles per hour. Everybody then knows exactly what the car is doing. Other quantities in physics are fully described by a mere number. They are called scalars; examples of scalar quantities are mass and temperature; the concept of direction is not associated with these terms. It has become common practice to call the scalar part of the velocity by the word speed.

Vector quantities are generally represented by arrows where the length of the arrow indicates the numerical value and the arrow head, the direction; the arrow is called a vector—merely a straight line having a definite length and a definite direction.

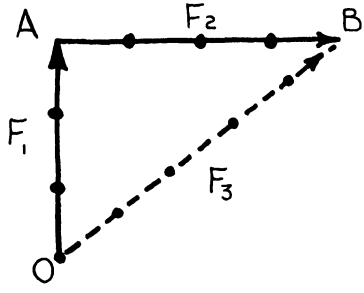
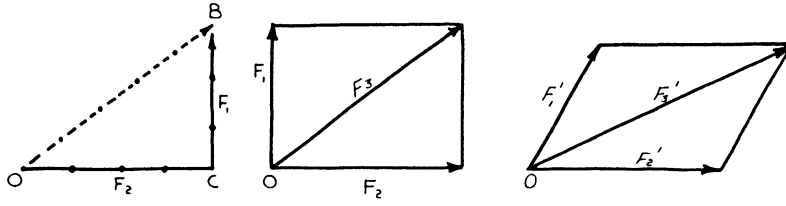


FIG. 74.
The sum of two vectors.

The interesting feature of these vectors is that they can be split up graphically into various components or, what amounts to the same thing, several vectors can be added by simple rules in a diagram. Let us illustrate this rule for a force diagram.

In Fig. 74, a force F_1 of 3 units, acts upon a mass situated at O in the direction O-A for a certain time so that the mass is moved from O to A. A second force, F_2, of 4 units is then applied for the same time at A in the direction A-B so that the mass is moved to B. The same result could have been obtained by having a force, F_3, equal to 5 units act on the mass at O in the direction O-B for the same time. As the vector F_3 accomplishes the same effect as F_1 and F_2 both acting together, F_3 is said to be the sum

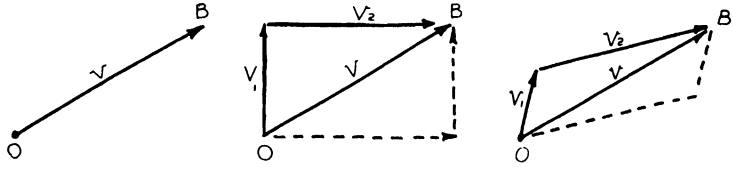
of F_1 and F_2. We could also have applied F_2 first to get to C (Fig. 75a) and then F_1 to get from C to B and would have obtained the same result. By drawing the two arrows F_1, F_2 from the common origin O (Fig. 75b), we find that a rectangle results of which F_3 is a diagonal. If the two original forces act at a differ-



(a) (b) (c)

FIG. 75. The sum of two vectors.

ent angle with respect to each other, as in Fig. 75c, we obtain a parallelogram. In every case, the diagonal of the rectangle, or parallelogram, obtained in this graphical manner gives the magnitude and direction of the force F_3 which brings about the same final displacement as that produced, in steps, by F_1 and F_2. This is the well known parallelogram of forces probably familiar to the reader from his school days. Instead of forces, the arrows may represent velocities or other vector quantities.



(a) (b) (c)

FIG. 76. A vector split into two components.

By reversing the vector addition, we find that we can split up a vector into two components that add up to the original vector as long as the original vector forms the diagonal in a rectangle or parallelogram.

If the arrow marked v in Fig. 76a represents the magnitude and direction of a velocity with which a body moves from O, we will get to B by moving in two steps, v_1+v_2, as shown in Figs. 76b, and 76c.

After this little excursion we now return to our main issue, i.e., the influence of a magnetic field on moving electrons. In Fig. 77, we picture an electron moving with a velocity v in a uniform magnetic field H, so that the direction of v and that of H make an acute angle. We have no rule that would enable us to predict directly the trajectory which the electron will follow. But we do know the effect of H upon electrons moving parallel with, or at right angles to, H. Here we find the breaking up of a vector to be a welcome solution to our problem. We simply assume for the moment that the electron moves first with a velocity, v_1, at right angles to H and then with a velocity, v_2, in the direction of H and deduce what path will result when both v_1 and v_2 are possessed by the electron at the same time.

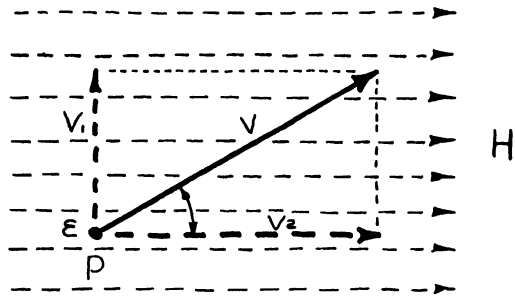


FIG. 77. The velocity of an electron in a magnetic field resolved into two new directions, one parallel to the field and the other at right angles to the field.

It is quite plain from the rules which we have stated above that the electron moving with velocity and direction v_1 in Fig. 77 describes a complete circle which is oriented at right angles to the direction of H and thus returns to P from where it started. We are also certain that the electron moving with v_2 in the direction of H is not affected by H and thus proceeds in a straight line. These two motions are represented in perspective in Fig. 78. Here a long solenoid is drawn which supplies the axial field, H. It has to be long in order to insure a uniform field in its central section where we shall study the electron movement through the cut-away shown. We assume that the electron has the velocity v represented by PB when it reaches the point P, on the solenoid axis O O′, which of necessity will be the axis of a vacuum tube

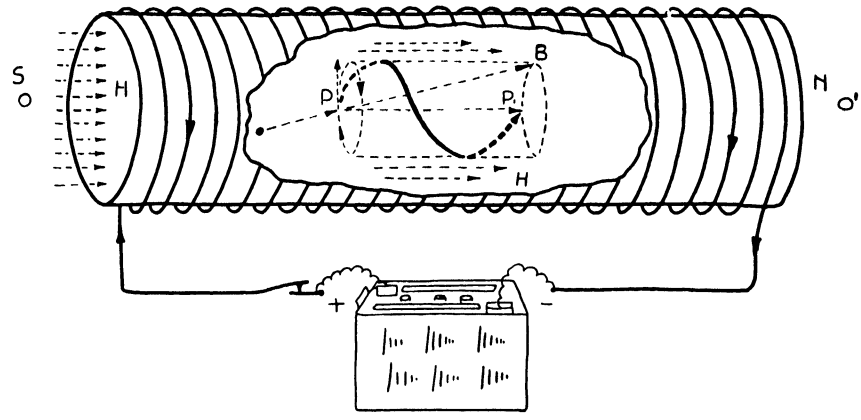


FIG. 78. The focussing action of a magnetic field on an electron diverging from the direction of the field.

inserted in the solenoid. What happened to the electron before it arrived at P does not concern us here as long as we assume that it had a linear motion in the direction PB. The moment it arrives at P the switch which actuates the solenoid is closed and produces the magnetic field instantly. Now we split v into v_1 and v_2 and ask what path the electron will follow when it has these two velocities simultaneously. The electron tends to describe the circle but at the saime time it progresses with the uniform velocity, v_2, toward the right. The path thus becomes a helix which is wound about a fictitious cylinder touching the axis

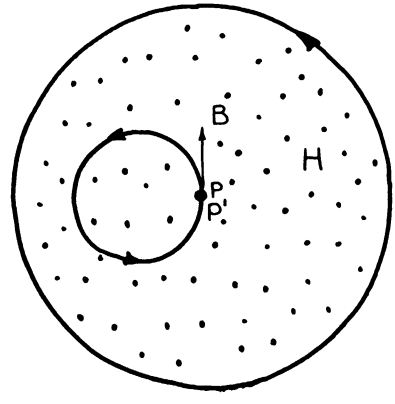


FIG. 79.

View of previous figure end-on.

O-O′. Fig. 79 shows the view obtained by looking into the solenoid from the right. By the time the circle would have been completed the electron has arrived at P_1. In the absence of a magnetic field, the path of the electron would be along the straight line to B. We thus make the important observation that an electron which tended to move away from the axis (in a divergent beam) has been forced back onto the axis some distance away, because of the action of the coaxial magnetic field. This coaxial field, then, acts upon a divergent beam of electrons in the same way as a lens acts on a divergent beam of light, *i.e.*, *it produces a focus*. Fig. 80 is the drawing of a space model which illustrates the trajectories of a number of electrons which originate at P with the same constant velocity but in different directions

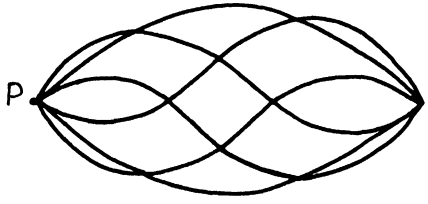
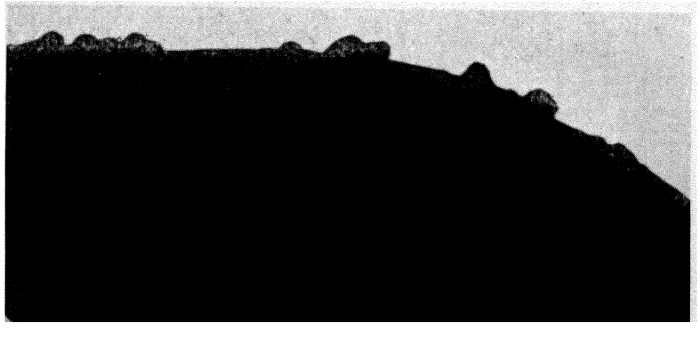


FIG. 80.

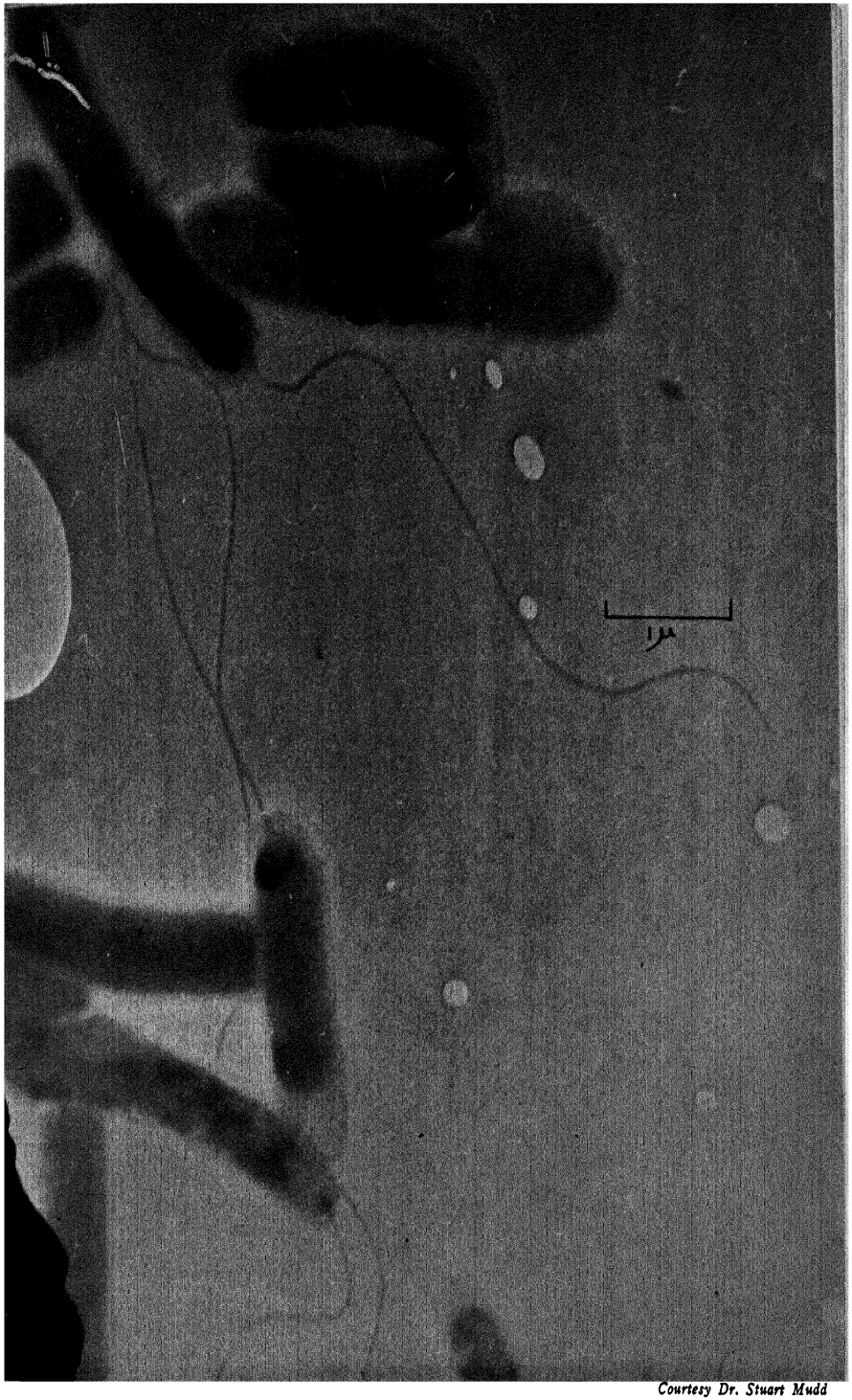
The helical paths of electrons from source P to focus P′.

with respect to the axis. They all converge toward P′, the focus of the magnetic lens.

The lens property of the long solenoid was recognized at an early date. E. Wiechert in 1899 introduced the concentration coil, as it was called, in connection with the Braun tube and it proved to be a most useful device in the early days of cathode ray tube technique.

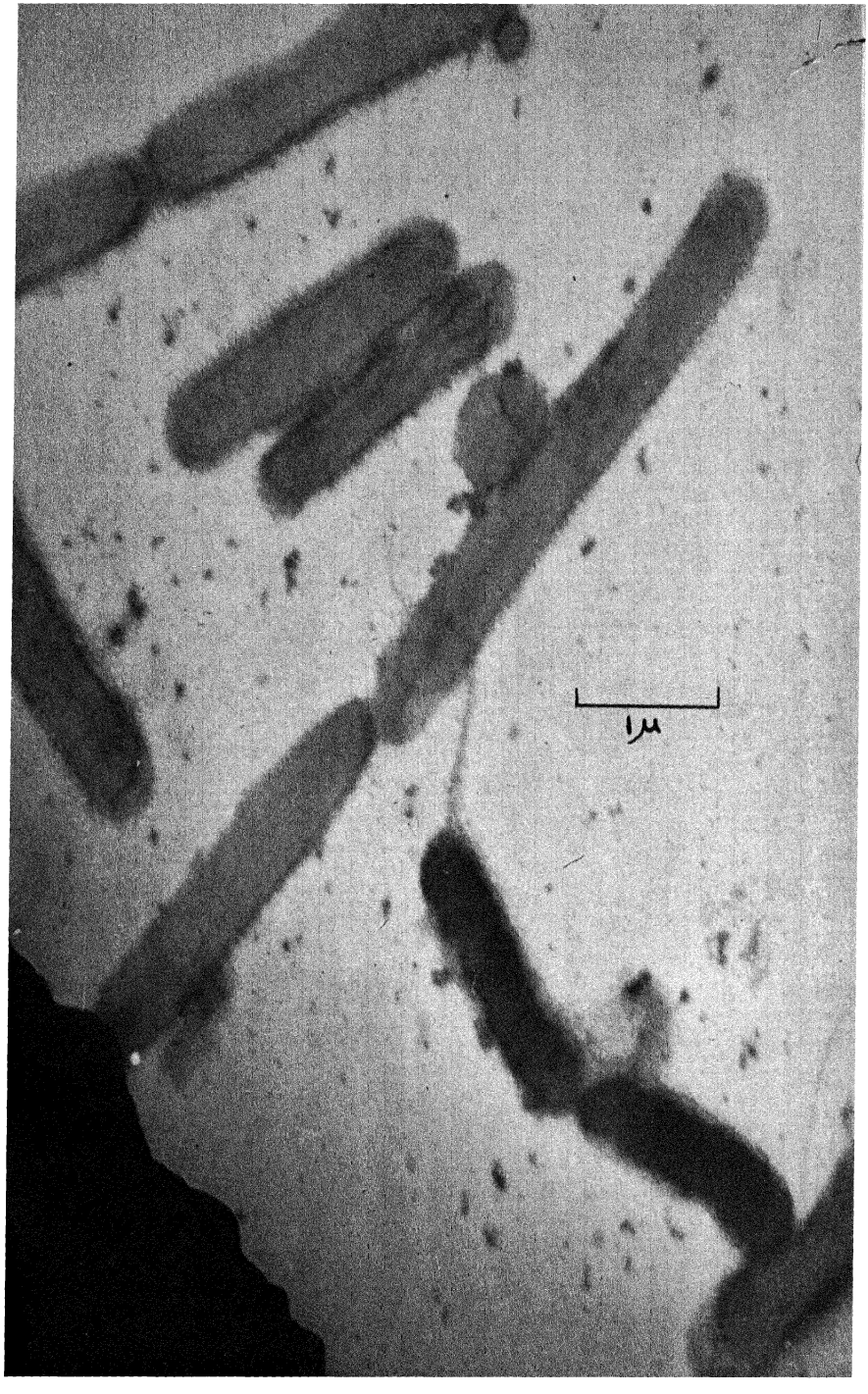


Edge of particle of pollen dust (×21,000).



Courtesy Dr. Stuart Mudd

Vibrio comma (×22,500) Cells dried from distilled water.



Courtesy Dr. Stuart Mudd, University of Pennsylvania

Vibrio Comma, ×25,000, after brief exposure to a lead salt.

Chapter 14

ELECTRON OPTICS
I. MAGNETIC FOCUSSING

The Magnetic Lens

It may be well here to review the conditions that prevailed in the experiments just described which led us to ascribe a lens action to a solenoid. Electrons emerging from a small spot of the cold cathode of a Braun tube were accelerated in the close vicinity of the cathode surface by the cathode potential drop of the gas discharge column and then traveled with a fairly uniform velocity toward the fluorescent screen. During their travel these electrons would suffer collisions with gas molecules and be deflected from their original direction of travel thereby, so that on the whole a diffuse cathode stream would result. This is illustrated in Fig. 81a, where the shaded part represents a cone filled with electron beams emerging from a point, P, on the cathode, K. The diameter of the fluorescent circle shown on the right of Fig. 81a would be correspondingly large, say several centimeters. It was necessary, for this reason, to insert an aperture disc, D, which served to block out most of the stray electron beams and permit passage only to a much narrower cone that could reach the screen, S. The diameter of the circle produced on the screen would then be much smaller, say a few millimeters; but the brightness of this luminous circle would be the same as that of the larger circle in Fig. 81a, since the same number of electrons impinges on the screen per unit area.

When, instead of the insertion of the aperture disc, a solenoid, C, is slipped over the entire length of the tube and a current passed through its winding, the diameter of the luminous circle on the screen may turn out to be as large as in Fig. 81a, or nearly so. By gradually increasing the strength of the current flowing

through the coil, by means of a rheostat inserted in the circuit, the large luminous circle first obtained will shrink and finally become a bright small spot, D_3. The brightness will increase continuously since the total number of electrons reaching the screen in Fig. 81a will be concentrated into a smaller and smaller area on the screen. The spot of minimum diameter will have a dazzling brilliancy. When the current is further increased, the spot diameter will increase again to its old maximum, then de-

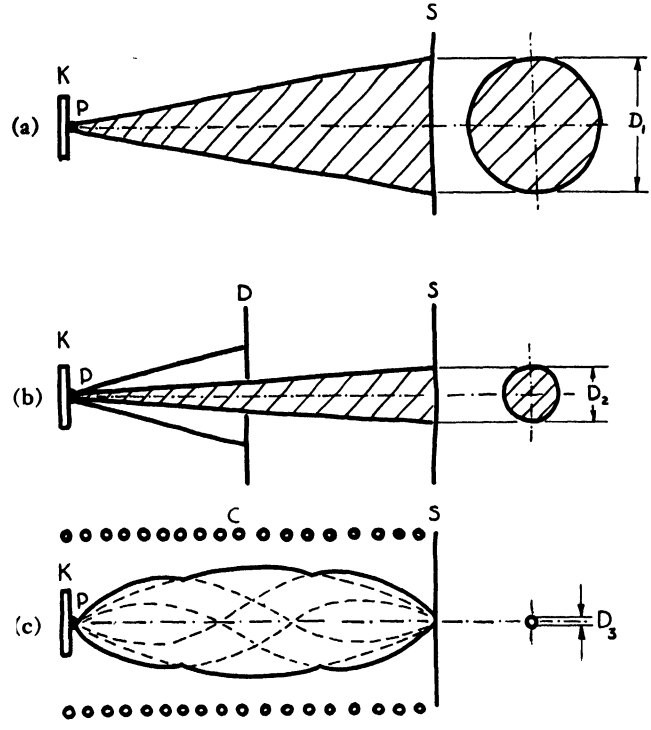


FIG. 81. Magnetic lens in and out of focus.

crease again, and so on. A great number of such cycles can be passed through.

The variation of the diameter of the spot on the screen when the solenoid current is continuously increased brings to mind the similar variation in diameter of a light disc produced by a sunglass on a piece of paper when the distance of the lens from the paper is varied. There is one position of the lens where we can

produce a sharp focus on the screen S (Fig. 82a). The parallel rays from the sun are gathered by the glass lens, L, and combine in a brilliant spot on the screen, which may burn it. The distance from the plane of symmetry of the lens to the screen is then equal to the focal distance f and coincides with the image distance b. If the lens is moved to the left (Fig. 82b) the focal distance remains unchanged and the image distance b_1, is now larger than f.

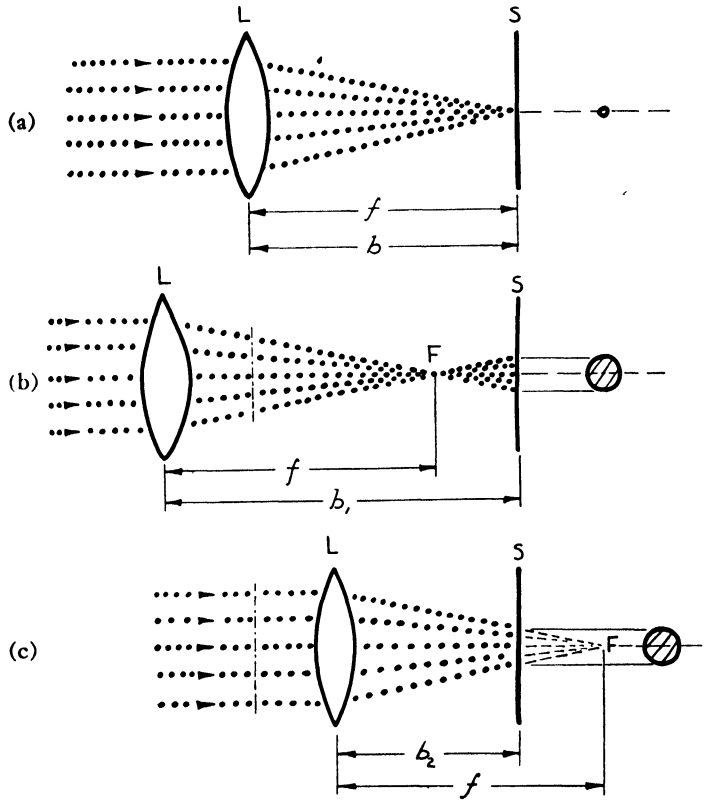


FIG. 82. Optical lens in and out of focus.

The result is that the rays cross in front of the screen and diverge toward the screen to produce a diffuse image which is larger than that in Fig. 82a. If the lens is moved toward the right (Fig. 82c), a similar diffuse spot results, since the screen intersects the rays at a distance b_2 before they have come to a focus. Instead of moving the lens the screen, S, may be moved to the right or left, giving the same effects. The essential point to be emphasized in

this optical experiment is that we can obtain only one focus. This is, of course, because the focal distance, f, of the lens is a fixed quantity which depends on the curvature of the lens surfaces, the thickness of the lens, and the type of glass used to make the lens.

When we come to describe the results obtained in the electrical experiment in which the coil current was continuously increased we arrive at Figs. 83a-e. The coil itself is not drawn in these figures but it is understood that a coaxial magnetic field is present in all five cases. Since we are dealing with a sealed-off vacuum tube the object-image distance, L, from cathode to screen remains constant. As a result of the increasing current intensity in the solenoid the focal length, f, of this magnetic lens evidently becomes shorter and shorter until in Fig. 83e its value has been halved. Since the electrons, after crossing the axis at F_4, continue to be subject to the coaxial magnetic field, they are brought to a second focus, F_4', on the screen. The long solenoid then acts in this particular case as a double lens. The variation of the spot diameter on the screen which is shown in Fig. 83 as D_1 . . . D_5 is now readily understood.

It is apparent from this experiment that a magnetic lens exhibits the unusual property of having a focal length which can be varied at will simply by varying the amount of current which flows through its winding. This feature is of the greatest practical importance. The magnetic field, H, represents the refractive medium which acts upon the electron beams as the glass does on the light beams in the optical microscope, and it is the value of H which is increased when the current increases.

The Short Magnetic Lens

When we compare the space that is occupied by the refractive medium in the case of a glass lens with that of a long magnetic lens we realize that the glass lens is very much shorter. It would be very desirable to have the magnetic lens also contracted to a shorter length, because this would make its use much more flexible. During the early years of experimentation with the Braun tube, not much attention was given to the dimensions of the concentra-

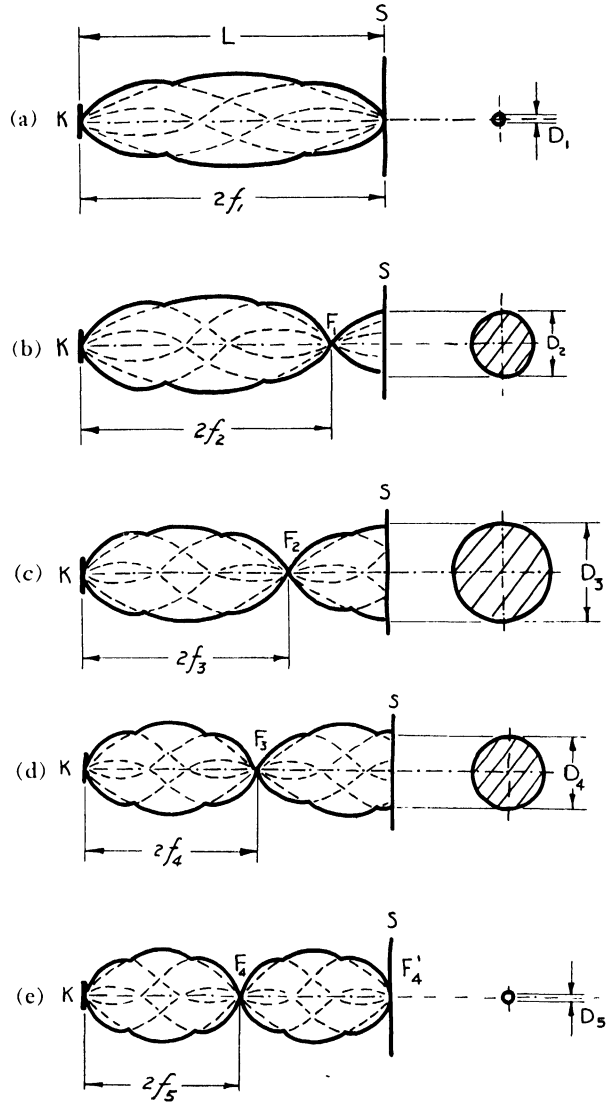


FIG. 83. Varying the focal length of a magnetic lens.

tion coil introduced by Wiechert. It was more or less fitted to the shape of the tube, sometimes extending over its full length, at other times fitted between cathode and aperture disk or between aperture disk and screen. In 1905, Rankin found that a spot of greater definition and brilliance could be obtained by arranging a solenoid between cathode and aperture disk, *i.e.*,

between K and D in Fig. 84. On the basis of the lens action of this coil, we can now explain this phenomenon. In the absence of any coil, only a small fraction of the total electron stream emanating from the cathode penetrates the aperture of D (Fig. 81b). A concentration coil, C, in the cathode-aperture disk region will focus all electrons in the aperture, thus making for a much brighter spot (Fig. 84).

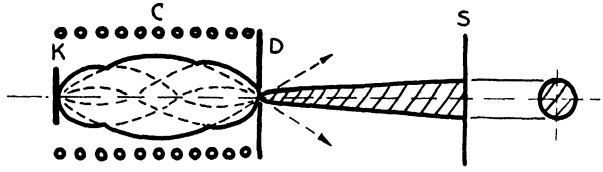


FIG. 84. Concentration of electrons on an aperture.

After the electrons leave the magnetic field at the aperture disk one would expect them to continue their flight along the dotted arrows in Fig. 84. In a gas-filled Braun tube they remain confined to the axis because of an effect known as gas concentration. Positive ions created along the axis of the tube exert an electrostatic attraction upon electrons which tend to diffuse away from the axis. In a tube free of gas, a high-vacuum tube, the one coil applied in Fig. 84 would indeed be of no use, since a very large luminous circle would be obtained. This condition is readily rectified by applying two separate concentration coils, one to the left of the aperture disk, C_1, and one to the right, C_2 (Fig. 85).

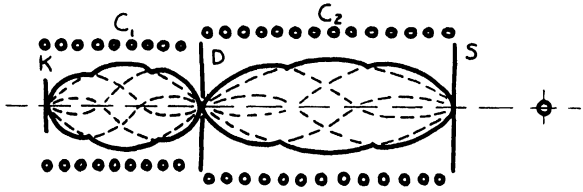


FIG. 85. Use of second concentration coil.

The first coil produces an image in the aperture plane and the second coil uses this image as a virtual object of which it produces in turn a sharp image on the screen, S. The size of the spot is now

determined by the diameter of the aperture in the disk, D. This system was first realized by Rogowski and Flegler in 1927.

The first demonstration of magnetic focussing was given in 1896 by MacGregor-Morris, together with Professor Clinton, who, on the suggestion of Sir Ambrose Fleming, pursued experiments on the effects of an axially placed magnet on cathode rays. They later mounted a circular coil on a Crookes tube between the metal cross target and the end of the tube, and found that by varying the current through the coil, the shadow of the cross upon the end of the tube could be varied in size. They also noticed a rotation of the image of the cross on the glass wall, an effect which is associated with all magnetic focussing.

Considering the relatively small size of a Crookes tube in comparison to that of a Braun tube, the experiments of MacGregor-Morris gave the first demonstration of the image-forming properties of a short magnetic coil. It was not until 30 years later that the vast implications of these experiments were fully realized.

Busch, in Germany, published a series of classical papers in 1926/27 which laid the theoretical foundation for the field of electron optics. He proved mathematically that a non-uniform magnetic field, in the direction of the tube axis, produced by a short solenoid also has the properties of a lens, and that the relation between focal length, magnetic field strength and electron velocity fitted well known optical formulae.

The action of a short magnetic lens is illustrated diagrammatically in Fig. 86. A divergent electron beam originating at P on the electron optical axis of the system enters the non-uniform magnetic field produced by the short solenoid, S, and is thereby brought to a focus at P′. The short solenoid thus fully satisfies the optical conditions for the formation of an image of an object. A point in the object is reproduced as a point in the image. In optics, the object must be the source of light beams; in electron optics, the object at P must be the source of electron beams. In optics, the refractive medium is a glass lens; in electron optics, the refractive medium is a magnetic (or electric) field. In optics, the image is formed on a screen, a photographic plate, or on the

retina of the eye of the observer; in electron optics, the image is formed on a fluorescent screen or on a photographic plate.

The equivalence of the action of a magnetic lens on an electron beam to that of a convergent glass lens on a light beam is further illustrated in Fig. 87, where the two corresponding systems of lenses are shown side by side. The focal points, F and F_1, on each side of the lens are also indicated. The distances along the axis from the center of the lens to the object P, the image P′, the first and second focus F and F_1 respectively, are related by a mathematical equation which applies in both cases.

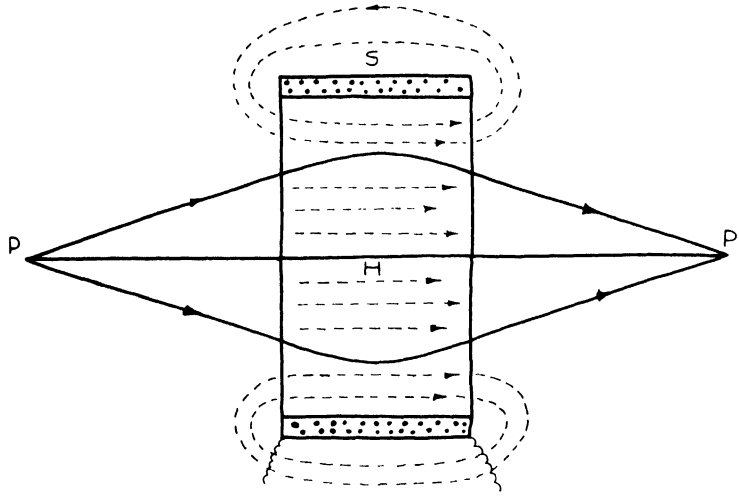


FIG. 86. The focussing action of the field of a short solenoid.

The transformation of an object point into an image point has been demonstrated in the previous examples for cases in which both these points were situated on the axis of the system. An object of physical dimensions must of necessity extend beyond the axis. Just as in light optics, the rule applies in electron optics, namely, that an image of objects can be formed as long as the image-forming rays do not diverge too far from the axis. Rays which travel near the axis are called *paraxial* rays. The means employed to insure that this condition is fulfilled are very similar for light rays and electron rays: it is the aperture stop familiar to everyone from the photographic camera. Fig. 88 illustrates

the function of this device for limiting the beam angle. Thus in Fig. 88a, the light emitted by the object O at rather large angles with respect to the axis is stopped by the aperture disc A, so that it cannot reach the lens. It has been mentioned in an earlier chapter that such wide-angle rays would cause severe distortions of the image if they were permitted to penetrate the marginal

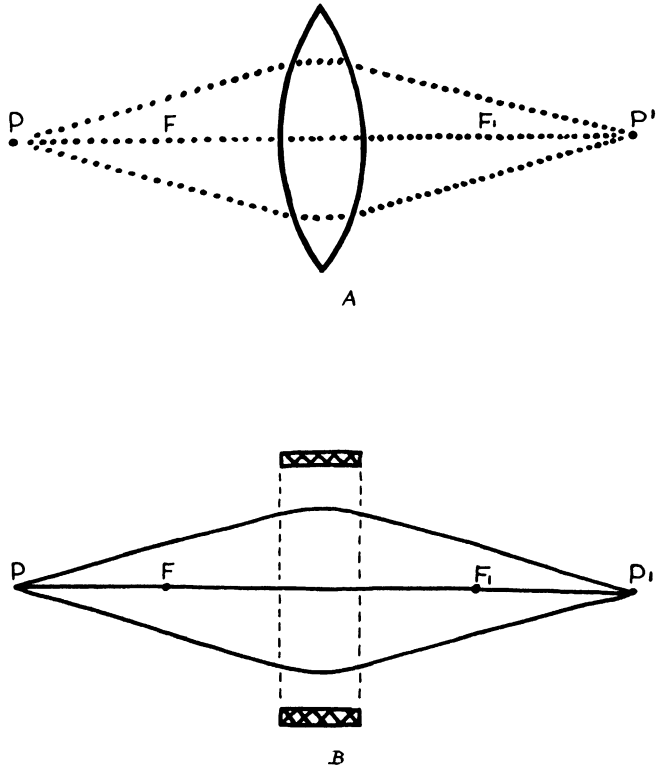


FIG. 87. Comparison of a convergent light (glass) lens and a convergent electron (magnetic field) lens.

regions of the lens. This state of affairs also prevails in electron-optical lens systems. Fig. 88b shows the electron rays originating at an oxide cathode, C, which is shielded by a guard ring, S. The anode, A, which accelerates the electrons, serves at the same time as an aperture stop and insures that only paraxial electrons reach the magnetic lens, L.

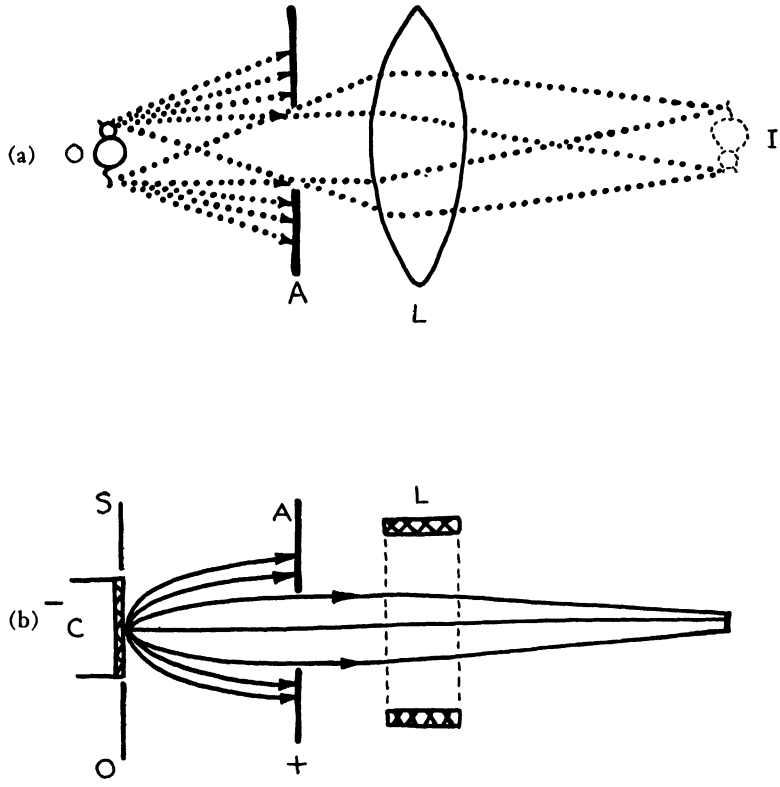


FIG. 88. Comparison of the use of aperture stops in light and electron lens systems.

The Iron-Shielded Magnetic Lens

When speaking of lenses in ordinary optical instruments a distinction is made between "thin lenses" and "thick lenses." These terms are used not only in their everyday meaning of thin and thick, but also to indicate that a different method of ray tracing or calculation must be followed in the two cases in order to determine the properties of the single and compound lens, respectively. A lens is called thin when its thickness along the axis is a small fraction of its diameter. This means, in turn, that the light ray travels only for a short fraction of its entire path through the medium of higher refractive index.

In the light of this terminology the introduction of Busch's short solenoid instead of the long solenoid was a step toward a thinner lens. But in optical language this Busch lens is still thick,

since the magnetic field strength along its axis is a considerable fraction of the maximum intensity at the center of the coil for quite a distance from the center of the coil on each side. Fig. 89 illustrates this condition.

It was recognized by Gabor in 1927 that the magnetic field could be concentrated along a shorter distance along the axis of the coil if the latter was encased in iron except for the inner wall

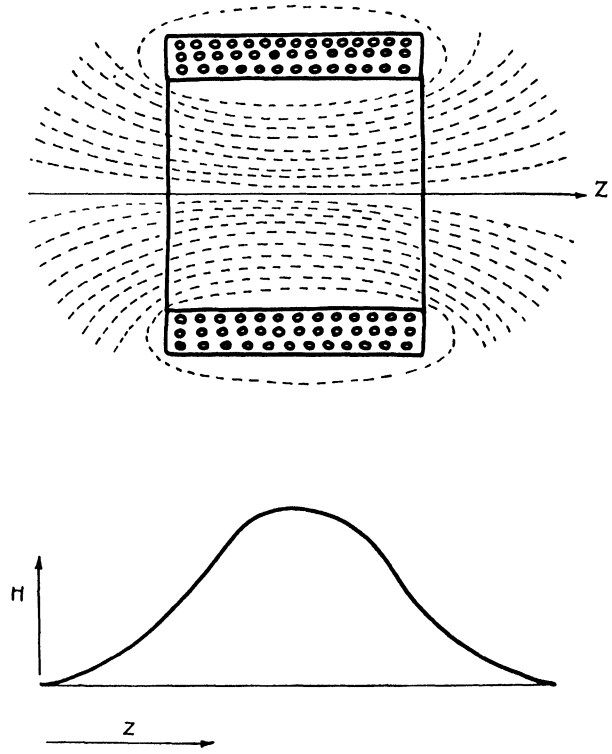


FIG. 89. Busch's original short solenoid magnetic lens. The graph shows the distribution of magnetic field strength along the axis.

of the coil where a non-magnetic metal is used. This is shown in Fig. 90; the cross-shading here indicates the winding, and the solid black frame the soft-iron enclosure. It is evident that the stray magnetic field is reduced considerably, since the magnetic field lines prefer to run through the iron casing.

Knoll and Ruska in 1931 carried this restricting influence of the iron shield to the extreme and utilized the stray field at a

narrow gap as the active field of the magnetic lens. Fig. 91a shows this type of coil in its earlier form and the field pattern obtained with iron filings. Fig. 91b gives the field distribution along the axis of the coil.

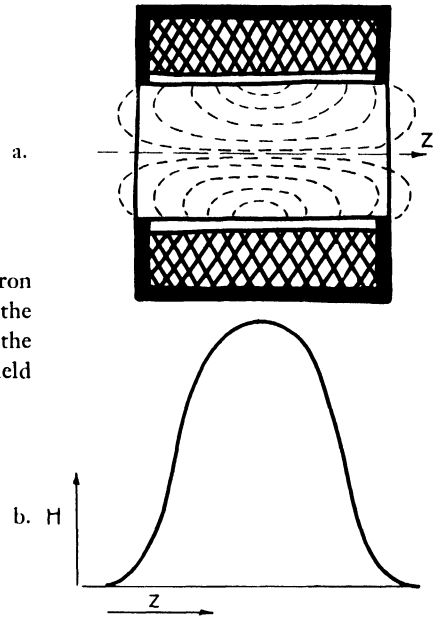


FIG. 90.

Solenoid encased in soft iron to concentrate the field at the center. The graph shows the distribution of magnetic field strength along the axis.

It was found that a reduction of the coil current by 30 per cent results from this type of construction, that is, a required field strength can be obtained with about two-thirds of the coil current that would be necessary in an unshielded coil. The distribution shown in Fig. 91b was obtained when a current of 100 ma. was sent through the coil shown in Fig. 91a. The winding of this coil consisted of 6500 turns of 0.2-mm diameter enameled wire, and it was operated from a 220-volt source. The focal length of this coil was of the order of a few centimeters. As a general rule it is stated that the minimum focal length of such a coil as shown in this figure is from one-third to one-quarter of the inside diameter of the iron shield.

The focal length of a magnetic lens is controlled by the intensity of the current which flows through the winding; it can thus be varied within a considerable range. The minimum value of

the focal length, which should be as small as possible if large magnifications are to be obtained, is determined by the geometry of the coil. Thus, when the physical dimensions of a magnetic lens are reduced to one-half their original size and the coil current is kept constant, then the power of the lens will be doubled or the focal length reduced by half. As the magnetic field intensity, H, depends on the number of ampere turns ($n \times I$, number of turns

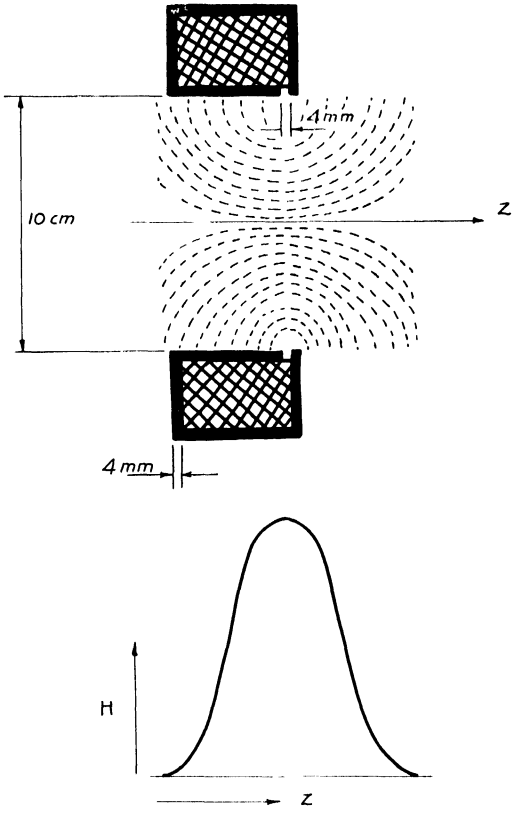


FIG. 91.

Magnetic lens of Knoll and Ruska (1931). The first use of narrow gap in soft iron casing.

times current in amperes) it is necessary to keep ($n \times I$) constant for the smaller coil. Thus reduction of the coil to one-half its size means that the current I will flow through a wire which has only one-quarter the cross-sectional area, since in order to allocate the same number of turns in half the space a reduction of the wire diameter by one-half is also necessary; this will lead to overheating of the wire if the reduction is carried too far.

Ruska overcame this difficulty (1934) by the introduction of pole pieces which are inserted in the threaded inner wall of the coil and in turn contain an annular gap made of non-magnetic material, such as brass, where the stray magnetic field protrudes and provides a concentrated magnetic field near the axis of the coil. The physical size of the coil itself can thus be kept conveniently large so as to prevent overheating of the winding; but the field is concentrated into a very small zone by the use of accurately machined pole pieces of very small dimensions. A magnetic lens of this type is shown in Fig. 92 in a schematic diagram which does not contain the details to be found in a modern

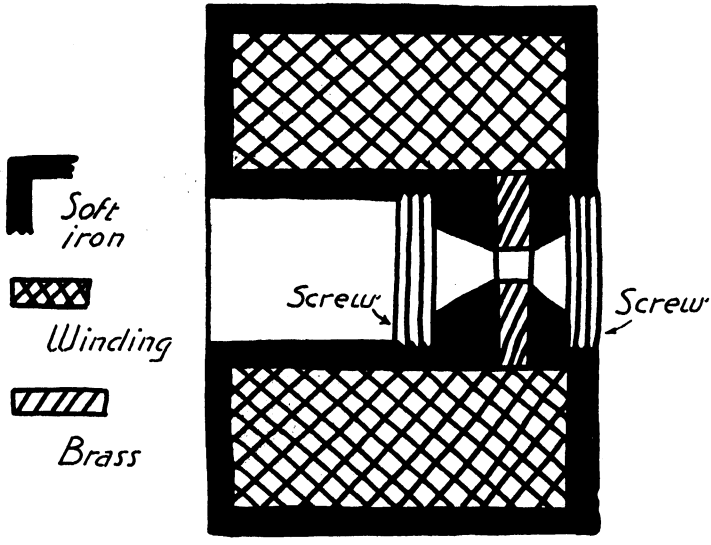
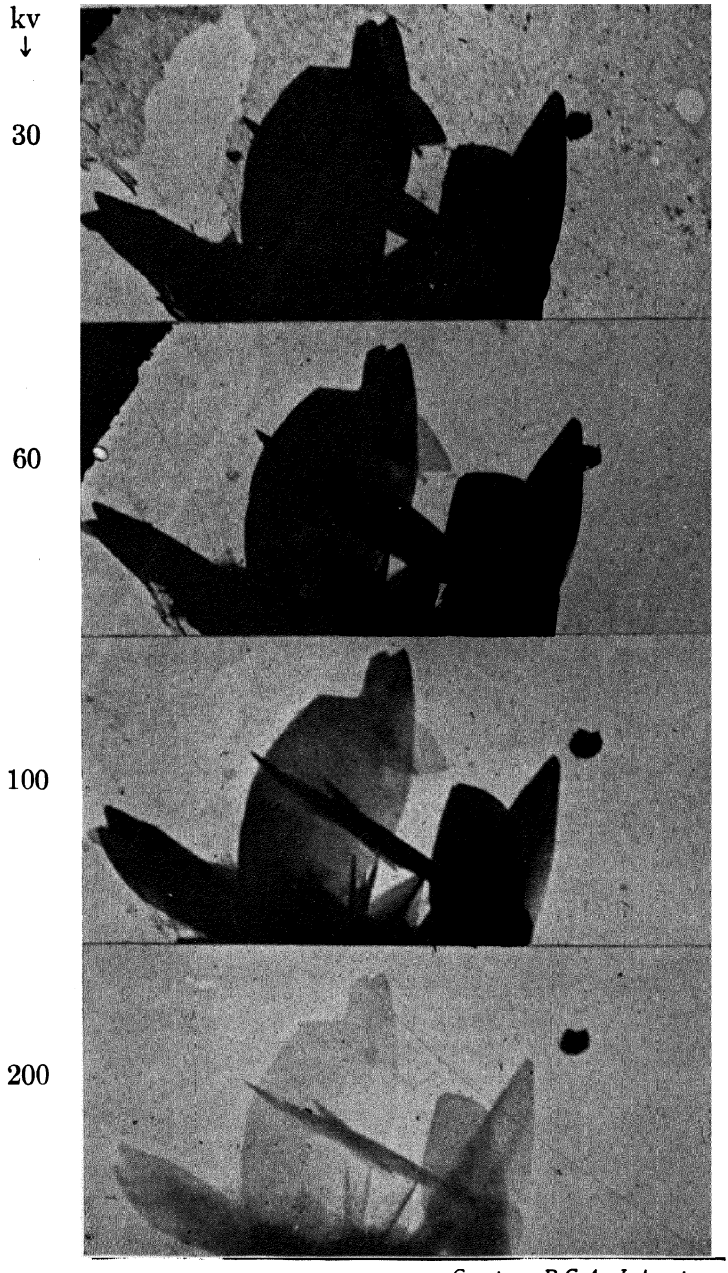


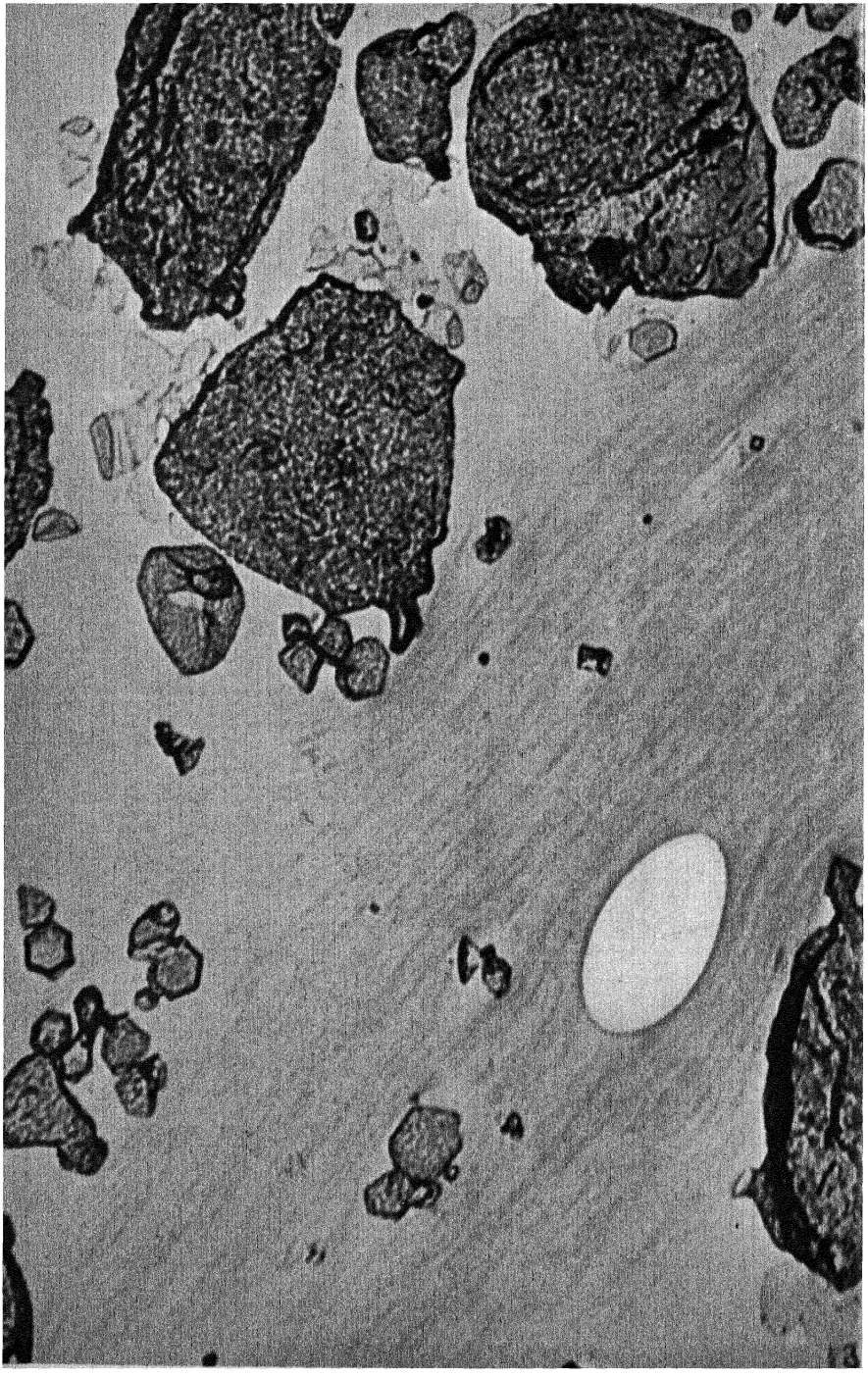
FIG. 92. Modern magnetic lens as used in magnetic electron microscope.

magnetic lens. The correct shaping of the pole pieces is a matter of great importance and has a decided effect on the quality of the image.



Courtesy R.C.A. Laboratories

Views of a sample of aluminum oxide taken with electrons with velocities corresponding to different fields (kilovolts).



Courtesy University of Michigan

Evaporated zinc on collodion film (×55,000).

Chapter 15

ELECTRON OPTICS
II. ELECTROSTATIC FOCUSSING

Historical Background

When we reflect for a moment on the contents of the previous chapter, we realize that the magnetic lens was developed experimentally without invoking in any way the wave concept of the moving electron. The theoretical foundation outlined by Busch indeed deals with the electrodynamics of the charged particle and not with its wave nature.

In the development of ordinary light optics also we know that lenses were used to form images of objects long before the dual nature of light was established. Even today, the designer of optical instruments leans heavily on the corpuscular concept in the sense in which it was associated with Newton, but has also to keep in mind that the fact that waves are involved limits his simple geometrical theory. He is thus very old-fashioned and very modern at the same time. When he wishes to determine the path that a light beam will follow through a number of lenses, he proceeds to draw straight lines according to geometrical rules. We have used this technique in Chapter 2.

The field of application where this method gives satisfactory results is called *geometrical optics*. It covers the effects of reflection and refraction and lends itself particularly to ray tracing on mirrors and through prisms and lenses. The effects which require the wave concept for their explanation form the domain of *physical optics*. Here we find the treatment of diffraction, interference, and polarization. Since we realize that the corpuscular and the wave concepts cannot be segregated in principle when dealing with the nature of light, some one may object to this classification of geometrical versus physical optics. After all,

it is the same light which produces the effects in both domains. Nevertheless, this terminology has been carried through the textbooks and may have its use at times.

We should then, likewise, speak of geometrical electron optics in cases when the corpuscular concept of the electron is uppermost in our minds, and of physical electron optics when we stress the wave nature of the electron, while being fully aware of the dual nature of the electron at all times. This practice has indeed been followed.

When we trace the trajectory of an electron beam through an electrostatic potential field we use a set of geometrical rules—different of course from that used in optics—and obtain a first approximation to the actual path. For this reason, the treatment of electron lenses and the associated electron paths forms the subject of *geometrical electron optics*. Davisson and Germer's experiments on the diffraction of electrons in a crystal lattice and the discussion of the resolving power of the electron microscope, where the wave nature of the electron plays the decisive role belong to the field of *physical electron optics*. At times it may be hard to decide which treatment will solve a certain problem the more easily.

We may now state that geometrical electron optics was developed as a result of—and not before—the full understanding of the dual nature of the electron. This need not have been so.

Long before the electron was discovered, Sir William Rowan Hamilton had clearly shown (in 1830) that a striking analogy exists between the law that governs the movement of a material corpuscle through a given field of force and the law which governs the trajectory of a light beam through a series of media of different refractive indices.

In the first case, the mass will move from a point P_1 to a point P_2 under the influence of the existing mechanical forces in such a manner that the sum of all the products of the momentum, mv, multiplied by the length of a small element of the path, ds, will give the smallest possible value when added up over the total length of the actual path from P_1 to P_2. Readers who have been exposed to a mathematical treatment of mechanics will recognize

in this rule the famous principle of Maupertuis, formulated in the middle of the eighteenth century, which may be given the mathematical form:

$$\int_{P_1}^{P_2} v\,ds = \text{a minimum} \qquad \text{(Mechanics)}$$

In the case of light, Fermat had shown, in 1667, that a beam of light will follow a path from a point P_1 to a point P_2 through various media of different refractive indices in such a manner that it takes the least possible time. This principle can be expressed mathematically as:

$$\int_{P_1}^{P_2} n\,ds = \text{a minimum} \qquad \text{(Optics)}$$

where n is the refractive index of the medium at any point.

Putting these equations side by side reveals the fundamental similarity between light and matter. We sense that the particle velocity, v, in mechanical laws takes the place of the refractive index, n, in the optical laws.

When the electron was discovered and recognized as a particle of a definite mass, m, and electron experiments had revealed striking similarities to optical experiments (1900), the way was open to develop geometrical electron optics on the basis of Hamilton's analogy between the basic mechanical and optical principles. By the time the dual nature of light was generally accepted by physicists, about 1910, there was really no excuse for not suspecting a like duality of the electron. Evidently, such a sympathetic approach to the study of nature, which would have been natural to the Greeks, was not cultivated at the time.

So the years went by; existing theories were carefully refined and much experimental work done with the aim of revealing the structure of the atom and the role which electrons played in it. Many times, when electron beams were caused to interact with atoms, whether they were in the form of a gas or in a solid array at the surface of a crystal, the observed effects were not in agreement with the conventional view of the corpuscular nature of the electron.

As we have seen, it was not until 1923 that de Broglie developed his electron wave theory and a few years later that Davisson and Germer and, quite independently G. P. Thomson, showed experimentally that a wave motion must be associated with an electron beam.

In 1926-27, Busch established the theory of the electron lens represented by axially symmetric magnetic or electric fields, and thus became the founder of geometrical electron optics. In 1931 Davisson and Calbick performed experiments on the lens properties of apertures and published the formula for the focal length of a circular and of a slit aperture. Thus the electrostatic electronic lens made its appearance. We shall now describe such lenses in more detail.

Electrostatic Lenses for Electron Beams

If we arrange three metal discs A, B, C, in a vacuum tube and assign to them the potentials as shown in Fig. 93a we may plot the potential values that exist along the axis O-O_1 of the system. Discs A and B are at zero potential and disc C is at 100 volts. The *space* between A and B is thus at zero potential, if the stray fields at the edges are neglected, and the potential plotted in Fig. 93b along the horizontal axis, Z, remains zero. In the space between B and C a potential gradient exists. The field is constant

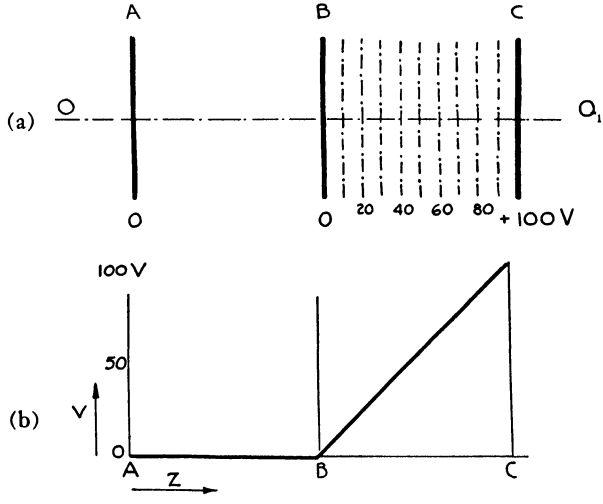


FIG. 93. Distribution of the electrical field between conducting plates at different potentials.

and has a definite positive value. This is indicated by the equidistant equipotential planes, represented by the thin vertical lines between B and C in Fig. 93a, and accordingly a linear rise of the potential plot in Fig. 93b along the axis between B and C.

In Fig. 94a the same electrode arrangement is shown, but the disk, B, is provided with an aperture. The field to the right of B now bulges through the hole in B into the space to the left of B, where previously no field existed. The equipotential planes become curved in the vincity of the aperture and straighten out only in front of plate C. The potential values are written on the potential areas in small figures. Fig. 94b gives the corresponding rise of potential along the axis. This plot is no longer a straight line throughout, but contains only a short straight section in front of C. The slope of the potential plot is small, *i.e.*, the field is weak to the left of B, and it increases rapidly to the right of B. It is worthy of note that the potential at the center of the aperture is greater than the potential of the disc itself.

Let us now assume (Fig. 95) that disk A is an electron emitter at the center. This is readily realized in practice by inserting

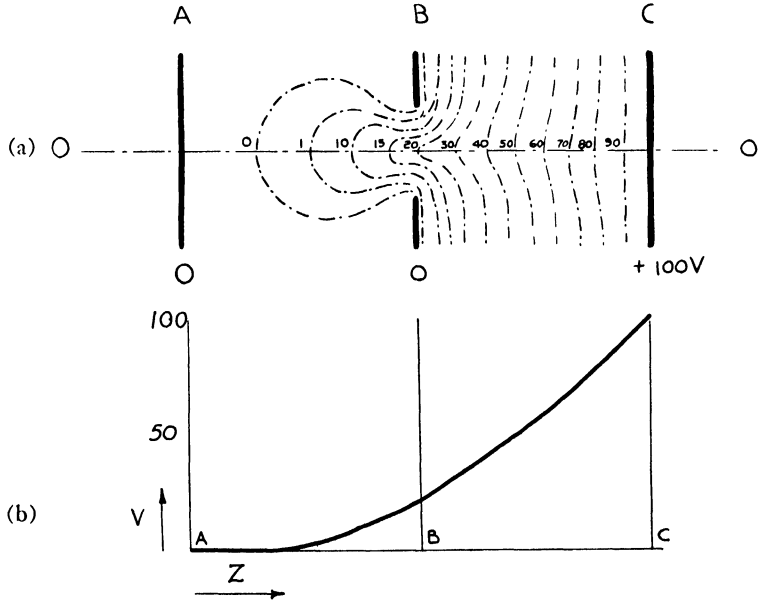


FIG. 94. How the potential distribution is affected by an aperture in an electrode

the oxide-coated face of a cathode sleeve at the center; this is heated by a flat spiral heater wire back of it. The cathode sleeve, generally made of nickel, is connected with the main disc A by a thin wire, w, so as to maintain zero potential on both of them. The disk A thus extends the zero potential face of the cathode without draining any noticeable amount of heat from it. This

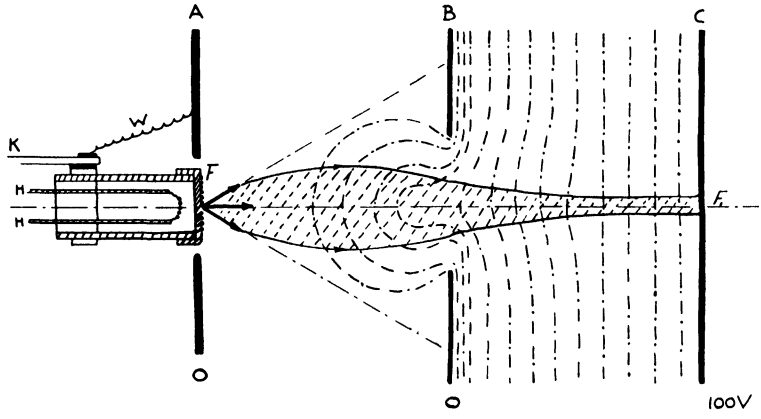


FIG. 95. The influence of an electrode with an aperture near the cathode.

arrangement is frequently used in cathode-ray tube practice and is known as a guard ring. When a current is sent through the heater wire, the oxide-coated face, F, will reach a dull red temperature and electrons will be emitted from it. The paths of electrons near the axis are shown brought to a focus, F_1.

Electrons Emitted with an Initial Velocity

We have previously assumed that electrons are released at the cathode surface with zero velocity. This is true for some electrons; others possess an initial velocity even in the absence of an electric field in front of the cathode. Furthermore, while most of the emitted electrons leave the cathode face at right angles in the direction of the Z-axis, others are emitted at an angle with respect to the normal. This is indicated by the three small arrows in Fig. 95 emanating from the center of F. We may illustrate this space distribution of the electrons emitted from a point, P, at the cathode, C, in Fig. 96. Here a circle is drawn in front of the cathode face and a number of arrows are inscribed, all of

which originate at P. The lengths of these arrows indicate the relative number of electrons emitted in the direction given by the arrows. It becomes clear from this diagram that many electrons are emitted in a direction normal to the cathode face, but that a definite fraction of the total emission occurs sideways.

It may then be stated that electrons are emitted from a cathode with different initial velocities and in different directions. Another noteworthy feature of the movement of electrons in an electric field must now be explained before the electron paths in Fig. 95 can be fully understood. It was stated earlier that electrons which start from a position of rest travel in an electric field in such a manner as to follow the field lines or, what amounts to

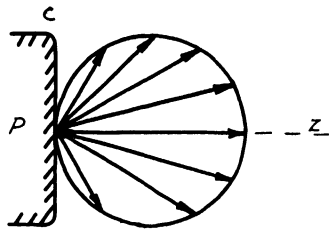


FIG. 96.

The number of electrons emitted from a point on the cathode with velocities in different directions.

the same thing, so as to penetrate the equipotential planes at right angles. This was the case in Fig. 58, where we assumed an emission with zero initial velocity.

We have learned in the meantime that the initial velocities may have positive values—up to about 0.2 volt, to be specific—and that these initial velocities may be directed sideways with respect to the normal to the cathode face. How will this affect the electron paths? A little earlier, the rectilinear movement of an electron in a uniform electric field from a position at rest was compared with a stone that falls to earth in a straight line in the gravitational field when released from a position at rest in the hand. If we now give the stone an initial velocity that is directed at an angle to the previous path, the trajectory of the stone will be a parabola, as shown in Fig. 97. The horizontal lines 1, 2, 3, 4, 5, represent equipotential planes, *i.e.*, points where the work that must be done to raise the stone from the ground level to the

height indicated is constant. We note from Fig. 97 that the stone moves at right angles to the equipotential planes from O to A, when it starts either from a position at rest or when its initial velocity is directed at right angles to the equipotential planes. On the other hand, when the initial velocity is directed sideways, the path O-B is no longer at right angles to the equipotential planes. The stone is then refracted at the respective equipotential planes.

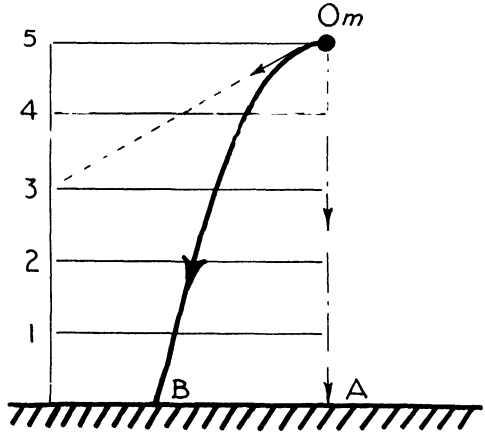


FIG. 97. The path of a falling stone which has been thrown out with a velocity in the direction of the arrow.

The same reasoning applies to an electron which moves in a uniform or non-uniform electric field with an initial velocity which makes an angle with the field lines. This is illustrated in Fig. 98. The electron trajectories in Fig. 95 are now readily understood. The electrons which are emitted in the direction along the axis travel in a straight line to F_1 on plate C, just as the axial ray in an optical system reaches the focus in a straight line. The focussing action of the potential field is exerted on the "stray electrons" which are emitted sideways at angles not too large.

As has been stated, the focussing action of an aperture system upon an electron stream was first recognized and expressed in mathematical form by Davisson and Calbick of the Bell Telephone Research Laboratories (New York) in 1931. These workers published the formula for the focal length of *an electro-*

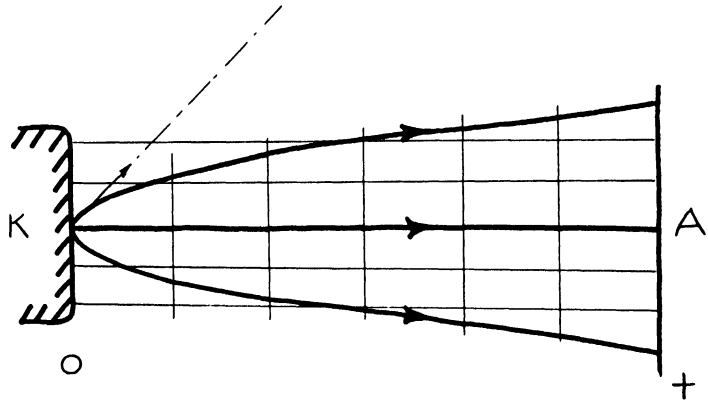


FIG. 98. The paths of electrons emitted with a velocity making an angle with the direction of the lines of force of the electrical field. This explains directions indicated in Fig. 58.

static electron lens of the aperture type expressed in terms of the voltages applied to the electrodes. Brüche and Johannson of the Allgemeine Elektrizitäts Gesellschaft (A.E.G.) in Berlin pursued similar work independently at about the same time. The German school was particularly successful in applying these new electron tools to the design of practical instruments, one of which was the electron microscope. The principles underlying these *aperture lenses*, as they are called, deserve closer study.

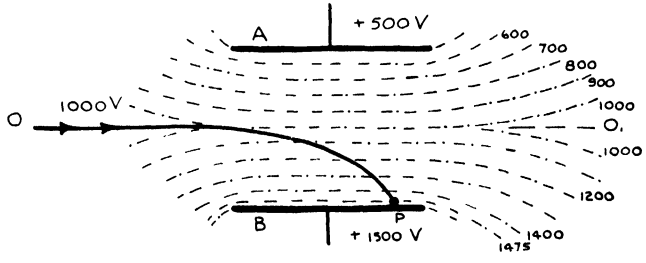


FIG. 99. How the path of an electron bends when travelling through a potential field.

The Refraction of Light and Electrons

In Fig. 99 the potential distribution between two plates, A and B, is shown for the case where plate A is kept at a potential of +500 volts and B at a potential of +1500 volts. The areas of equipotential will be distributed symmetrically as marked.

If an electron beam with a velocity equivalent to 1,000 volts enters along the axis O-O_1 from the left, it will follow a curved path as shown and strike the plate B at P, if the potential of B is high enough, or the plate sufficiently long. The layers of increasing potential thus act upon the electron beam in much the same way as the layers of differing refractive index act upon the light beam. Fig. 2 is repeated here in order to bring out the analogy that exists between the refraction of light in the layers of the atmosphere of different densities and this electron refraction.

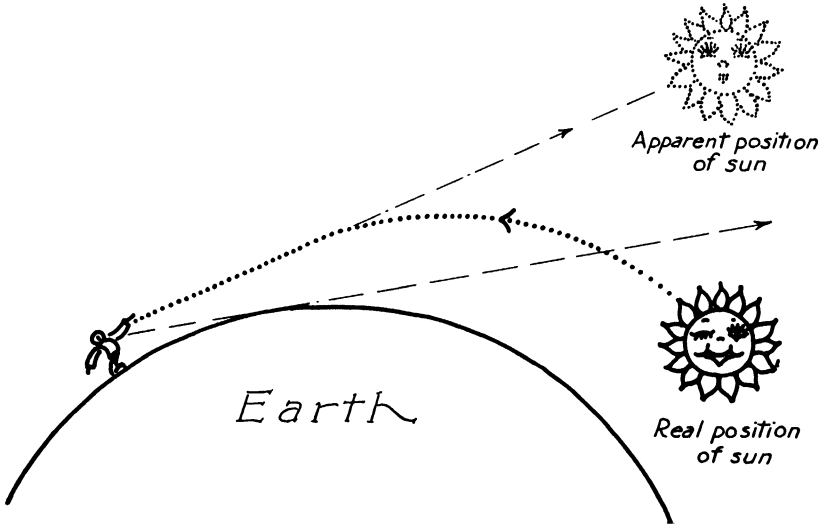


FIG. 2 repeated to show clearly the analogy between the refraction of light and the bending of the path of electrons.

The refraction of a light beam when it passes from one medium, such as air, into a denser medium, such as water, is accurately described by Snell's law to which reference was briefly made on page 45. Fig. 100 describes the experimental conditions which serve to demonstrate this fundamental law of optics. The line AA′ with its shading represents the boundary between two different optical media which are characterized by the refractive index n_1 above the boundary and n_2 below it. Thus AA′ may represent a water surface with air above and water below the boundary. If a narrow beam of light produced by the

lamp L, behind a screen, S, is directed toward the boundary, AA′, where it impinges at O, it will continue its path in the water in the direction OP. The vertical line, NN′, represents the normal to the surface, AA′, at O. The angle α_1 is then called the "angle of incidence" and the angle α_2 the "angle of refraction." These two angles can readily be measured. It is found that the light beams above and below the surface and the normal at the point of incidence always lie in one plane, which in Fig. 100 is the

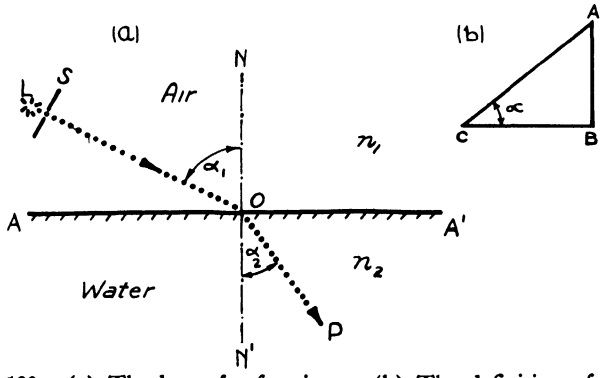


FIG. 100. (a) The law of refraction. (b) The definition of sin α.

For any angle α, if we draw any right-angled triangle containing α as one angle, the ratio of the side opposite the angle (AB) to the hypotenuse (CA) is called the sine of the angle α and is written sin α.

plane of the paper on which the diagram is drawn. When the light source with the screen is moved in the plane of the paper on a half circle, with O as center, the angle of incidence, α_1, will take on different values, and the angle of refraction α_2 will also change. It was found by Snell that, irrespective of the position of the light source above the boundary, the ratio of the sine of the angle of incidence to the sine of the angle of refraction is identical for all positions of the light source, as long as the medium above or below the boundary is not changed. This ratio $\frac{\sin \alpha_1}{\sin \alpha_2}$ is called the index of refraction of the water. If n indicates the index, $n = \frac{\sin \alpha_1}{\sin \alpha_2}$. Strictly this definition is true only when the upper space is a vacuum, but air differs very little from a vacuum

in its effect on the bending of the ray at O. In the case of air and water as the two media, the ratio will have the constant value 1.33. If the water is replaced by glycerin, the ratio becomes 1.47. When the experiment in Fig. 100 is performed between two liquids or two different kinds of glass, with indices n_1 and n_2, the ratio $\frac{\sin \alpha_1}{\sin \alpha_2}$ is equal to the ratio $\frac{n_2}{n_1}$. This general form of Snell's law governing the refraction of light passing from a medium with index n_1 to a medium with index n_2 may be written:

$$n_1 \sin \alpha_1 = n_2 \sin \alpha_2$$

According to Sir William Rowan Hamilton's conception of the identity of the optical laws describing the passage of a light ray through a series of refractive media with the mechanical laws describing the motion of a small mass through a potential field, we are led to expect the validity of a modified form of Snell's law applying to electrons moving through a field of electrical potentials. This belief is based on our conviction that an electron is a particle of a small but uniquely defined mass. The comparison of the two basic principles which govern the path of a light beam and that of a moving mass, respectively, (p. 177) indicated that the electron velocity v should take the place of the refractive index n in the optical law, so that we would obtain by analogy a law governing electron refraction thus:

$$v_1 \sin \alpha_1 = v_2 \sin \alpha_2 \qquad (1)$$

It remains to be shown that this is correct.

Fig. 101 is an enlarged view of a small portion of Fig. 99, where an electron beam crosses the equipotential plane marked 1200V. It might apply to any one such potential plane crossing. In order to make Fig. 101 a more complete counterpart of Fig. 100 and to be intelligible without reference to Fig. 99, the light source, *L*, in Fig. 100 is replaced by an electron source or a small electron gun. The shield, S, in front of the cathode, K, is the accelerating anode at potential V. The boundary, AA′, separates two regions of different potential, V_1 above and V_2 below the boundary and it is assumed that V_2 is larger than V_1, so that the

electrons are accelerated when crossing the boundary. Thus there exists a potential gradient at the boundary in the direction NN′ normal to the surface. This gradient represents a force which will act on the electrons when they reach the point O.

In order to find out how this force affects the trajectory of the electrons we resort to an artifice which we used once before (p. 152) in a similar problem. Since the electron beam travels in a field of uniform potential V_1 above the boundary, its trajectory is a straight line and the velocity v_1 of the electrons is constant along this path from the aperture S to O. This velocity is a directed quantity and can thus be represented by a vector XO, where the origin of the vector is an arbitrary reference point along the electron beam. We split up this vector v_1 into two

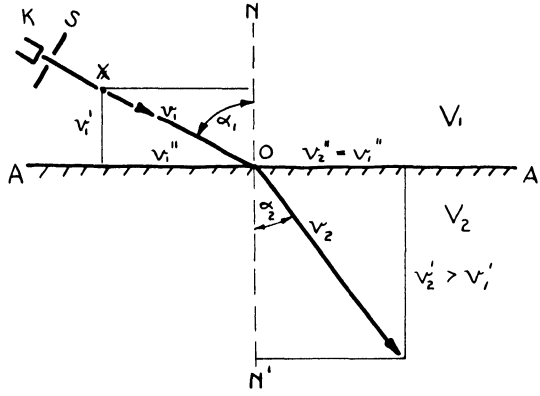


FIG. 101. Refraction of electron beam.

components at right angles to each other where v_1' is the resolved part in a vertical direction and v_1'' the part along the boundary AA′. We then consider what happens when the electron at X has reached the point O, where the force due to the potential gradient acts upon it. Since this force lies in the direction of the velocity component v_1', the velocity in the direction ON′ will be increased while the velocity component v_1'' will be unaffected since no force acts in its direction. The two vector components v_2' and v_2'' (which equals v_1'') add up to the vector v_2, which gives the new direction and velocity of the electrons in the region below the boundary where the potential is V_2. If we now relate the velocity vectors to the angle of incidence, α_1, and the angle of

refraction, α_2, we obtain the following expressions by putting in the values of sin α_1 and sin α_2 in the two vector triangles in Fig. 101:

$$\sin \alpha_1 = v_1''/v_1 \qquad (2)$$
$$\sin \alpha_2 = v_2''/v_2 \qquad (3)$$

By dividing equation (3) into equation (2) we get

$$\frac{\sin \alpha_1}{\sin \alpha_2} = \frac{v_1'' v_2}{v_2'' v_1} \qquad (4)$$

Since v_1'' equals v_2'' they cancel out, so that

$$\frac{\sin \alpha_1}{\sin \alpha_2} = \frac{v_2}{v_1}$$

or

$$v_1 \sin \alpha_1 = v_2 \sin \alpha_2 \qquad (5)$$

Equation (5) is identical with equation (1), which we deduced by analogy. It is thus established that the electron velocity v represents the electron optical refractive index. As we have shown (p. 134) the electron velocity is determined by the potential difference through which the electron has been accelerated; it is related to V by the equation

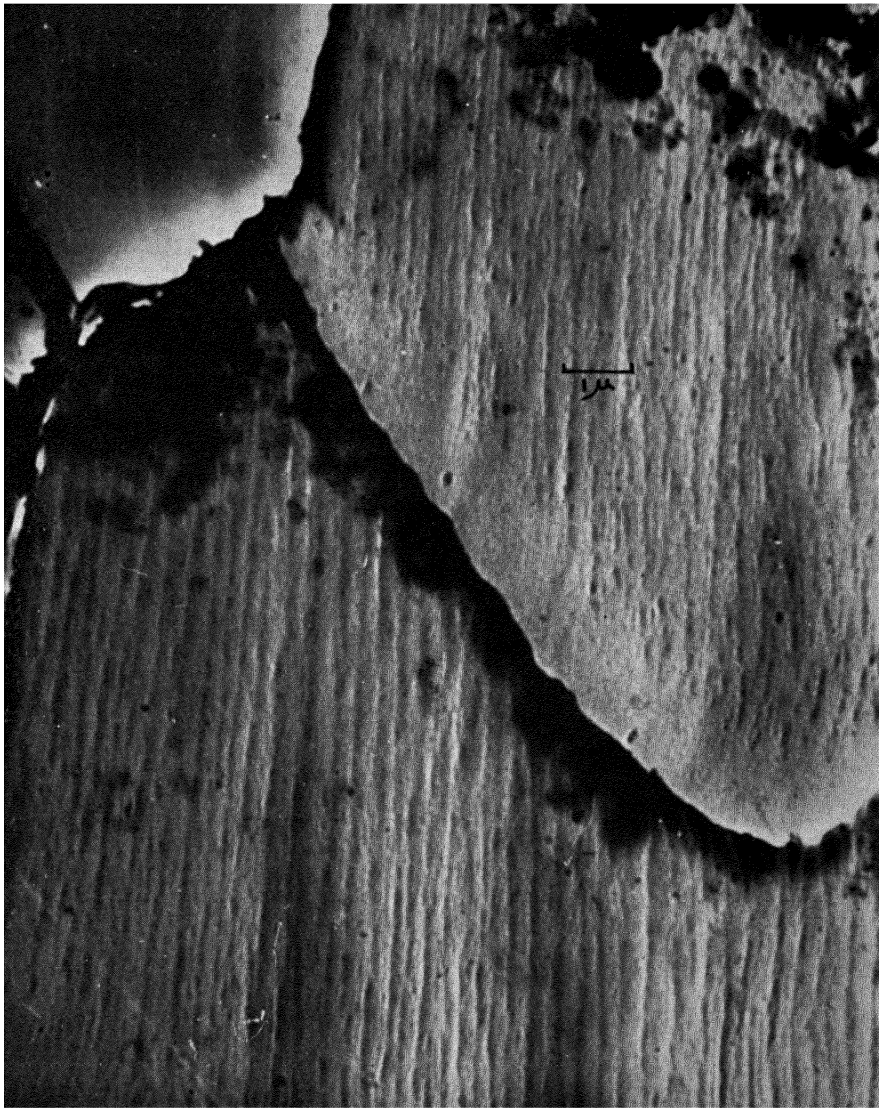
$$v = K\sqrt{V} \qquad (6)$$

where K is a numerical constant equal to 5.93×10^7 when V is expressed in volts and v in cms. per sec. We can substitute equation (6) in equation (5) and obtain

$$\frac{\sin \alpha_1}{\sin \alpha_2} = \frac{\sqrt{V_2}}{\sqrt{V_1}}$$

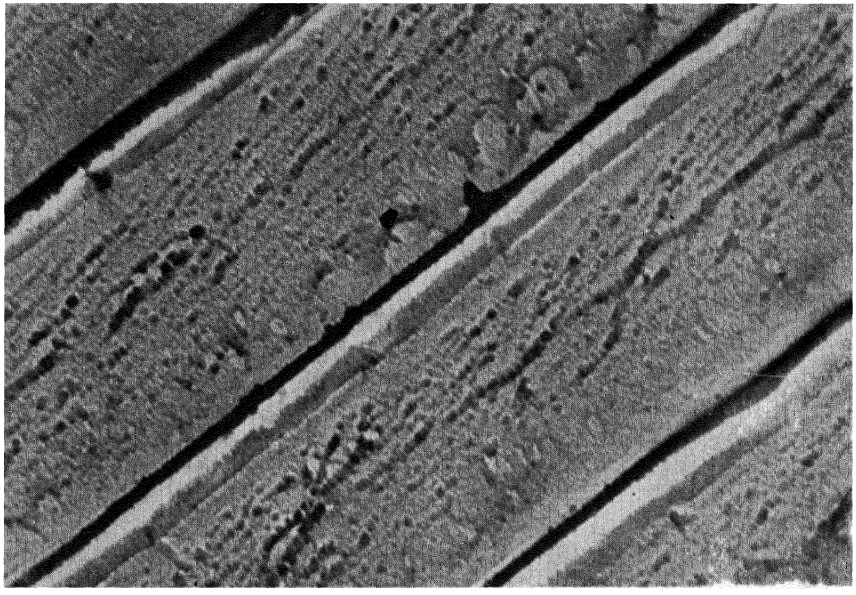
The fundamental law of electron optics is often quoted in this form.

We shall now proceed to give in the following chapters a description of the structural features of the electrostatic and magnetic electron microscopes as far as it is essential to the understanding of their operation. Many details must of necessity be omitted in a general text of this type.



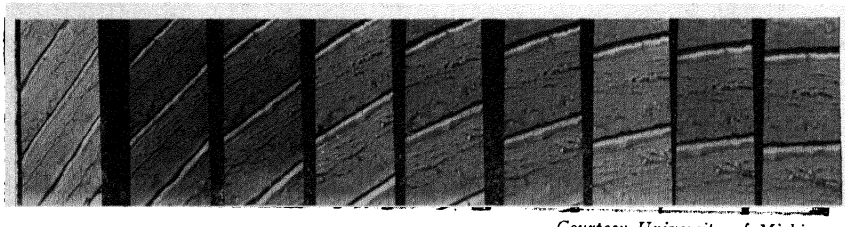
Courtesy [illegible] *Co.*

Replica of surface scales on wool fiber, ×9,000 (3,000× electronic, 3× optical).



Courtesy University of Michigan

Replica of grating with line interval of 1.76μ.



Courtesy University of Michigan

Same as above, illustrating method of calibration. The distance between the lines is known and magnification is changed by changing the current in lens coil.

Chapter 16

THE ELECTROSTATIC ELECTRON MICROSCOPE

Object and Image

In order to form images of objects with the aid of electron beams, one essential condition must be satisfied. Electrons which leave a point on the object at small angles with respect to the normal to the object plane must be reunited at a point in the image plane. In order to bring this about the object and image planes are parallel to each other and separated by a given distance along the electron-optical axis of the system. Object points in the object plane are confined to the close proximity of the axis, whereas image points in the image plane are located within the circle of sharp image formation which may have a diameter of several inches, depending on the magnification of the system. These statements are illustrated in Fig. 102 in a simplified manner. Five representative points A, B, C, D, E are chosen in the object plane (O, P) and form the apex of five cones of divergent electron rays. In the plane indicated by L an electron lens, or a combination of several such lenses, which in effect can be replaced by an ideal thin lens, is located. The function of this lens is twofold. The cone of electron rays which diverges from the object point must be inverted so as to converge to a point in the image plane. The lens plane thus becomes the base of a series of double cones. In order to bring about this result the forces acting upon the electrons in any one of the various beams must be directly proportional to the radial distance of an electron from the axis of any one beam to which it belongs. In this manner, the electrons which tend to diverge the most undergo the greatest constricting force. At the same time, the electron lens will impart to the beams a deflection which will make the distances between

the image points, A'B'C'D'E', respectively, greater than the corresponding distances between the points, A B C D E, in the object plane. Thus a magnification of the object results which is given by the ratio of the distance of an image point from the optical axis, CC', to the distance of the corresponding object point from the axis. This ratio M, the magnification, must be constant for all image points in order to obtain a linear representation of the object in the image plane.

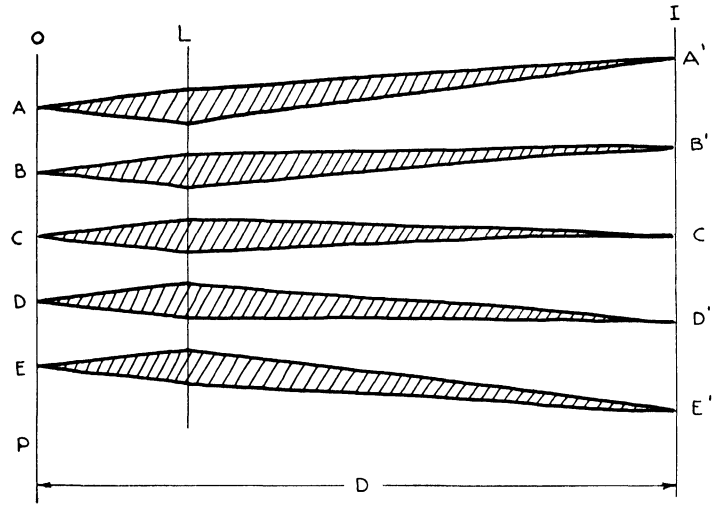


FIG. 102. Object points and corresponding image points produced with a negative electron lens.

Figs. 102 and 103 illustrate how the electron beams may either spread out from the lens plane or cross each other in an intermediate plane, F, near the axis. (It may be remarked here, that this so-called "cross-over" is of particular interest in the theory of cathode ray tubes since it represents a virtual cathode of high current density. A limiting aperture is placed in this plane, F, and an image is formed of it on the fluorescent screen with as low a magnification as possible so as to obtain an intense and very small pin point of light on the screen.)

An Electrostatic Negative Lens

In the first case (Fig. 102) the lens action would be equivalent to a negative lens in optics (see Fig. 12b) and could be brought

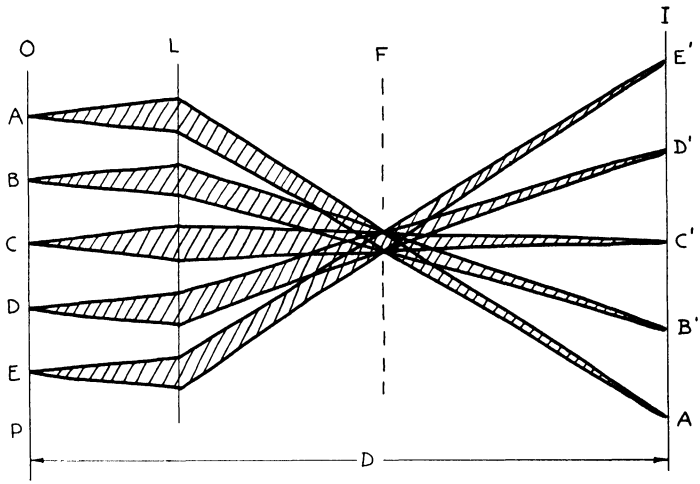


FIG. 103. Object points and corresponding image points produced with a positive electron lens.

about by an aperture lens, A, in front of a cathode, K, followed by a field free space to the right of A (Fig. 104). This arrangement represents the only negative electron lens known. All others are positive in their action (see Fig. 12a). Since the lens field in Fig. 104 extends to the cathode, which now becomes our object in electron optics, we have to classify this arrangement as an immersion lens. Unfortunately this system has no practical value because the voltage that can be applied in close

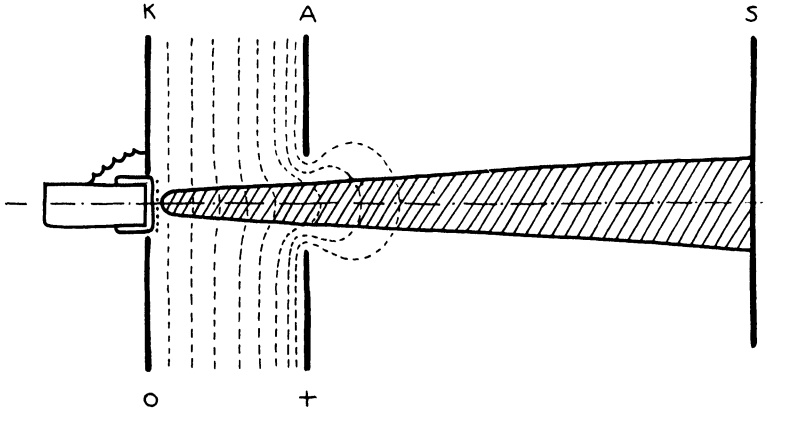


FIG. 104. The theoretical arrangement for a negative electron lens.

proximity to the cathode is limited to values of the order of 50 volts, and electrons of such low velocity barely excite fluorescence on a luminescent screen. We find then, in most electron image-forming systems, that the beams cross the optical axis and that the position of the image is inverted with respect to the object, as shown in Fig. 103.

Electrostatic Positive Lenses: The Three-Electrode Lens

The first practical electron lens system which lent itself to the construction of an electrostatic electron microscope was described by Brüche and Johannson in 1932. It is called "the immersion objective lens." We shall here briefly describe the structural features of this lens without going into a discussion of its theory, which is rather involved. For purposes of brevity we shall use the letters I.O. as an abbreviation for immersion objective.

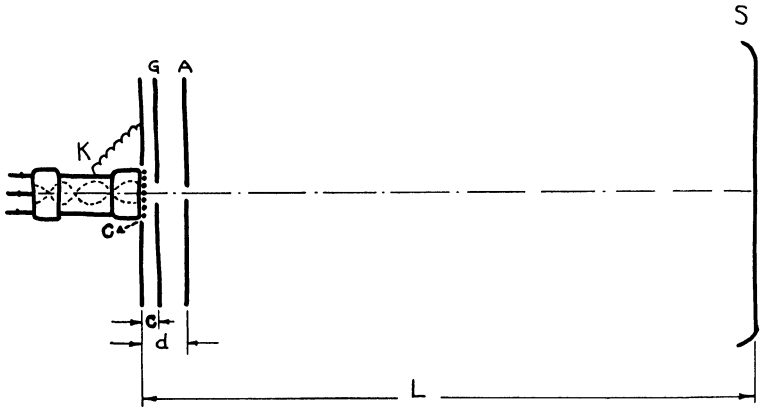


FIG. 105. Brüche and Johannson electrostatic electron microscope.

Diameter	C= 5 mm.	L=	240 mm.
Aperture	G= 1.2 mm.	V_G=	140 volts
Aperture	A= 1.0 mm.	V_A=	750 volts
	c= 0.5 mm.	V_S=	750 volts
	d= 1.0 mm.*		

*Dimension d is distance from G to A, not from K to A as shown in the figure.

In its original form, the I.O. consisted of two aperture disks located in front of the cathode, as shown in Fig. 105. The indirectly heated cathode, K, of the oxide-coated variety, is surrounded by a guard ring at cathode potential as we have described

on other occasions in this text (see Fig. 95). In front of it, at a distance, c, from the cathode surface, a first disk of molybdenum sheet, 0.2 mm thick, is mounted with aperture G, 1.2 mm in diameter. In conformity with radio-tube practice, this disk element is called the grid, G. At a distance, $d = 1$ mm, from G, a second molybdenum disk, A, with an aperture 1 mm in diameter, is mounted; this serves as anode. The fluorescent screen, S, which is maintained at anode potential, is mounted at a distance, $L = 240$ mm, from the cathode surface. It goes without saying that the various electrodes must be aligned most accurately with

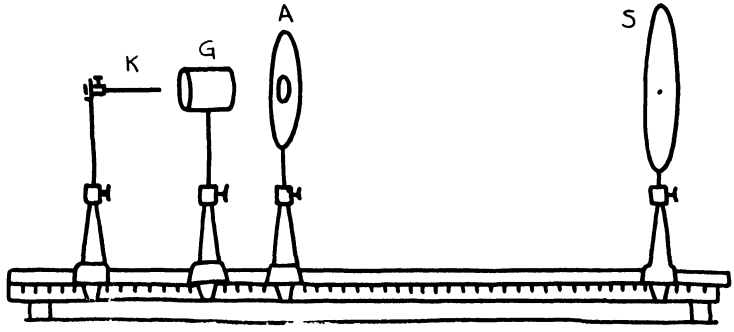


FIG. 106. Arrangement of part of the electron microscope on an optical bench built inside a vacuum tube.

respect to the axis and with respect to one another, since the slightest deviation from axial symmetry will produce image distortions. The aperture edges must not only be perfectly round but also free from burrs and carefully polished. In practice, this accuracy of the mount is achieved by the use of ceramic spacers between electrodes or by jig mounting in glass beads which are softened during assembly so that the electrode supports can set in the glass while the proper distances are maintained by the jig. In an experimental setup such as that of Johannson, the elements were mounted on an optical bench along which they could be moved *in vacuo* by means of external magnets. Provision was also made for varying the distance, c, between cathode and grid aperture, G, by mounting the cathode on a system of bellows. Fig. 106 shows the elements on the optical bench support, Fig. 107 shows the cathode bellows, and Fig. 108 a cathode image

obtained with the I.O. by C. E. Hall at Toronto in 1936. By adjusting the voltages on the electrodes C, G, A, Brüche and Johannson found that a sharp image was obtained for $V_G = 140$ volts and $V_A = 750$ volts corresponding to the dimensions given in the legend of Fig. 105.

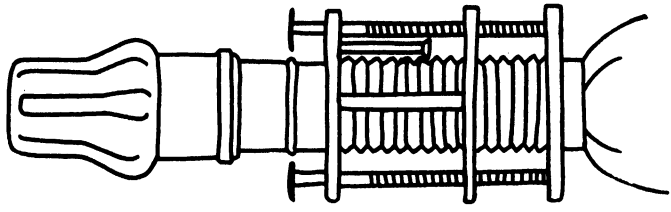


FIG. 107. Arrangement of bellows for adjustment of the position of the cathode in a three-electrode lens.

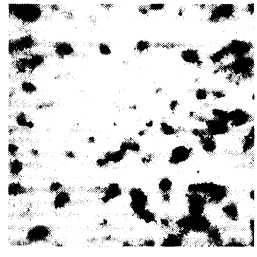


FIG. 108. Image of cathode with electrostatic lens.

The Magnification of a Three-Electrode Lens

Fig. 109 shows how the grid potential V_G must be adjusted in order to maintain a sharp image when c is varied. Fig. 110 gives the resulting effect on the magnification, M.

It turns out that, for any given value of c, a sharp image is obtained with a definite value of the ratio V_G/V_A, and the magnification, M, depends only on this ratio, irrespective of the magnitudes of V_G and V_A, which satisfy this ratio. This is simply an experimental verification of the general law for electrostatic electron lenses which we derived above; the power of such a lens depends always on a potential ratio. In Fig. 111 the magnification, M, the diameter of the sharply reproduced image B_0, the diameter

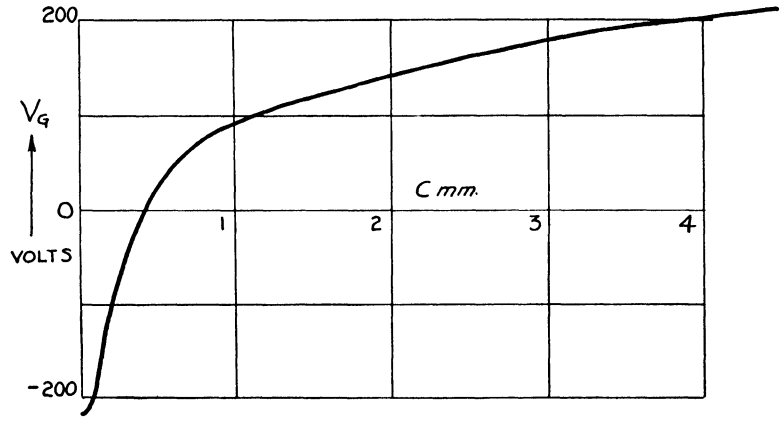


FIG. 109. Graph showing the value of the grid potential, V_G, necessary to give a sharp image in the three-electrode lens as the distance, c, between the cathode and the grid is changed.

of the sharply reproduced region on the cathode $A_0 = B_0/M$ and the distance, c, are plotted against the ratio V_G/V_A as abscissa.

If one aims to reproduce sharply as large an area of the cathode as possible, the I.O. must be operated at a value $V_G/V_A = 0.1$, for which A_0 is a maximum in Fig. 111, and c must be made equal to 1.0 mm. The magnification then is about fifty-fold. We also learn from the characteristic curve that M reaches values as high as 200 if we are satisfied to reproduce smaller areas of the cathode. The cathode must then be very close to the grid aperture and the latter will assume negative potentials according to Fig. 109. This is analogous to light microscope technique, where large magni-

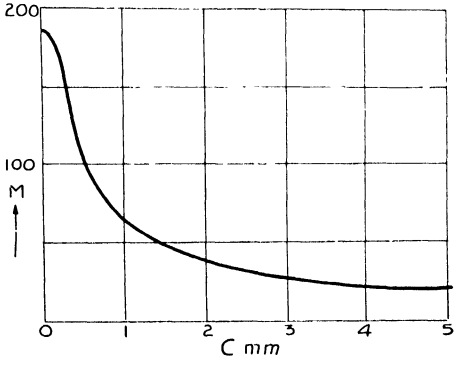


FIG. 110.

Variation of the magnification, M, of a three-electrode lens with the distance, c, between cathode and grid.

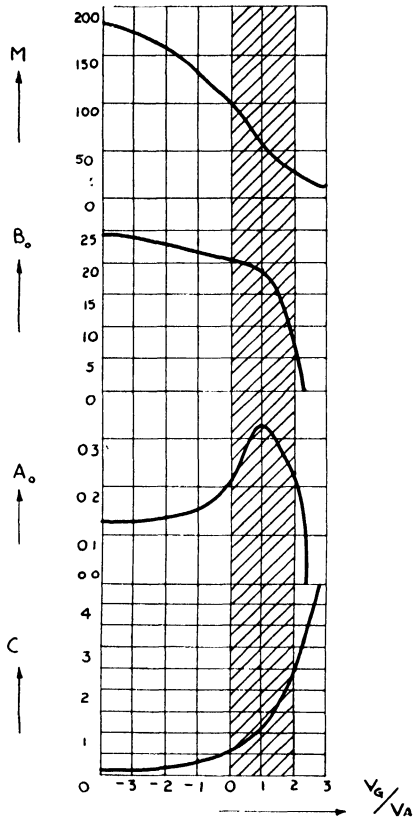


FIG. 111.

How (1) the magnification (M), (2) the diameter of the sharp image (B_0), (3) the diameter of the region on the cathode ($A_0=B_0/M$) which is sharply reproduced in the image, and (4) the distance between cathode and grid (c), severally vary with the ratio of grid potential (V_G) to anode potential (V_A), for the three-electrode lens. B_0, A_0, and C are expressed in millimeters.

fications are obtained with an objective lens of very short focus which demands that the object must be placed almost in contact with the lens.

The Four-Electrode Lens and its Magnification

A modified I.O. of superior quality was described by Johannson in 1934. It differs from the system just described by having an additional electrode which makes it a four-electrode system. Fig. 112 gives the diagrammatic view. The performance of the four-electrode I.O. is superior to that of the three-electrode system by about 50 per cent, as measured by a figure of merit B/L; B is the diameter of the sharply reproduced image. It makes possible not only a larger useful magnification, by 25 per cent, but

also permits of the variation of M over a wider range. The focal length is correspondingly reduced to the order of 1 mm.

Much larger magnification can be obtained with the electrostatic electron microscope if all the dimensions of the I.O. are reduced by a constant factor. M = ×4,000 has thus been reported by Johannson. Since the size of the aperture must also be correspondingly reduced we would obtain aperture diameters of the order of 0.1 mm (4 mils) when using a reduction factor 10 to

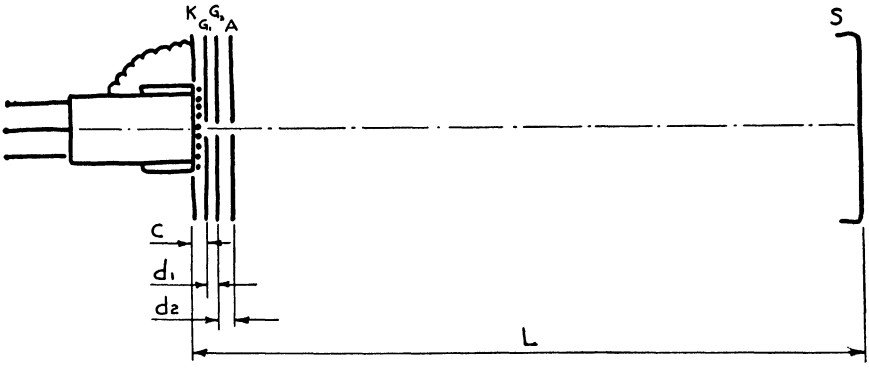


FIG. 112. Johannson's four-electrode electrostatic electron microscope.

D_c =	5 mm.	c =	0.05-1.5 mm.
D_{G1} =	1.1 mm.	d_1 =	0.48 mm.
D_{G2} =	1.0 mm.	d_2 =	0.72 mm.
D_A =	1.0 mm.	L =	240 mm.

get M = ×2,500. This will necessarily weaken the intensity of the beam and reduce the brightness of the image obtained on the screen. For this reason the instrument is generally operated to give a magnification of the order of a few hundred times.

The Resolving Power of the Electrostatic Lens

When we come to consider the resolving power of the I.O., we must remember that it depends on the electron wave length in the object plane. The initial velocities of electrons emitted from an oxide cathode are of the order of 0.1 volt. Introducing this value into de Broglie's formula for the electron wave length (see p. 123).

$$\lambda = \frac{12.24}{\sqrt{V}} \times 10^{-8} \text{ cm}$$

we obtain:

$$\lambda = \frac{12.24}{\sqrt{0.1}} \times 10^{-8} \text{ cm} = 38.92 \times 10^{-8} \text{ cm}$$

This value for λ must then be substituted in the formula given on page 72 so that we obtain for the distance, d, of two object points which can just be separated in the image (0.61 replaces ½):

$$d = \frac{0.61\lambda}{\text{N.A.}} = \frac{0.61 \times 38.92 \times 10^{-8}}{\text{N.A.}} \text{ cm}$$
$$= \frac{23.70}{\text{N.A.}} \times 10^{-8} \text{ cm}$$

The numerical aperture (N.A. $= n$ sin A), as defined on page 72, is much smaller in electron-optical microscopes than it is in ordinary optical microscopes where values N.A. = 1.5 can be realized with an oil-immersion objective.

In electron-optical systems severe limitations are imposed on the size of the aperture diameter in order to keep lens aberrations to a minimum. These aberrations are caused by rays divergent from the optical axis beyond a permissible amount, as we have learned above. To prevent such excessive divergence is the purpose of a very small aperture diameter which leads to a reduced value of sin A. We have also found in Chapter 15 (page 188), that the electron velocity corresponds to the refractive index n in optical systems. Since we are dealing with even very slow electrons in the I.O. this value becomes very small, so that n sin A is smaller by three orders of magnitude in comparison to values common in ordinary optics; *i.e.*, N.A. = 0.001. If we introduce this value in the last equation we obtain

$$d = \frac{23.7}{.001} \times 10^{-8} = 23.7 \times 1000 \times 10^{-8} \text{ cm}$$
$$= 23{,}700 \text{ A.U.}$$

Actually, Brüche and Knecht determined experimentally that a resolution of 15,000 A.U. had been reached with their instrument (1934).

There are other factors which operate against obtaining high resolving power with the I.O. when it is used for the investigation of self-emitting objects, in particular of oxide-coated cathodes. The granular structure of the cathode surface will distort the first refracting surface of the electron lens, *i.e.*, the equipotential area which matches the surface of the cathode. A local negative space charge in front of the cathode produced by particularly active spots on the cathode may act in a similar manner. For refined investigations, it is then necessary to provide as smooth a surface as possible and to operate it at a relatively low temperature, so that space charge distortions are avoided.

In spite of these restrictions, the service of the electrostatic electron microscope in manifold researches has been invaluable. We shall give a brief survey in the following chapter of the various applications to which it has lent itself.

The Possibilities of Using Bright Emitter Cathodes

We have thus far considered only the case of an oxide-coated cathode being used as an electron source in conjunction with the I.O. Nothing stands in the way of using a bright emitter such as a tungsten or molybdenum ribbon as the object. Due to the elevated temperature at which these materials have to be operated in order to yield emission currents comparable to those obtained from dull emitters, a certain amount of direct light will reach the central area of the image and produce a background illumination. This need not be serious since the apertures are small in any case. The metallic surfaces of these cathodes can be highly polished so that field distortions are greatly reduced at the surface. In addition to this, higher voltages may safely be applied so that the resolving power will be increased considerably.

Photoelectric Surfaces as Cathodes and other Variations

Photoelectric surfaces can also be used as cathodes in the I.O. Provision must then be made that a light beam reaches the photocathode from the side, or from the rear when a transparent photocathode is employed. This latter principle is the basis of Zworykin's image tube which has found many useful applications.

Since the emission yield from photo-cathodes is comparatively small, it is necessary to apply voltages of the order of 10,000 volts to the lens anode in order to obtain images of sufficient brightness on the luminescent screen.

The cathode may be the source of secondary electrons produced by the impact of primary electrons either under angle from the side or from the rear in the case of a thin metal film.

Finally, high-speed electrons may be shot through a thin film, a technique which was explored experimentally by Behne in 1936. He was thus able to obtain images of aluminum foil 0.6μ thick with a magnification nearly $\times 100$, when 500-volt electrons were shot onto the foil from the rear and then accelerated by 3,000 volts and more on the anode of a three-element, Johannson immersion objective.

Mahl, in particular, has published a series of papers since the outbreak of the present war on the high-voltage electrostatic electron microscope, which, unfortunately, are not accessible to the authors of this book at the present time. Consequently we must confine our remarks to information gathered from reviews. It is stated that a resolving power of from 80 to 100 A.U. has been obtained; this is a vast improvement over the 15,000 A.U. reported by Brüche and Knecht in 1934. It represents an improvement over the greatest possible resolving power of the optical immersion microscope, using ultraviolet light (2000 A.U.) by a factor of twenty.

The G. E. Electrostatic Electron Microscope

During the early part of 1943 a simplified type of electrostatic electron microscope was described by Bachman and Ramo, of the Electronics Laboratory of the General Electric Company at Schenectady (see plate p. 205). This is the first commercial design of this type of electron microscope on this continent and contains many interesting features. It is comparatively small in size, simple in construction and operation, and its resolving power is about 10 times better than that of the light microscope, in other words, 200 A.U.

Fig. 113 is a cross-sectional diagram of the General Electric

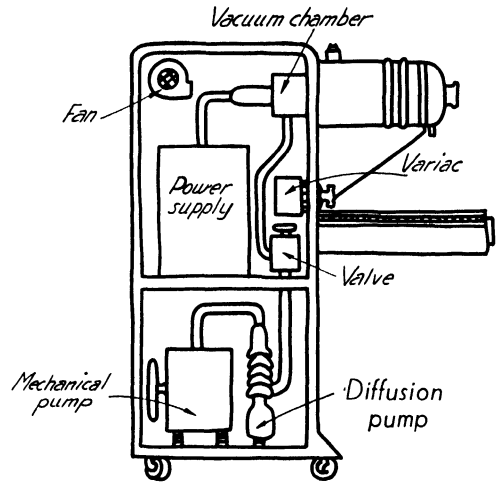


FIG. 113.

Cross-sectional diagram of the small G. E. electrostatic electron microscope.

instrument. The lower portion of the cabinet contains the pump unit and the upper portion the power supply and the microscope proper. A work table with drawer protrudes from the middle and the whole unit is mounted on casters so that it can be moved about easily. It is operated on 110 volts. Two minutes after insertion of the specimen into the vacuum chamber, observations can be made on the screen in front of the observer.

Fig. 114a gives a schematic diagram of the electron-optical components of the electrostatic microscope under discussion. A tungsten filament, F, of hairpin shape serves as the source of electrons which originate at the tip of the filament where the temperature of the filament is highest. We are thus dealing with a filamentary cathode in distinction to indirectly heated plane oxide-coated cathodes which were used in the earlier German models of this type. The filament is surrounded by a cylindrical shell, K, to which one side of the filament is connected. The position of the filament tip with respect to the aperture of the surrounding shell can be adjusted by means of side screws and the shell in turn can be lined up accurately with the microscope axis. The filament and shell are maintained at a negative potential which can be varied smoothly by a variac mounted on the front panel from a low value up to about 35,000 volts. The filament current is likewise controlled by a variac similarly mounted on

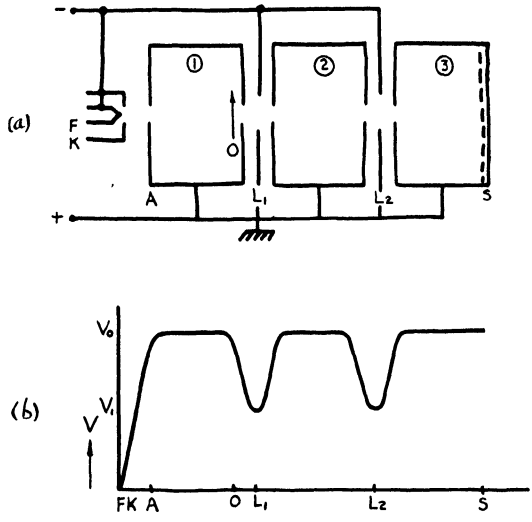


FIG. 114.

(a) is a schematic diagram of the optical components of the G. E. electrostatic electron microscope, (b) shows the potential variation along the axis of the microscope.

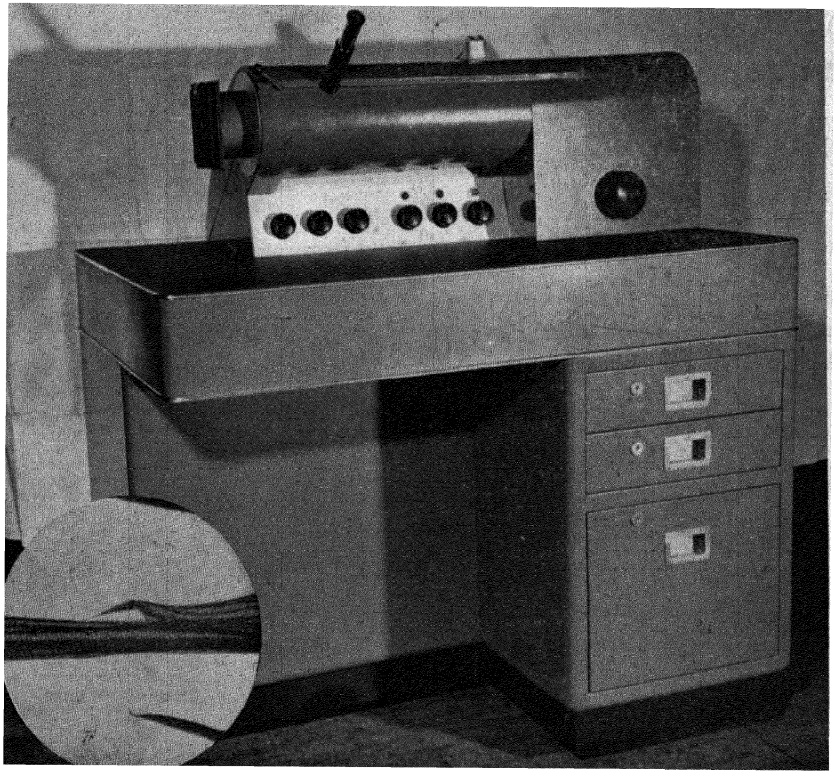
the front control panel. Leaving the cathode aperture and traveling along the optical axis, the electrons are accelerated to a high velocity equivalent to the voltage applied to the anode A. They maintain this velocity in the spaces denoted in Fig. 114a by 1, 2, 3, but slow down momentarily in the intermediate lens regions L_1 and L_2. The potential plot in Fig. 114b indicates the potential variation along the axis brought about by the electrode configuration of Fig. 114a.

The representation is similar to that used earlier in Fig. 94 (p. 136). As a matter of fact, the latter might well represent the first part of our potential plot in Fig. 114b, where it rises steeply from the origin. After reaching the full value of V_0 in space 1, the potential drops to nearly half, as indicated by V_1 in the lens region L_1 and L_2 which are separated by the space 2 and followed by 3 where the electrons again reach the full value V_0. The potential troughs at L_1 and L_2 represent the main electron lenses which form an image of the object O on the screen S. Since the potential rises to a constant value V_0 on either side of the lens plane, this type of lens is called a unipotential lens.

It is worthy of note that the electron gun proper, comprising F, K, A, and the two lenses L_1 and L_2, are operated from a single voltage supply, V_0. This makes for great simplicity of operation.

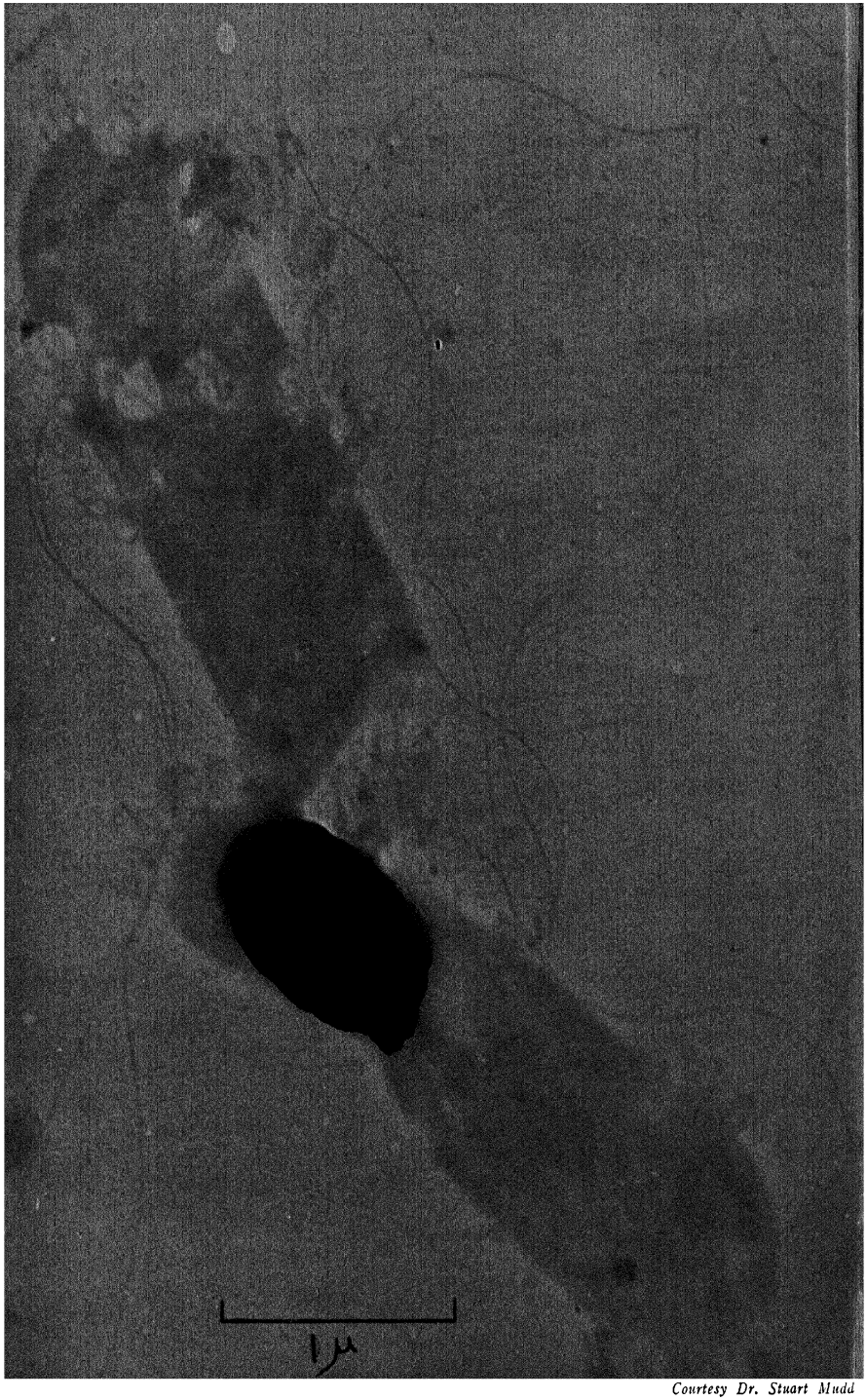
Furthermore, since the focussing action of the electrostatic lenses depends on a voltage ratio V_0/V_1 rather than on any single voltage, voltage fluctuations will not disturb this ratio and the focal length of the lenses is thus kept constant regardless of such fluctuations. This eliminates the need for elaborate voltage regulators in the power supply unit.

The image produced on the fluorescent screen, S, which may be replaced by a photographic plate, is further magnified about seven times by a light optical system. An electronic image on the screen giving a magnification of $\times 1000$ may thus be further enlarged to a total magnification of $\times 7000$.



Courtesy General Electric Co.

Small General Electric Electrostatic Electron Microscope. Circle Insert: Portion of fringe on mosquito wing taken with a General Electric instrument.



Courtesy Dr. Stuart Mudd

Clostridium sporogenes, showing a mature spore within the remnants of the vegetative cell (×40,000).

Chapter 17

THE MAGNETIC ELECTRON MICROSCOPE

Emission and Transmission Types of Electron Microscope

The preceding chapters on electrostatic and magnetic lenses and on the electrostatic electron microscope have revealed the great flexibility of these electron-optical counterparts of light optical elements. We have encountered the equivalent of the simple microscope, or reading glass, in the single electrostatic or magnetic lens and also described combinations of electrostatic and magnetic lenses which represent in principle the compound optical microscope.

The simple reading lens may be used for two purposes:

(a) By holding it in a beam of sunlight we can focus on a screen an intense spot of light which is really an image of the sun; the same effect can be found by focussing the light from a an electric lamp. The feature of this experiment is that we get an image of the light source in each case.

(b) We may also obtain on a screen an image of a window frame—an image of an object illuminated from an external source. In this case we are not primarily interested in the way in which the object is illuminated.

When we come to deal with small (microscopic) objects we use several lenses which make up the compound microscope and, in this case, very great attention must be paid to the illumination of the object.

We find the same two divisions in the development of electron microscopes. They fall into two classes:

(a) Those in which the image is a reproduction of the surface of the cathode—the source of the electrons. Consequently this class, whether using electrostatic or magnetic lenses (or some of each) is known as the *emission type of electron microscope.* Electron microscopes of this type were the first produced.

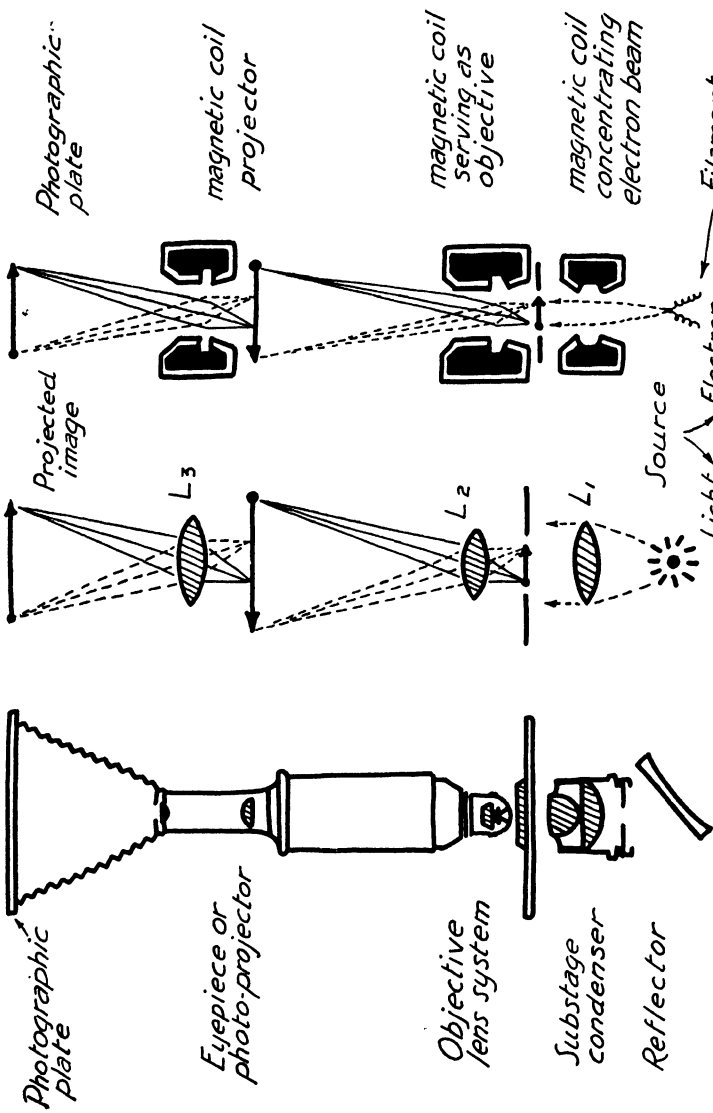


FIG. 115. Comparison of light microscope and magnetic electron microscope. (See opposite page)

Comparison of Compound Light and Magnetic Electron Microscopes.
(See Fig. 115, opposite)

Elements	Light microscope	Electron microscope
1. Source of illumination.	Sunlight or electric light.	Electron source: cold cathode or hot filament.
2. Control of illumination.	Sub-stage condenser, L_1.	Converging action of the magnetic field of the first coils.
3. Specimen support.	Microscope slide of glass about 1 mm. thick.	Film of collodion about 10 millimicrons thick.
4. First image forming system.	The objective, L_2.	Converging action of the magnetic field of the second coil forming the first image.
5. Accessory magnification.	The eyepiece or photographic projector, L_3.	Converging action of the magnetic field of the third coil forming a second enlarged image of a portion of the first image.
6. Medium.	Air and glass.	A very high vacuum.
7. Viewing image.	The eye directly.	The eye (image projected on fluorescent screen.)
8. Method of focussing.	Movement of lenses as a result of judging the sharpness of the image with the eye.	Alteration of the intensity of the magnetic fields in the coils as a result of judging the sharpness of the image on a fluorescent screen.
9. Recording of image.	Photographic plate.	Photographic plate.
10. Smallest particle photographed in detail.	$\frac{2}{100,000}$ cm.	Less than $\frac{1}{1,000,000}$ cm.

(b) Those in which an object is inserted along the optic axis between the cathode and the screen and in which the image is a reproduction of this object, brought about by the interaction of the illuminating cathode ray stream and the material of the object. This class, whether using electrostatic lenses or magnetic lenses (or some of each), is known as the *transmission type of electron microscope.*

In Figs. 21 and 22 we have indicated the two ways of making use of a compound microscope, *viz.*, either to project the final (real) image on a screen or photographic plate or for observation of the final (virtual) image by the eye. The electron microscope is used only in the first sense; we have to depend on projecting the image on a fluorescent screen, for focussing and observation, and on the photographic film, for reproducing pictures of the image.

The term "simple" and "compound," as applied in microscopy, could be used of either the emission or the transmission type of electron microscope, depending on whether we are making use of *one* lens or *more* than one.

The use of two solenoids in Fig. 85 (p. 164) for the purpose of producing a sharp image of the cathode spot on the screen is an example of a magnetic compound microscope. Since in this case a small spot is required on the fluorescent screen, the overall magnification has to be kept as low as possible, but full advantage is taken of the image-forming properties of the systems.

Likewise, in Fig. 114a (p. 204) the two electrostatic lenses in the G.E. electron microscope comprise a compound microscope.

During the first ten years of development (1932-1942), most emission type microscopes were of the electrostatic class, but those using magnetic lenses were also developed. Scott and his co-workers (St. Louis) described a two-lens magnetic type in 1937 and in additional papers in 1939. They used the microscope to determine the distribution of metallic residues in biological tissues which were heated strongly on the surface of the cathode. Such emission types are usually used to determine some structure on the surface of the cathode.

The basic patents for both electrostatic and magnetic electron microscopes were written in 1931 by Reinhold Rüdenberg, and were assigned to his employers, the Siemens-Schuckertwerke, in Germany. Rüdenberg later came to the United States, where he filed his patents in 1936 and 1937. Although these were broad in their specifications, and though Rüdenberg never constructed an instrument, he has entered a claim to be considered the inventor of the electron microscope.

History of the Compound Magnetic Electron Microscope

The first emission-type microscope was built in Germany by Knoll and Ruska and described in the technical literature in 1932. It was of the emission type and served for the investigation of cold cathode surfaces; it was also used, for example, to form images of specially shaped apertures and wire mesh.

Fig. 116 shows a diagram of the first Ruska-Knoll microscope as described in 1932. It was built at the High Voltage Research

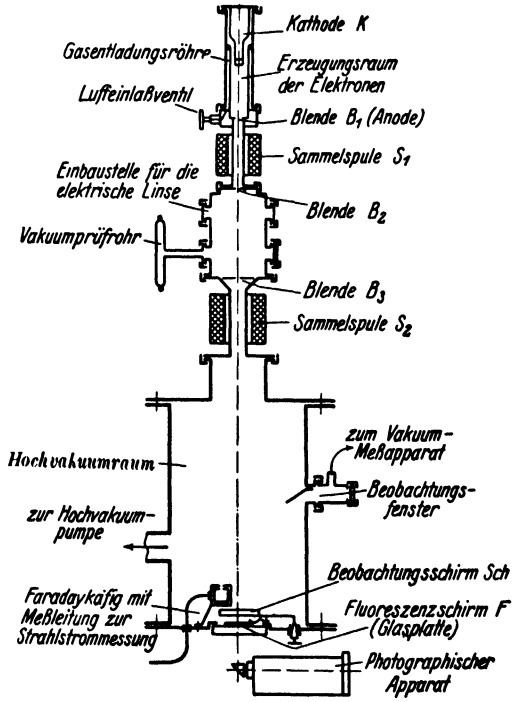
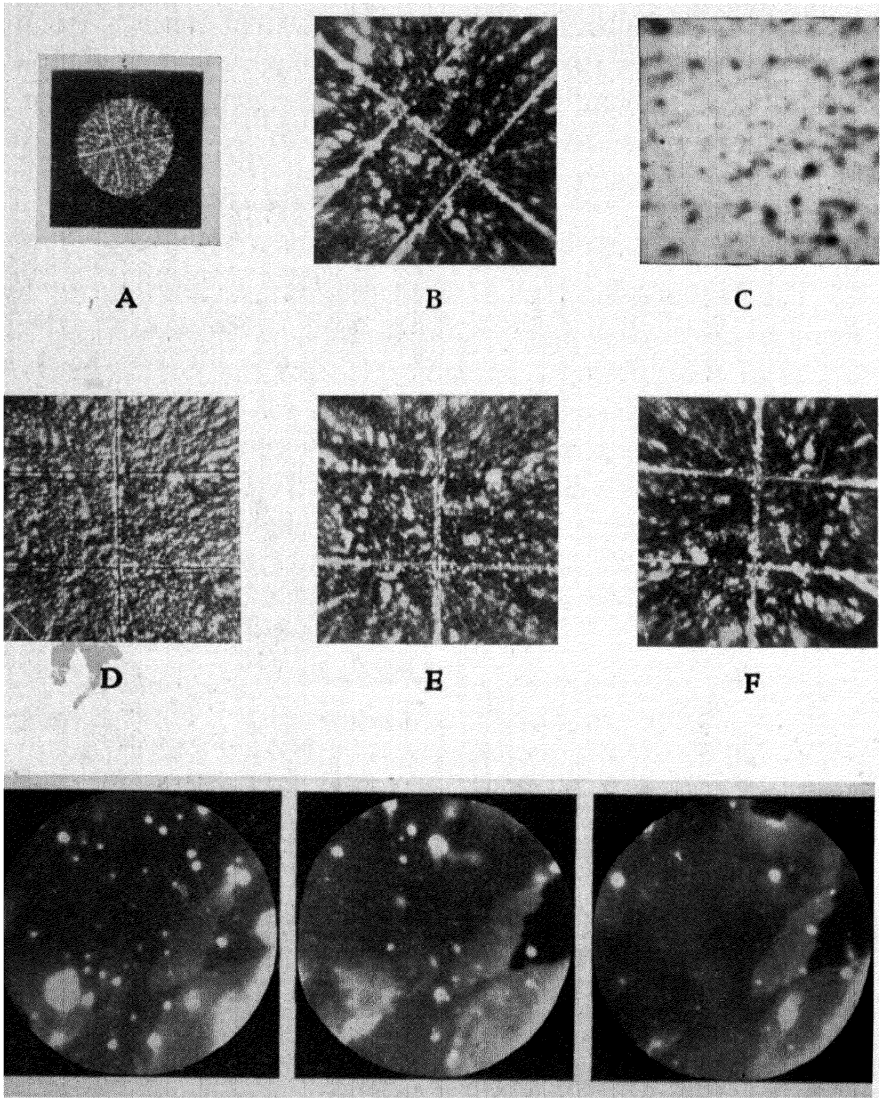


FIG. 116.

Diagram of the Knoll-Ruska magnetic electron microscope.


A
B
C
D
E
F
G
H
I

All the reproductions on this plate are of cathode surfaces emitting electrons. These cathodes are the sources of the electron beam which is focussed on the photographic plate by means of single electrostatic or magnetic electron lenses.

A, B, D, E and **F** are from a paper by Knecht [*Ann. d. Physik*, **20**, 171 (1934)]. **A** has magnification $\times 9$, the rest, $\times 31$. **D, E,** and **F** are optical, electrostatic electron and magnetic electron microscope pictures, respectively.

C is an electrostatic electron microscope picture of an emitting cathode obtained by C. E. Hall at Toronto in 1936.

G, H and **I** are from a paper by Brüche and Mahl [*Z. Techn. Physik*, **16**, 240 (1935)], showing electrostatic electron microscope pictures of emitting thoriated tungsten cathodes, giving the distribution of the emission points.

Institute in Berlin and followed in general outline the technique applied to the construction of high-voltage cathode ray tubes. This was only natural, since a cathode ray tube is essentially an inverted microscope, as we pointed out before, *i.e.*, a microscope aiming at the smallest possible magnification of the cathode spot or of the anode aperture in front of it.

In these early instruments the electron stream was obtained from a cold cathode in a gas discharge tube at the top of the microscope, according to the principles of cold-cathode emission in the presence of gas or air as described on p. 164 for the operation of the Braun tube. A voltage of 50-80 kv was applied to the anode, which had a small aperture. Since the presence of gas was necessary in the discharge space above the anode and undesirable in the main body of the microscope below the anode, air was admitted through a valve into the discharge space to produce a pressure of about 10 microns (0.01 mm Hg) and a powerful vacuum pump continuously exhausted the main body of the tube to produce a pressure of 1 micron (0.001 mm Hg). The anode thus served the dual purpose of accelerating the electrons and separating the low-vacuum space from the high-vacuum space below. A condenser lens, S_1, served to gather the diffuse electron streams into a narrow beam, which was further constricted by a second aperture stop and directed to a third aperture which could serve as the object. The solenoid below this aperture formed the magnetic objective lens, which produced an image on the fluorescent screen. This image could then be photographed from the outside. For the purpose of focussing and visual observation of the image quality a side port was used in conjunction with a mirror and a fluorescent screen above the photographic glass plate. When the anode voltage and coil current were properly adjusted, the observation screen could be moved aside and a photograph taken. The beam currents ranged from 10 to 100 ma.

A little later, during the same year, Knoll, Houtermans and Schulze built an instrument adapted to the investigation of oxide cathode surfaces which was operated at about 1000 volts. The axis of this microscope was horizontal and the components were

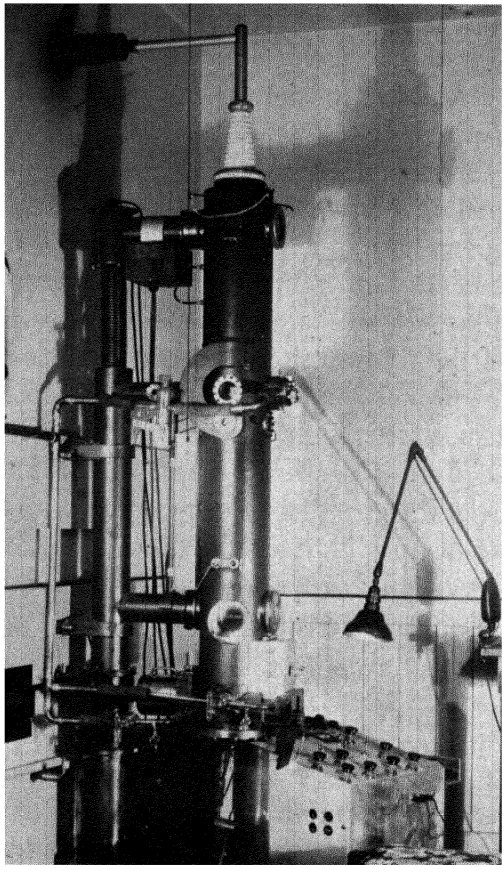
arranged on an optical bench. Iron-clad coils were used instead of unshielded solenoids; but in this, and the first instrument described above, the coils were arranged outside of the main tube and in cardanic suspensions for ease of adjustment.

The desire to obtain larger magnifications soon made necessary the construction of magnetic lenses with shorter focal lengths and the use of two lens stages in addition to the condenser lens. This brought about the construction of modern compound magnetic electron microscopes, one by Ruska and one by Marton, in 1934. They were both of the transmission type and provided an object stage for the insertion of specimens. Marton was the first to investigate biological specimens with this instrument. He built a more elaborate type during the same year; this comprised such features as air locks for changing the specimen without losing the vacuum in the main volume of the microscope, a mechanical stage of the cross-movement type, and an electrostatic shutter system for the control of exposure times.

It may well be said that the two-stage magnetic electron microscope of Ruska, described in 1934, served as the prototype of all similar instruments which have been built since. Improvements were made continually by workers in many countries, and we may well marvel at the degree of perfection reached in modern designs when we consider that this art is only fourteen years old.

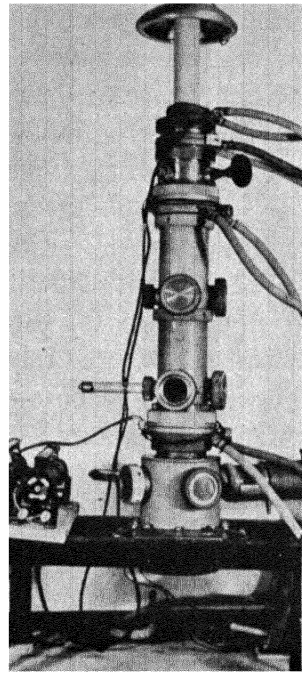
The Ruska compound microscope of 1934, of which a photograph is shown in the plate on page 216, gave an overall magnification of $\times 10{,}000$ and a resolving power of about 500 A.U. The objective and projector lens had a focal length of the order of 5 mm. The operating voltage ranged from 10 to 100 kv.

In 1937 a compound microscope was described by L. C. Martin, R. V. Whelpton and D. H. Parnum in London, England; they incorporated an optical microscope in the magnetic microscope in order to be able to compare the relative image quality of optical and electron optical images. The minimum focal length of their magnetic lenses, which were of a special design, was 6 mm, while Ruska had obtained 3 mm. The results obtained were limited by technical difficulties later described by Martin.



Courtesy L. Marton

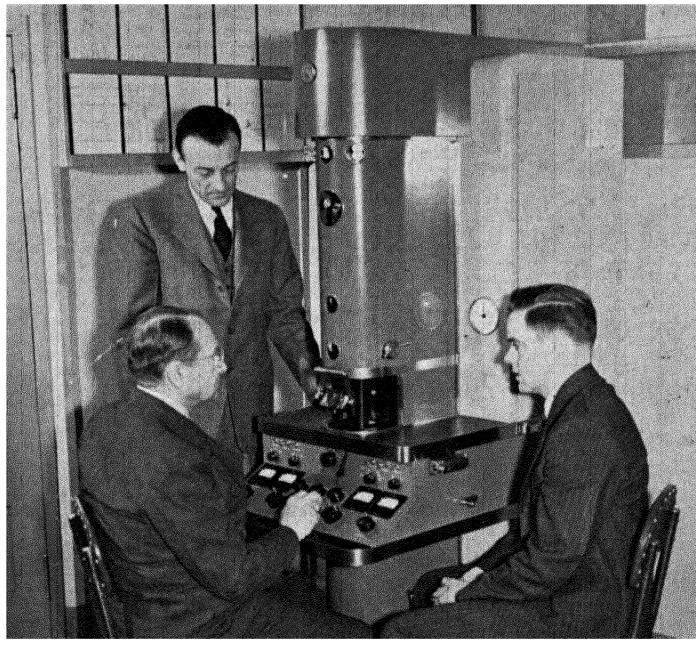
View of 100-kv electron microscope at Stanford University.



Knoll-Ruska electron microscope built in 1934.

Early in 1938 a compound microscope was described by von Borries and Ruska which served as the prototype for the first commercial electron microscope produced by the Siemens Company in Berlin.

Also in 1937, the authors of this book initiated the construction of the first compound electron microscope on the American continent by James Hillier and Albert Prebus, at the University of Toronto. This instrument was described in April 1939 and a picture of it is shown on page 80. The source of electrons was a tungsten filament bent into a hairpin shape. An operating voltage of 45 kv was used and a resolving power of better than 200 A.U. was obtained. Electronic magnification up to $\times 20{,}000$ was



Courtesy R.C.A. Laboratories

The RCA Universal model electron microscope. Left to right, Drs. V. K. Zworykin, Perry Smith and James Hillier.



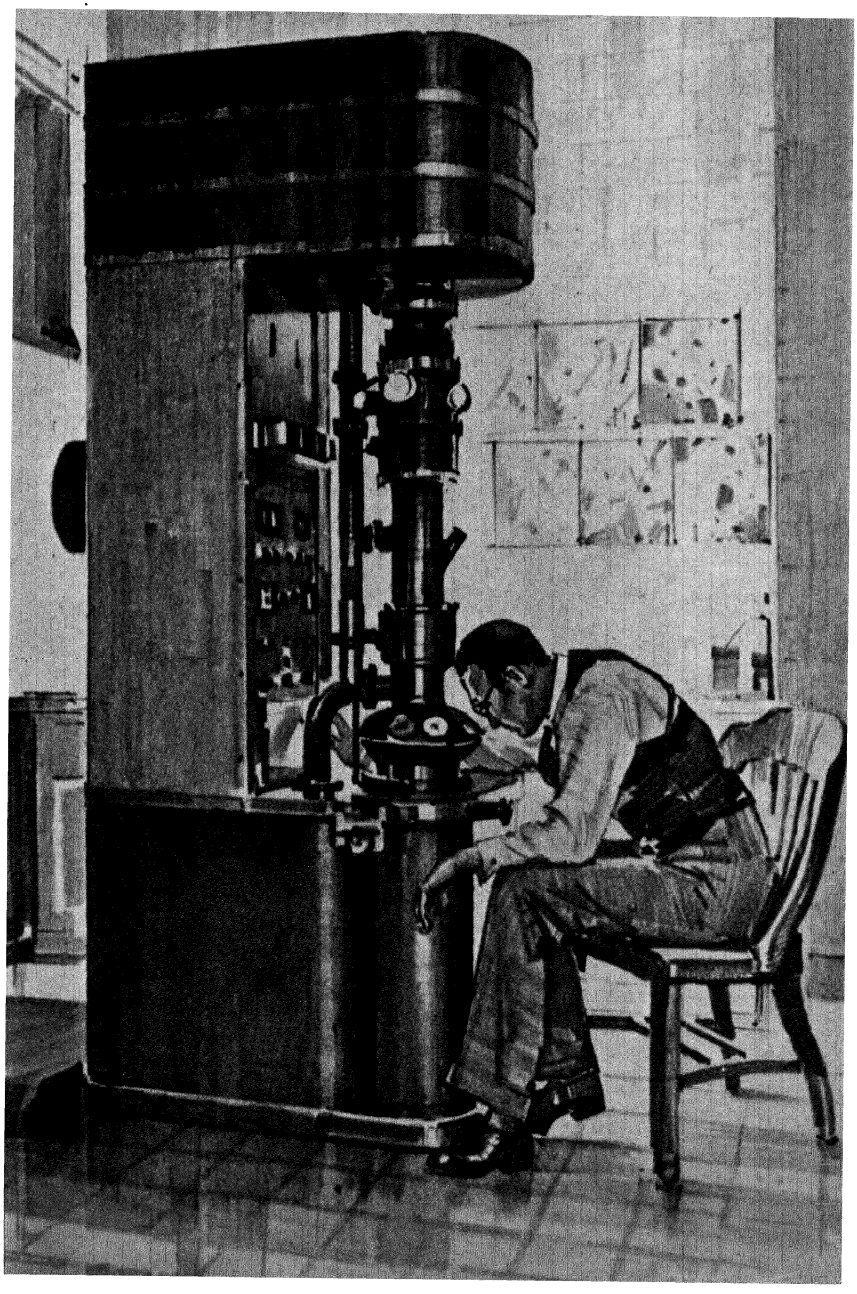
Courtesy R.C.A. Laboratories

The small magnetic electron microscope.

reached and photographs taken with an exposure time of the order of five seconds.

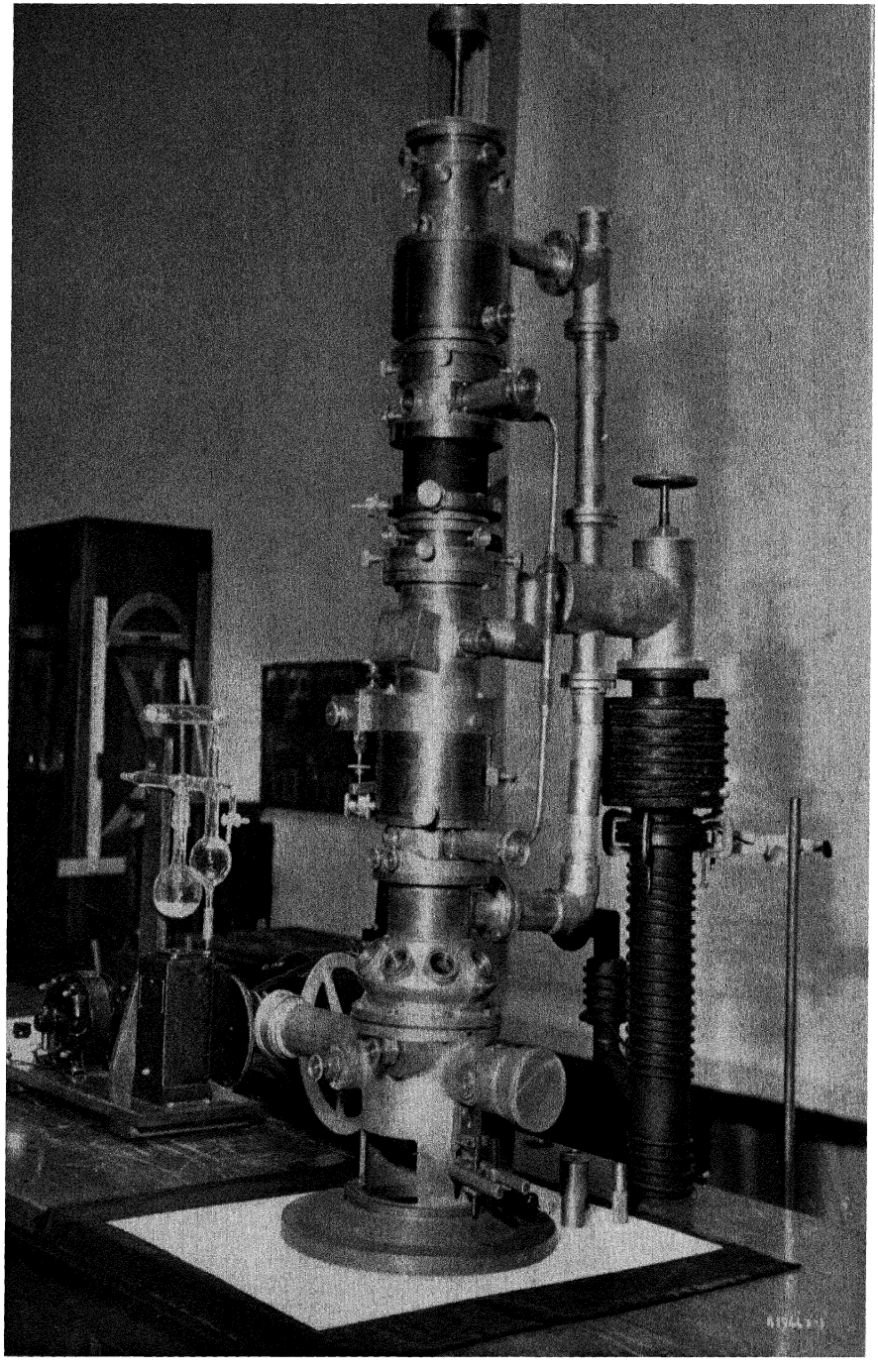
In 1940, von Ardenne described a new magnetic electron microscope in Germany and Marton and his co-workers, M. C. Banca and J. F. Bender, developed the first R.C.A. electron microscope under the direction of V. K. Zworykin; this developed into the first commercial R.C.A. microscope, following the design of Hillier and Prebus (Toronto). Prebus, who joined the faculty of Ohio State University, published a description of his new instrument in 1942 . Zworykin and Hillier built a small-scale magnetic microscope in 1943.

In addition to the commercial instruments installed in various laboratories and those already mentioned, electron microscopes of this type have been constructed by C. E. Hall at the Research Laboratories of the Eastman Kodak Co. at Rochester and by Professor Marton at Leland Stanford University. A new and improved microscope has recently been built at the University of Toronto; it was first used in June, 1944.



Courtesy Goodyear Tire and Rubber Co.

Rubber research with the electron microscope. (Pencil drawing by T. Kautzky.)



Courtesy University of Toronto

View of the electron microscope now in use at the University of Toronto. This instrument, built in the Physics Department workshop, was completed in 1944.

Chapter 18

THE 1944 UNIVERSITY OF TORONTO ELECTRON MICROSCOPE

A detailed description of the design, construction and operation of this latest Toronto instrument will now be given, for no other reason than that this is the instrument with which the authors are most familiar. With this treatment will be interwoven comparative remarks referring to other modern instruments in order to give a general description of the fundamental technique as it is known and practiced today.

This instrument was designed by Drs. Newman and Watson in the light of experience gained with the microscopes built at Toronto in 1938. The makers and users of the R.C.A. model B microscope were also consulted during the design of the Toronto model. The microscope proper was constructed entirely in the workshop of the McLennan Laboratory, University of Toronto, and was first put into operation in the summer of 1944.

Description of the Instrument

Fig. 117 shows the detail. G is the electron gun. A tungsten filament, heated by a D.C. current of about 3 amps is maintained at $-45{,}000$ volts with respect to ground. S is a cathode shield at the same potential as the filament; it produces an electrostatic lens which focusses the electrons leaving the filament. The region of minimum cross-section of the beam, the cross-over, see Fig. 103 (p. 193), may be considered the source of illumination for the microscope. A is the anode, which is connected directly to the body of the microscope and is at ground potential.

Electrons passing through the central hole in the anode are concentrated on or just above the object or specimen by the con-

denser lens C. A diaphragm of about 0.5 mm diameter, (not shown), within the condenser lens serves to limit the maximum aperture or semi-angle of the cone of electrons falling on the part of the specimen under observation.

Some of the electrons which leave the object are focussed by the objective lens O on the intermediate fluorescent screen I.S.

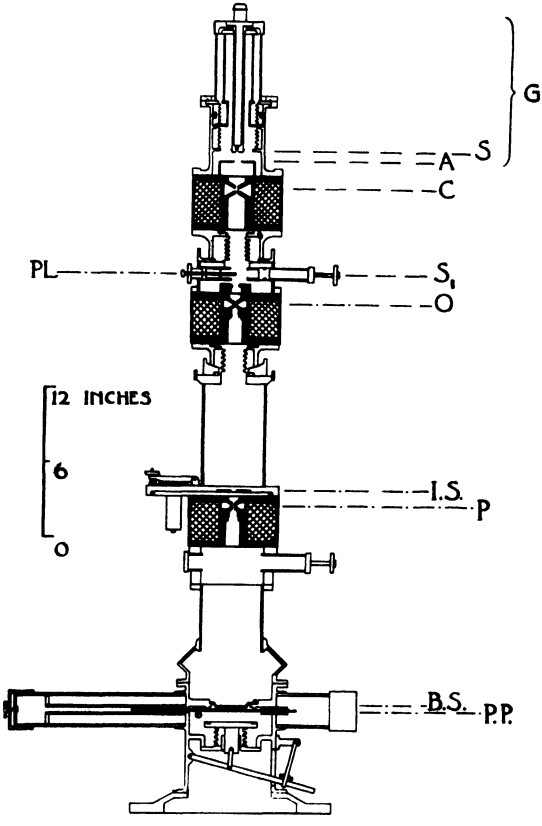


FIG. 117.
Diagram of the 1944 Toronto magnetic electron microscope.

A hole in this intermediate screen permits some of the electrons to pass through and be focussed by the projector lens P on the bottom fluorescent screen B.S. The screen material is zinc-cadmium sulfide. Here there is formed an enlarged image of the part of the first image corresponding to the hole in the plate I.S. When this lower screen is turned up, the image is formed on the

photographic plate P.P. The camera allows a 2 x 10-inch photographic plate to be racked through step by step and the electron beam can be masked to expose an area of, say, 1½ x 2 inches, and thus gives six exposures on each plate. Provision is also made for the use of roll film.

The Magnetic Lenses

The lenses of the latest Toronto electron microscope consist essentially of the core, coil and pole pieces.

The iron core of the lens ends at conically ground faces F, Fig. 118. The pole-pieces of the lens, P_s and P_n, are joined by

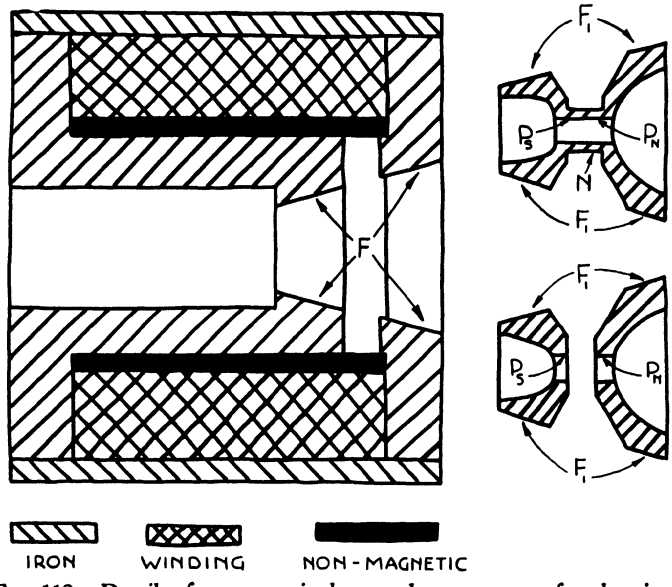


FIG. 118. Detail of a magnetic lens and two types of pole pieces in the 1944 Toronto electron microscope.

a narrow neck of iron N, so that they can be machined *en bloc*, thereby assuring a high degree of symmetry. The pole-pieces are made of Armco iron. This type of pole-piece at the top was designed by Prebus. The outer faces, F_1, are accurately ground to fit the faces, F, of the lens core. This design was produced in order that developmental work could be carried out on the pole-pieces. New pole-pieces can be machined and fitted to the lens with the minimum of structural alterations.

The mode of image formation in the electron microscope is rather different from that of the light microscope. Electrons from a heated filament are focused on the object by a magnetic condenser lens. Some electrons are absorbed or collected by the object and others are scattered in varying angles both with and without loss of speed. Only those electrons passing through or close by the object without loss of speed are brought to a focus on the photographic plate (See Fig. 119).

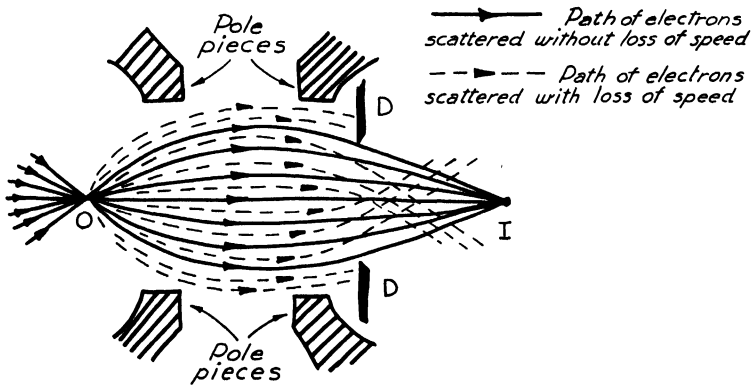


FIG. 119. Diagrammatic view of the path of electrons through a magnetic lens.

If then, there is a particle of matter at O, it will scatter electrons out of the beam and leave a deficiency of electrons in the image plane at I. This deficiency can be enhanced, and thus also the contrast in the image, by using a diaphragm, D, to remove electrons scattered through angles greater than a certain value. Thus in the positive prints, dark areas correspond to the presence of matter in the object plane.

In the Toronto microscope diaphragms can be placed at the center, or below, any or all of the lenses and aligned from outside the instrument while it is in operation. Good results have been obtained with an objective diaphragm placed immediately below the lower pole-piece. In this position the diaphragm sheet can be pierced by one hole of 2 mm diameter and three holes of 0.05 mm diameter. The alignment of the lenses is carried out with the large hole approximately centered, and then one of the smaller

apertures can be moved into place. If this one becomes dirty, another aperture can be moved into position without breaking the vacuum.

Since the varying magnetic fields produced by transformers and motors in the laboratory would deflect the electron beam during photographic exposures, and thus blur the image, the beam is shielded from such fields by mu-metal shields.

The optical performance of the microscope will depend on the stability of the electrical supplies, both for the gun and for the various lens coils.

Structural Features

The body of the microscope must be designed so that the microscope can be aligned and then clamped to keep the lenses rigidly in position. The object holder must be capable of controlled motion in two directions, mutually perpendicular, so that different parts of the specimen can be examined. The whole microscope must be protected against vibration, for even a minute vibration of the specimen relative to the objective lens aperture would blur the final image. These conditions must be met while maintaining a high degree of vacuum within the microscope. It is also desirable that the interior of the microscope be readily accessible for cleaning and changing the diaphragms from time to time.

The filament can be raised or lowered relatively to the cathode shield and moved laterally in two directions at right angles. The cathode shield can be moved laterally with respect to the anode aperture. The condenser lens and all parts above it can be shifted laterally with respect to the objective; the objective and all parts above it can be moved and also tilted with respect to the projector lens. These movements can all be made from outside the instrument while it is in operation.

The object stage consists of two flat bronze carriages, the upper moving on the lower and the lower moving on a plate fixed to the objective lens. The two carriages move at right angles to each other on ball bearings in *V*-grooves lubricated slightly with Celvascene light grease; they are driven by 0.5-mm pitch mi-

crometer screws. The carriages are held down and against the micrometers by rubber bands. This results in a smoother motion than is readily obtained with metal springs. A conical taper is cut in the upper carriage, and into this the object cartridge is lowered by two nylon threads. The use of the conical taper seats the object cartridge very accurately for depth and holds it rigidly. When a plunger, PL (Fig. 117) on the side of the instrument is withdrawn, the object cartridge is first raised vertically and then turned into a horizontal position so that the object air lock can be closed by screwing in the seal, S_1.

Vacuum Arrangements

The pressure within the microscope must be maintained at a value below 10^{-5} mm of mercury in order that the mean free path of the electrons shall be longer than the optical path they have to travel, and also in order that gas discharges shall not occur within the electron gun. It is further desirable that this low pressure be attained as rapidly as possible when the microscope is put into operation, or after the photographic plate or the specimen is changed.

It is important that materials facing the interior of the microscope shall have a low vapor pressure. In the Toronto microscope the seals between sections are made by neoprene gaskets. Rotating members such as those for moving the diaphragms and the object-stage micrometers pass through featheredge neoprene seals of the type developed for use in the cyclotron. Where tilting or traversing motions have been introduced the vacuum is maintained by the use of Sylphon bellows. The glass insulators in the electron gun are sealed in with apiezon W wax, and the only use of grease is for lubrication of some of the moving parts; this grease is Celvascene light vacuum grease.

For rough checks of the pressure a discharge tube is sufficient. The absence of a visible discharge indicates that the working vacuum has been obtained. For more precise measurements a good McLeod gauge or ionization gauge is used.

Both the object and the photographic plate can be introduced through air locks which are evacuated by a Hyvac pump, so that

the specimen or photographic plate can be introduced and the microscope brought to the operating vacuum in less than two minutes. This can be done without switching off the high voltage on the gun. The main pump is a Distillation Products MC 275 oil diffusion pump, backed by a Hypervac pump. Three 2-inch diameter tubes connect the microscope, through sylphon bellows, to the oil-diffusion pump.

Associated Equipment

The associated equipment consists of that for the high voltage, and the circuits for providing the lens currents. Since the focal length of a magnetic lens is directly proportional to the square of the electron velocity, and inversely proportional to the square of the magnetic field strength, it is very important to maintain the accelerating voltage applied to the electron gun and the currents through the lenses as nearly constant as possible, because the speed of the electrons entering the object depends on the accelerating voltage, and the field strengths within the lens depend on the currents through their windings.

The stabilities of the power supplied to the R.C.A. model B microscope are listed below:

Circuit	Range	Stability (%)
Acceleration potential	55 kv	0.002
Condenser lens	20–120 ma	0.02
Objective lens	20–130 ma	0.002
Projector lens	25–125 ma	0.004

The methods for obtaining such a high stability in voltage and currents have been discussed by Vance. At Toronto, methods simpler in conception, if more wasteful of space, are used. The lenses have between 2,000 and 3,000 turns of copper wire and resistances of the order 20 ohms. The currents are supplied by a 24-volt storage battery, and are controlled by two rheostats in series with each lens, one for coarse adjustments, and the other for fine adjustments. The general method is shown in the circuit diagram of Fig. 120.

The transformer, T_1, steps the voltage up to 45 or 60 kilovolts (peak), the kenetron, K, rectifies the voltage, and the resistance

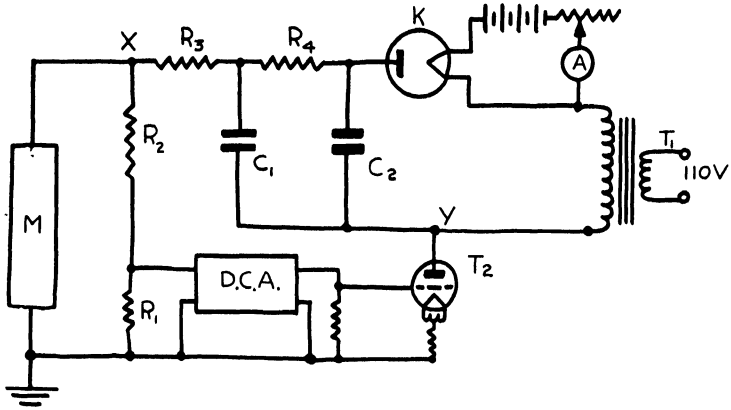
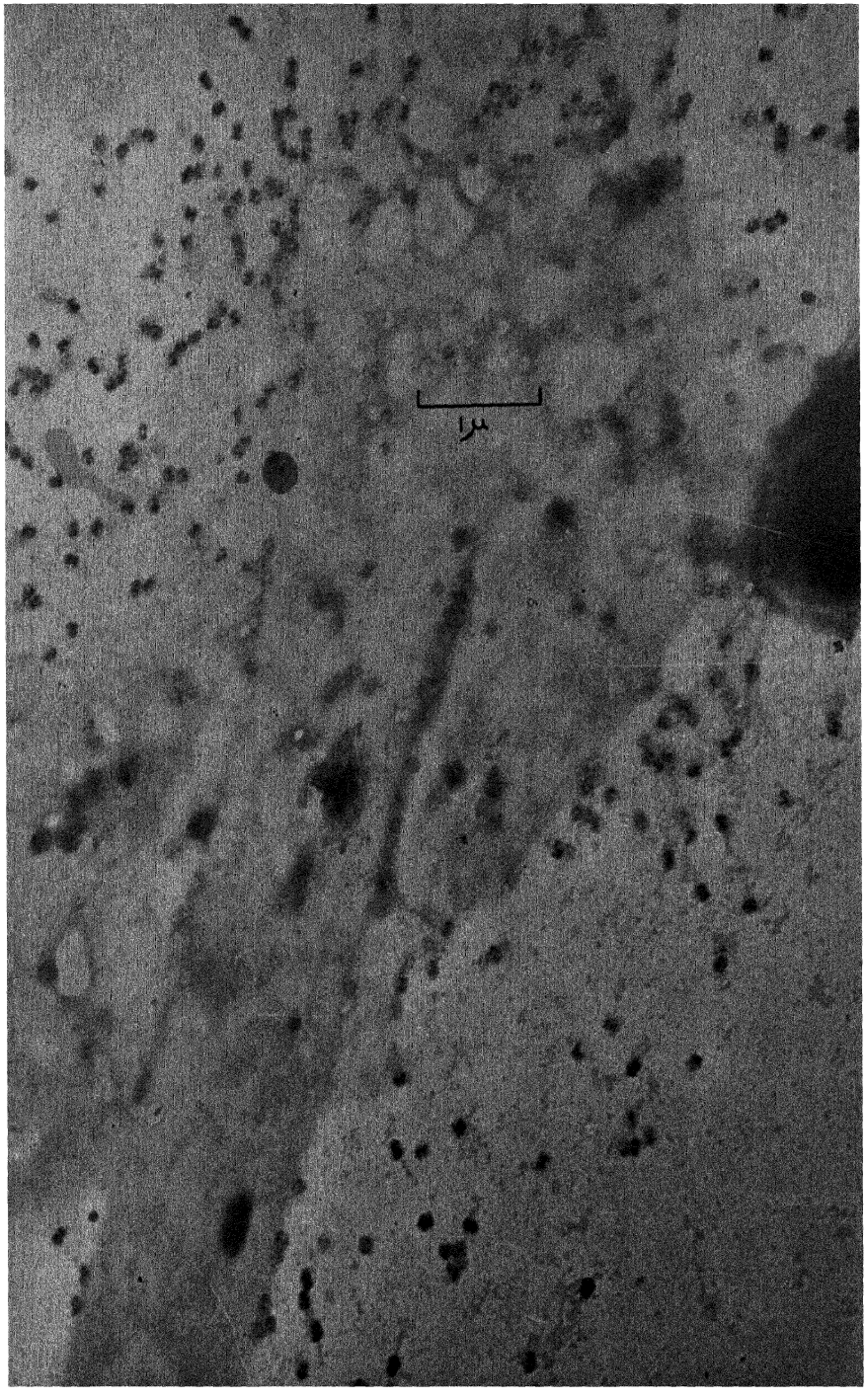


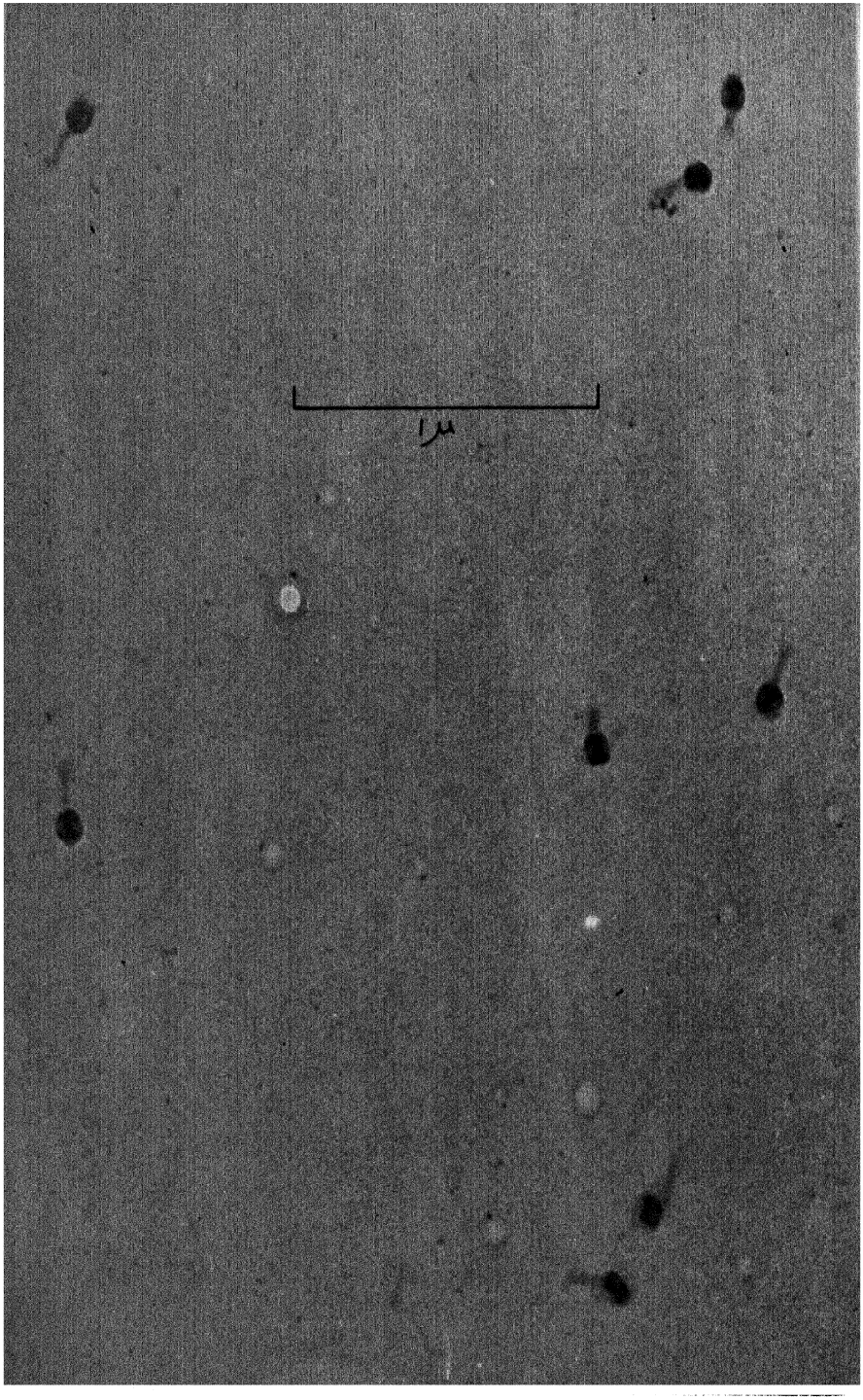
FIG. 120. Circuit diagram of power-supply for the 1944 Toronto electron microscope.

capacity filter R_4, C_1, C_2 reduces the ripple to a few volts. R_3 is a protective resistor to prevent C_1 from discharging destructively through the microscope if a gas discharge occurs. A fraction $R_1/(R_1 + R_2)$ of the high voltage is amplified by the D.C. amplifier (D.C.A.) to drive the tube T_2, so that the fluctuations in its anode potential tend to counteract fluctuations in the potential difference between X and Y, thus preserving a more constant voltage across the microscope, M. Arrangements of this sort have been discussed by Hunt and Hickman, and by Parratt and Triska.



Courtesy Dr. T. F. Anderson

E. coli and virus (×21,000).



Courtesy Dr. T. F. Anderson

Bacteriophage and coliphage (×53,000).

Chapter 19

USEFUL MAGNIFICATION

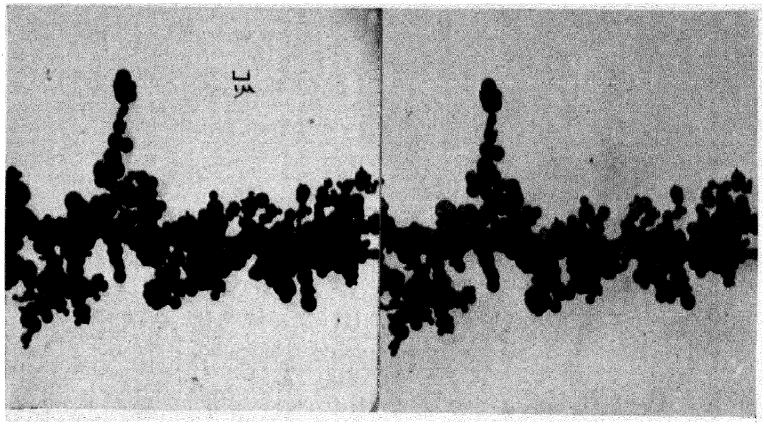
Resolving Power and Magnification

While the phenomenon of diffraction and consequently the wave length of the light used determines the limit of the resolving power of the ordinary optical microscope, in the case of the electron microscope, we cannot reach anything like the theoretical resolving power set by the wave length assigned to the electron beam. We are limited rather by our inability to get rid of aberrations and structural deficiencies. In other words, our limits are not set by the equation: $d = \frac{1}{2}\lambda_0$ (p. 73), as, in this case, the value of λ_0 is very much smaller than the dimension which we can attain experimentally as the limit of resolution of the electron microscope. The reason for this is that the aberrations, particularly the spherical aberration produced by magnetic lenses, are large unless the angular aperture of the illuminating beam is kept small, *e.g.*, of the order of 10^{-3} radian, as compared to 1 radian in light microscopes.

Theoretically, for accelerating voltages of the order 50 kv and apertures of the order 10^{-3} to 10^{-2} radian, d will be approximately 10 to 20 A.U. Such resolutions have been claimed by some in practice.

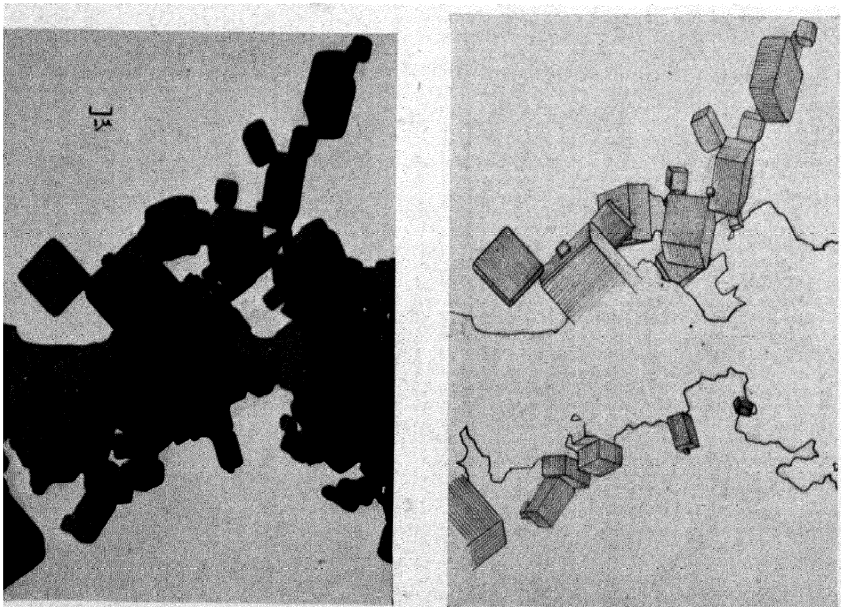
The Practical Limit of Useful Magnification

If, to err on the safe side, we assume that the smallest particles or details resolved by present-day electron microscopes are about 30 A.U. in linear dimension (*i.e.*, three ten-millionths of a centimeter), we can estimate the magnification required of the microscope. As a matter of practice, all measurements must be made by observations of an image impressed on a photographic emulsion (plate or film). We thus have to consider the limitations of



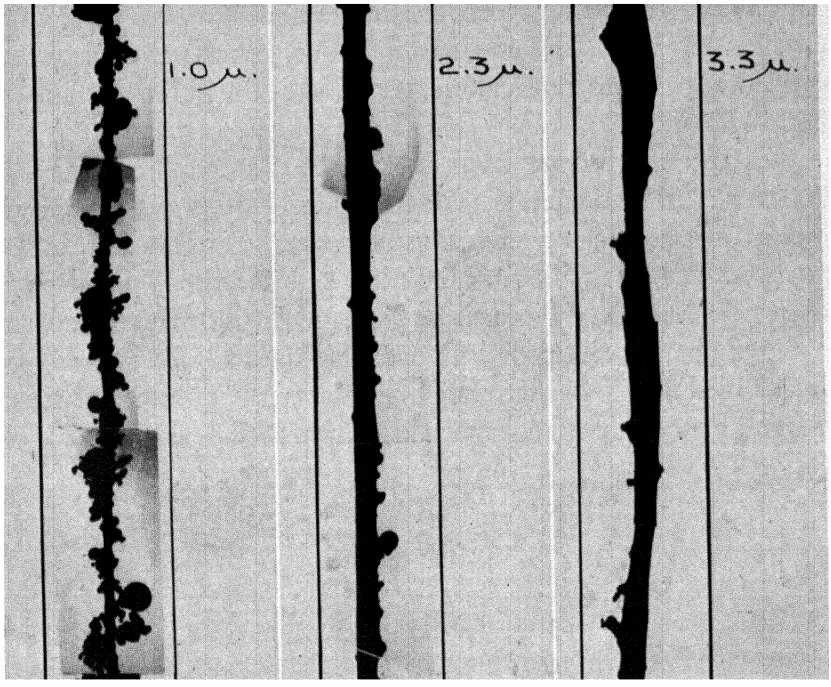
Courtesy University of Toronto

Stereoscopic views of particles caught on single fiber.



Courtesy University of Toronto

Sodium chloride crystals caught on a rubber fiber.



Courtesy University of Toronto

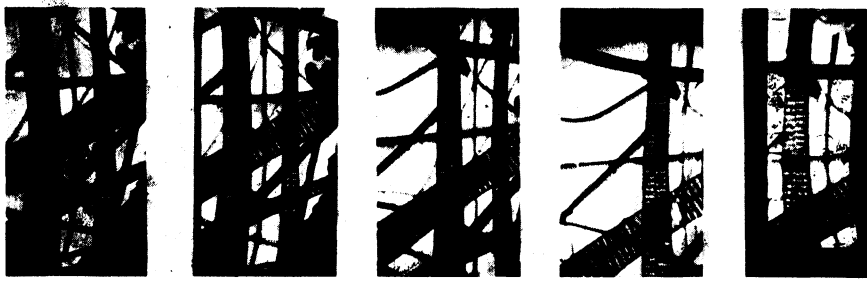
Illustrating how particles collect more abundantly on smaller fibers. The diameter of the fibers are recorded at the top of diameters 1.0μ and 3.3μ.

the photographic film—the resolving power of the photographic emulsion. An ordinary value for this is about 70 lines per millimeter. This means that such a photographic film will not separate lines which are closer together than 1/70th millimeter, or 1/700th centimeter, or record images having linear dimensions smaller than this. Consequently, it is quite apparent that a particle which has an overall linear dimension of 30×10^{-8} cm must be magnified to a dimension of at least 1/700th cm in order to be distinctly outlined on the film; that is, the particle must be magnified by an amount given by 1/700 divided by 30×10^{-8}, or about 4760 times, to give an image on the film.

Now, for the photograph to be useful, we must be able to see the finest detail in an image with the naked eye. The naked eye cannot see particles as small as 1/700 cm; the limit for the eye is

about 1/100 cm. Therefore, the above photographic image must be magnified at least seven times in order that the eye may see it. Thus the total magnification will have to be approximately 4760 × 7, or 33,320.

"As the microscope itself is capable of magnifications from 1200 to 23,000 diameters, the useful magnification for photographic purposes falls well within its range. Considerable latitude in procedure is available for obtaining high total magnification for naked eye viewing. Pictures may be made with the microscope at 23,000 diameters and slightly enlarged optically to a convenient size for study, or they may be made as low as 5000 diameters and enlarged ten or fifteen times. Experience has shown that the



Courtesy University of Toronto

Diatom (*Synedra delicatissima*) ×1,600. Collection of diatoms to show distortion of the image of one diatom taken in different parts of the field.

latter procedure is not too satisfactory; because, in order to get a photograph capable of such enlargement, extreme care must be taken in the development and fixing of the plate to avoid excessive clumping of the silver grains and hence loss of resolution. The former procedure is also subject to objections, chiefly because the intensity in the final image is so low that accurate focussing is difficult and the exposure time becomes so long that the electrical stability of the instrument cannot be relied upon to give the ultimate resolving power.

"It has been found most satisfactory to photograph at a microscope magnification of about 9000 diameters for general work, and if extremely high resolution is needed because of the detailed structure of the specimen (particularly for thin metallic films) a series of photographs made at about 17,000 diameters will give

excellent results. Sharp enlargements with over-all magnification ranging from 50,000 to 150,000 diameters can regularly be made from these plates without using special fine grain development technique." (Picard and Duffendack, *J. App. Physics*, **14,** 291 [1943]).

Since it is sometimes desirable to compare electron micrographs with light micrographs at nearly the same magnification, this and the preceding considerations make it desirable that the microscope shall be capable of producing magnifications in the range $\times 1500$ to $\times 20{,}000$. This can be achieved by using an objective lens which will give a magnification of $\times 100$ with a projector lens giving a maximum magnification of $\times 200$, or by using both lenses with a magnification of about $\times 140$ each.

The magnification produced by a magnetic lens is given very approximately by v/u, where u is the distance from the object to the point of maximum axial magnetic field and v is the distance from the image to the maximum axial magnetic field. It is desirable to keep v as small as possible so that the microscope shall not be too large and unwieldy. At the same time if a very small value is chosen for u it will bring the object within the pole-pieces of the objective lens where it will not be possible to move it laterally over any considerable distance. The field available for investigation will be reduced; in any case the magnification will not have increased as rapidly as v/u. Another reason for preferring larger values of u is that the focal length of the lens may then be made larger, and the pole-pieces in the lens may be made larger with consequent increase in the degree of accuracy in the machining.

For these reasons the values of v for the objective and projector stages of the Toronto microscope have been made about 40 cm. An advantage of these dimensions is that the necessary optical adjustments can be made by the operator while the fluorescent screens are in full view. This facility of adjustment has also been maintained in the choice of the distances between the electron gun and the condenser lens, and between the condenser lens and the object stage. In a well made magnetic lens there is a straight path along which electrons can travel without

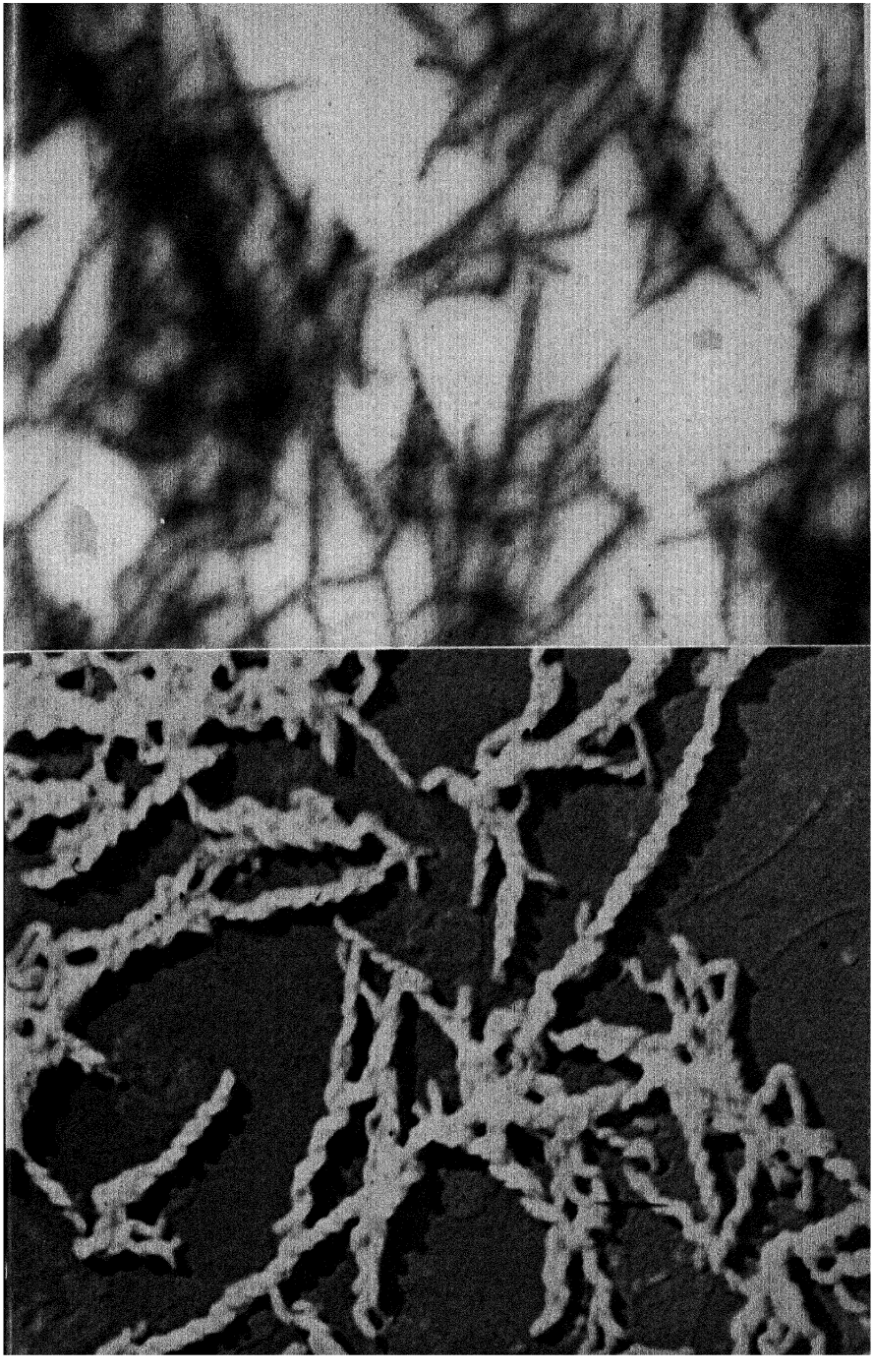
being deflected; this is called the axis of the lens. Images of points off the axis of the lens rotate about the axis as the current through the lens coil is changed. In order to produce good electron micrographs it is necessary to bring the axes of the three lenses into coincidence and to bring the source of electrons onto this axis. This is called aligning the microscope.

Since it is often desirable to determine the size of small objects photographed in the electron microscope it is necessary to know the magnification produced by the instrument. Two general methods are available. If we can measure the displacement of the object stage (and hence the object) necessary to move the final image through 3, 4 or 5 cm, the overall magnification can be calculated from

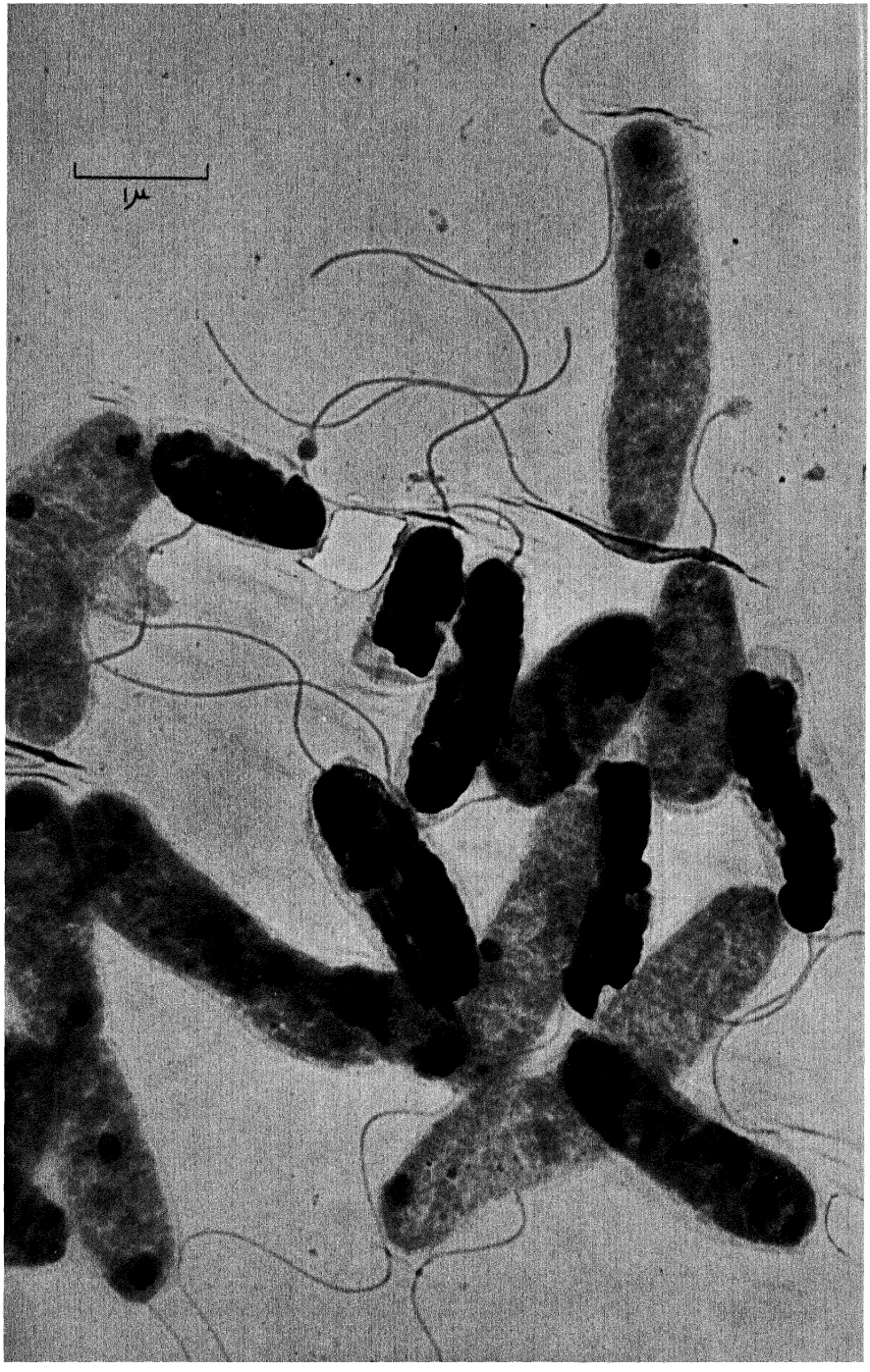
$$M = \frac{\text{displacement of image}}{\text{displacement of object}}.$$

In the new Toronto microscope, circles of radii 1, 2, 3, 4, and 5 cm are drawn on the bottom fluorescent screen, and the micrometers that move the object stage are calibrated to read to 0.0005 cm; displacements can be estimated to one-tenth of this. At magnifications above $\times 5000$ this method becomes insensitive.

The second method is to introduce into the microscope objects of known size and then to measure the size of the image on the developed photographic plate. For this purpose C. J. Burton, R. Bowling Barnes, and Rochow have used the invar replicas of diffraction gratings, and Fullam has used microscopic glass spheres of predetermined size.



Above: Ordinary electron microscope picture of a calcium stearate grease (×20,000).
Below: Shadow electron micrograph of sample of a similar grease (×35,000);
shadows are cast by chromium molecules. See also page 86.



Courtesy Dr. Stuart Mudd

Vibrio schuylkilliensis (×22,500).

Chapter 20

THE USE OF THE ELECTRON MICROSCOPE

The general problem of electron micrography falls into three main parts (1) the preparation of the specimen, (2) the production of the micrograph, (3) the interpretation of the micrograph. These will be considered separately.

Specimen Preparation

The methods of specimen preparation employed are very diverse and will have considerable influence on the quality of the final micrograph. There is also the possibility of introducing artifacts, or of modifying the specimen during the mounting and introduction into the microscope. The methods at present employed are. (1) direct mounting; (2) mounting on, in, or between formvar or collodion films; (3) replica techniques; (4) mounting in water. These methods will be illustrated by considering special cases.

Direct Mounting. Certain biological specimens, such for instance as the wing of a midge (*chironomidae*) can be mounted by placing them on a 200-mesh screen for support, or by cementing them to the end of the object holder. Again, in studying the action of fibers in collecting air-borne particles, the fiber may be mounted across the end of the object cartridge, the particles blown past it and the cartridge then put into the microscope for examination. The advantage of this method is that it avoids the scattering produced by a film and gives rather better contrast in the image than is usually possible with specimens mounted on a film.

The Use of Films. There are many variations of this method. Three are considered here. A method often used in mounting bacteria is to produce a formvar film and transfer it to the top of a 200-mesh screen. The organisms to be investigated are suspended in water and a drop of the suspension is placed on top of the film and allowed to evaporate. If the suspension is concentrated, the residual liquid may be removed with a filter paper after a little of the specimen has settled out. If the suspension is dilute several drops may be allowed to evaporate in succession. This method is commonly used in mounting bacteria and may be used in mounting colloids dispersed in water.

In another method, a glass microscope slide is dipped into a 0.1 per cent solution of formvar in ethylene dichloride. On removal, the ethylene dichloride evaporates, leaving a thin film of formvar on both sides of the glass. If the film is cut with a needle it may be floated off on water and then mounted on a 200-mesh screen and used as before; or the specimen may be mounted or dispersed on the film while it is still attached to the glass; it is then cut into suitable sizes, floated off on to water and mounted as before. In this method a larger area of film is available for mounting and it is well supported on the glass. Finally, the substance can in some cases be dispersed in the solution from which the films are to be made, and it then appears encased in the film and is mounted as before.

Specimens mounted on a film may be covered with another film. This is not usually necessary and in any case it leads to an increase in electron scattering in the microscope and a decrease in contrast.

Films of collodion formed on water can be used in place of formvar films. Both are used at Toronto, but our preference is the latter.

Replica Techniques. The surfaces of solids cannot be directly examined in the transmission type microscope since even the thinnest films of most solids are in general opaque to the electron beam. However, a formvar copy or replica of the surface can be made and examined in the microscope. In fact, if stereoscopic micrographs are made, the depths of scratches and cavities

in the surface can be determined. In a variation of this technique, a polystyrene replica (a negative) of the surface is made and from this a silica replica (a positive) is produced; the latter is examined in the microscope. While replicas were used originally for the study of etched metal surfaces the technique is now being extended to the study of many other types of specimen.

Mounting in Water. A cell for mounting substances in water and examining them at atmospheric pressure has been described. At the time of writing, micrographs by this method have not been published, but owing to the speed and magnitude of the Brownian movement, micrographs can be obtained of small particles only if they are attached to the containing films, and even then good contrast can only be expected with particles of high specific gravity, such as metallic colloids.

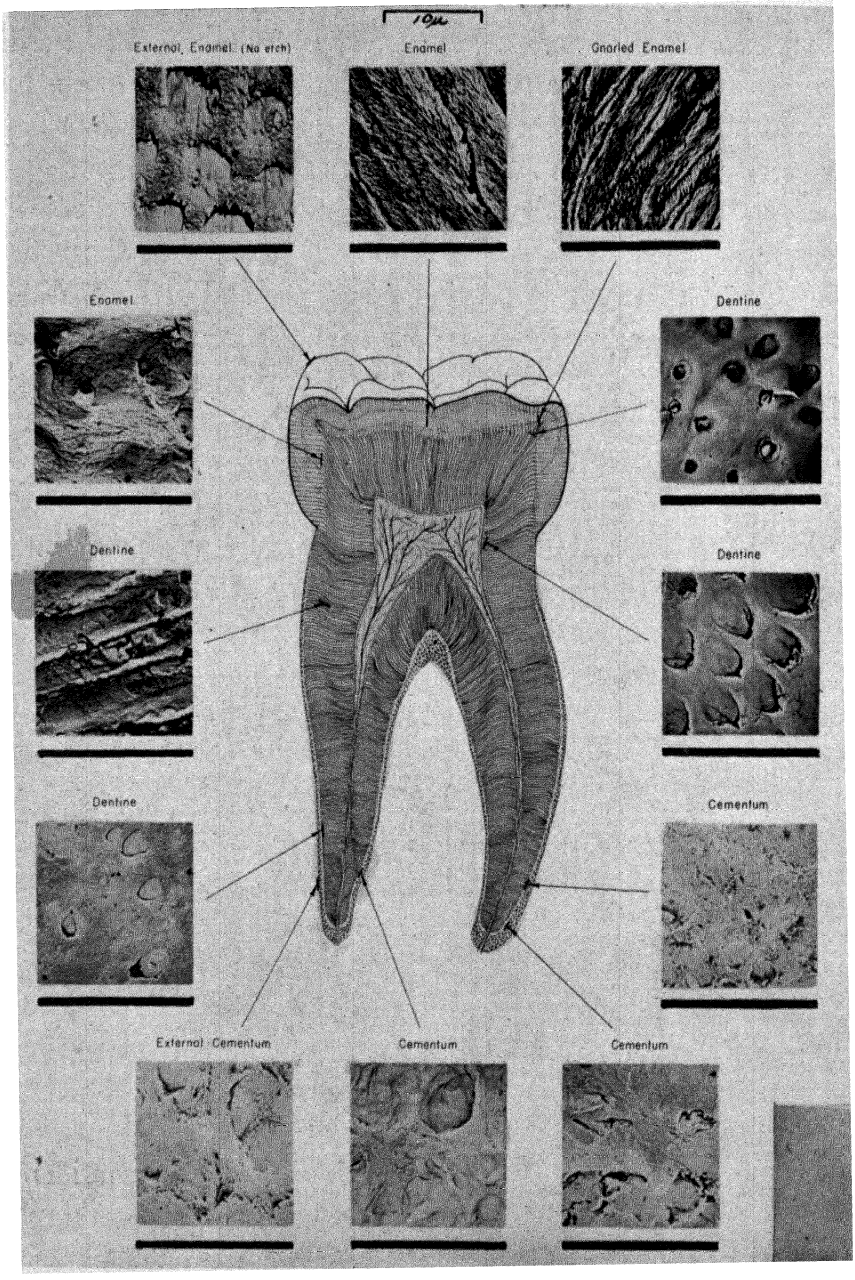
After the specimen has been mounted by any of the above methods it is good general practice to make a light-microscopic examination of the dry specimen in order to see if the deposit on the film is of suitable density and free from dust and foreign matter.

The Production of the Micrograph

Before the specimen is examined in the electron microscope it is desirable to align the microscope, if this has not already been done. The minimum intensity of illumination consistent with ease of focussing is then chosen by adjusting the filament current and the specimen introduced. The following methods of micrography are then available: (1) direct illumination; (2) dark-field illumination; (3) stereoscopic micrography; (4) motion-picture micrography.

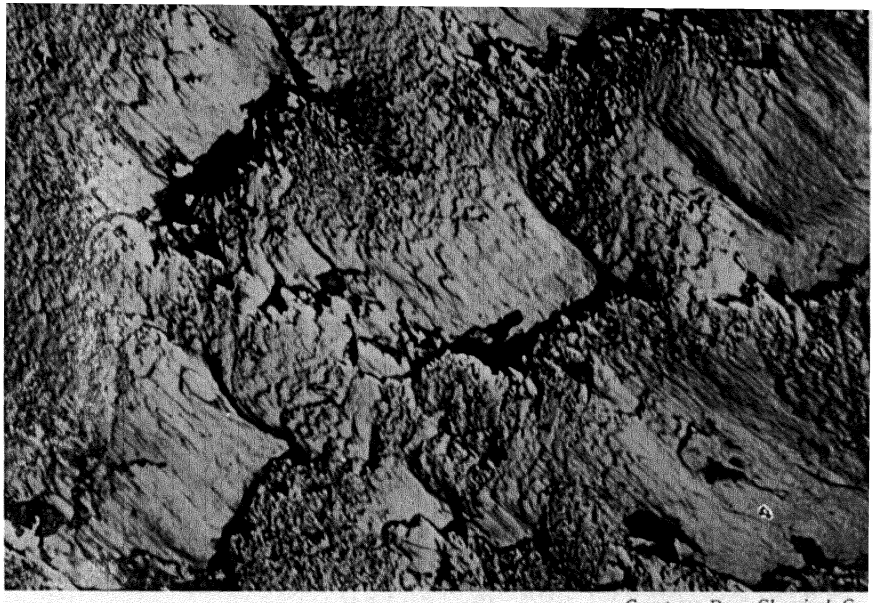
Direct Illumination. The major factors to be considered here are the choice and measurement of the magnification, the choice of intensity and time of exposure, the use of diaphragms and the observation of features not readily reproduced in a photomicrograph.

Generally speaking, the minimum magnification is used in the examination of small particles when size distribution and structure



Courtesy Dow Chemical Co.

Electron micrographs of etched surface and interior structures of a human tooth. Polystyrene-silica replicas (×1,200).



Courtesy Dow Chemical Co.

Polystyrene-silica replica of external surface of human tooth enamel (×5,300). No etch.



Courtesy Dow Chemical Co.

Polystyrene-silica replica of the interior structure of rabbit bone, polished and etched (×5,300).

are to be found, for the smaller the magnification the greater is the area of the object observed and hence the greater the information provided. However, the desired resolution in the micrograph and the grain size of the photographic plate set a lower limit to the permissable magnification.

The image is usually focussed at maximum intensity as obtained by changing the condenser current until the electrons from the gun are brought to a focus in the plane of the object. The angular aperture of the illuminating beam is then given approximately by

$$\frac{\text{radius of diaphragm in condenser lens}}{\text{distance from condenser diaphragm to object}}.$$

The angular aperture of the illuminating beam is then reduced by increasing the condenser current slightly, and the exposure is made. For particles mounted on a film, particularly the less dense particles and the thicker biological specimens, the use of a diaphragm immediately behind the objective lens improves the contrast.

The visual observation of the image on the bottom fluorescent screen will sometimes provide information not readily recorded on a photographic plate, though the motion-picture method might show it. For instance, the specimen may change its form under electron bombardment; it may evaporate, signs of dehydration or drainage may appear, and a breakage of the film may lead to mechanical forces being exerted on it, the results of which can be seen on the screen. Sometimes parts of the specimen may move or vibrate due to their becoming charged by the electron beam, with the consequent result that they are repelled by the following electrons. The movement and vibration may give further information as to the shape, rigidity, and structure of the specimen. Crystalline material in the specimen will sometimes give rise to spots and bands of light on the fluorescent screen which move with small changes in the objective current. This may be used as a test for the presence of crystalline material in some cases.

Dark-field Illumination. This method, analogous to the method of the light ultramicroscope, has been used by von Ar-

denne and by Levy, the latter reproducing some interesting pictures. At present the resolving power of the electron microscope used with dark-field illumination does not show any great improvement over that with direct illumination. It is probable that there is room for development here.

Stereoscopic Micrography. The relatively large spherical and chromatic aberrations of the magnetic lens have made it necessary to work at angular apertures of the order 10^{-3} and 10^{-4} radian. This is very much less than the value used in light micrography, and consequently the depth of focus in the electron microscope is relatively large. In practice, particles separated by 10μ along the axis of the microscope can be considered in focus. If one micrograph is made and the object then tilted through an angle of say 10° and another micrograph is made, and the two are viewed by the right and left eye respectively, an appearance of depth is given which is qualitatively useful. Further, the parallax between the micrographs can be measured by the aid of the instruments used in contour plotting from aerial photographs and quantitative measurements made in the third dimension.

With crystalline material, such as fine metallic particles deposited on a collodion film, this method may break down, since the appearance of the field may change considerably when the specimen is tilted. The reason for this is the interference between the reflected electrons that produces the light and dark spots and bands previously mentioned. Approximate measurements of the heights of particles can still be obtained, however, if a metal such as chromium or uranium is evaporated on to the supporting film, obliquely, so that the object under study casts a shadow—a region in which no chromium is deposited. From the length of this shadow, as observed in the electron microscope, a minimum height for the object can be deduced.

Surface irregularities of the order of 30 A.U. have in this way been detected on collodion films.

Motion-picture Micrography. This has been reported by von Ardenne in attempting to secure pictures of the progress of chemical reactions.

Interpretation of the Micrograph

An electron micrograph taken by direct illumination gives information only about the shape, size, and structure of the specimen in the two dimensions of the object plane.

Owing to the great depth of the focus of the electron microscope the objects of Figs. 121 (a) and (c) would both produce images of the form of Fig. 121 (b). The two objects could, however, be distinguished by the aid of stereoscopic examination. This effect should be kept in mind when examining the electron micrograph of clumped particles, since the particles may build up off the plane of the film in "chains" and "trees."

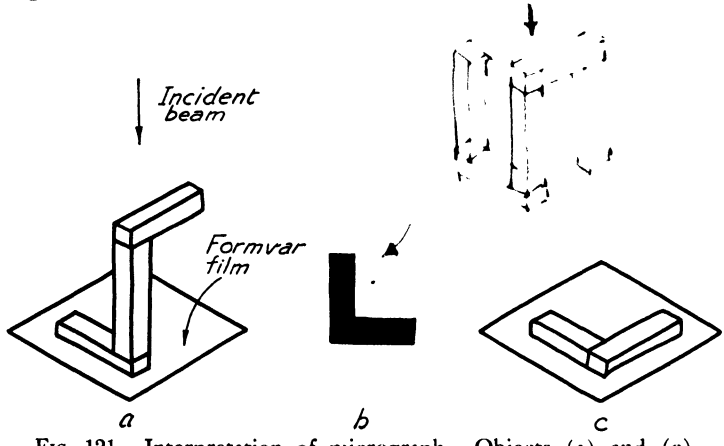


FIG. 121. Interpretation of micrograph. Objects (a) and (c) would each produce an image (b).

This is perhaps the most difficult point to grasp in the interpretation of electron micrographs and is more difficult for observers used to light micrographs in which a thin slice of the object is in focus and the adjacent planes are blurred.

In the photographic plates (negatives) the blackening is a function of the total mass that the electrons have had to traverse, (neglecting the effect of scattered electrons) and cannot usually be interpreted in terms of thickness unless uniform density of the material can be assumed. If the specimen is known to possess uniform thickness, blackening indicates regions of lower density.

An important step in the interpretation of any micrograph is the detection of artifacts, that is, appearances in the micrograph which do not correspond to actual structures in the naturally occurring substance. They may be introduced by the method of specimen preparation, or by the method of micrography. The general method of detecting artifacts is to change the factors which may produce them and look for changes in the micrograph. A few of the more common are listed below.

Narrow light bands around particles. These are due to chromatic aberration and diffraction, and might be misinterpreted as sheaths in pictures of bacteria if care is not taken.

Bands or spots. These appear in images of crystals, and are most readily apparent if no diaphragm is used in the objective; they shift with a change in focus.

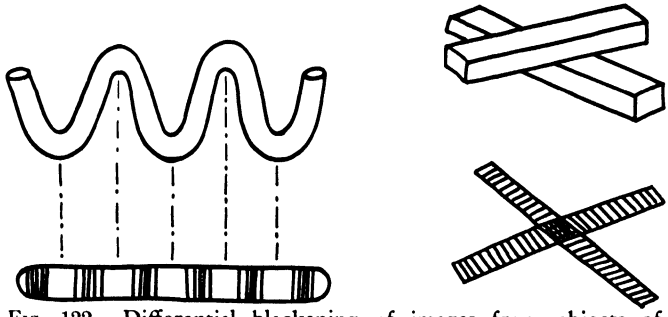


FIG. 122. Differential blackening of images from objects of uniform density due to twisting or packing.

Blurring of edge of image. This may be due to improper focus, lack of resolution, change of focus during exposure or a shift of the object during exposure. Another cause sometimes observed, *e.g.*, with flowers of sulfur, is evaporation during exposure. Shrinkage, dehydration or spontaneous changes of shape occur with some materials. Shrinkage and dehydration sometimes occur with biological specimens, and a spontaneous change of shape from a jagged to a smooth shape has been observed with egg albumen under intense illumination. These effects are best detected by visual examination of the image on the fluorescent screen.

Distortion. This can occur in some microscopes, but it appears to be negligible in the new Toronto microscope at magnifications above ×2500. It is detected by measuring the size of particle photographed first at the center and then at the periphery of the field. Visual observation of the straight edge of a sodium chloride crystal, as the image is moved across the bottom fluorescent screen, provides another method of detecting its presence.

Deformation caused by method of mounting. Salt crystallizing from thin layers of salt solution on formvar produces platelets rather than cubic crystals. Mechanical deformation of the specimens is not very likely, as most specimens are handled suspended in water. The possibility that small particles may take up preferred orientations on the formvar film should not be overlooked.

It has already been pointed out that photographic enlargement may be necessary before all the detail in the micrograph is readily visible. At Toronto, the 2 x 10-inch negatives are usually examined in a Leitz projector giving a further magnification of ×15, in order to decide which fields shall be enlarged. This procedure also facilitates rapid comparison of micrographs and provides an image in which particle-size distribution counts can be made without the production of a large number of standardized photographic enlargements.

In conclusion, we may say that an experienced observer can make accurate statements as to size, shape, and structure (which will include size distribution) down to magnitudes ten times greater than the resolution limit of the microscope, and that the artifacts do not impose serious limitations on the use of the electron microscope.

This type of information, taken in conjunction with results from bacteriological investigations or in chemistry from colloidal, x-ray, electron diffraction or electron analyzer experiments, will go far to systematize and develop the science of small particles and the industries which are based on them.

That the electron microscope is limited to the measurement of size, shape, and structure and also that the results it produces must

be considered in their relation to other experiments on the specimen should be emphasized. The electron microscope is not a cure-all for research difficulties, but in its own field it is unrivaled and it will often lead to the clarification of difficulties in other fields of research.

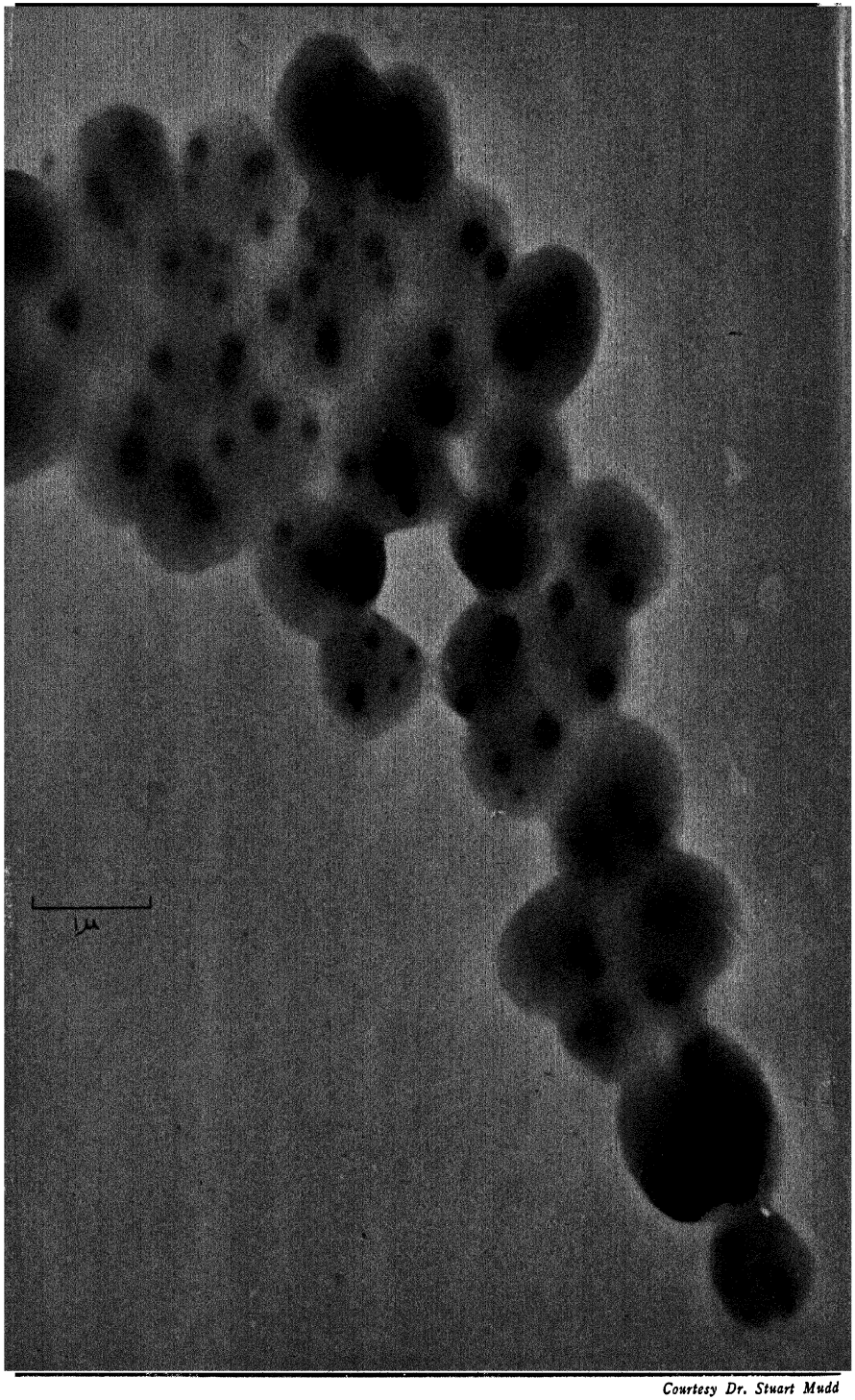
Trends in Electron Microscopy

In the design of modern compound electron microscopes of the magnetic type we may notice two trends. One is the production of a "Universal" microscope which can be used at magnifications between 2000 and 20,000 diameters for ordinary, dark-field and stereoscopic work. Such microscopes often contain the necessary equipment for electron-diffraction investigations. The other tendency is to the production of small, simplified microscopes restricted to one or two values of magnification and without the electron diffraction attachments. The larger model can be used for any research in the field of electron microscopy; the smaller is intended for production checking, diagnosis or other more restricted uses.

At the same time the universal model has been modified to perform new functions; stereoscopic photography, motion-picture photography and electron-diffraction techniques are examples of this.

Research is being made upon the lens aberrations and already basically new procedures are being devised to reduce or nullify them.

The basic technique has also been turned to the production of a different type of instrument, the electron analyzer, which can be used for the detection of chemical elements in a previously observed small region of a sample. Here we have a further development in the experimental methods of studying small particles.



Courtesy Dr. Stuart Mudd

Staphylococcus flavocyaneus: The first indication of intracellular granules (×21,000).

Chapter 21.

PRACTICAL APPLICATIONS OF THE ELECTRON MICROSCOPE

All the important practical applications of the electron microscope are due to two great advantages which it has over the optical microscope:

(1) increased resolving power, enabling one to see and photograph fine particles and fine detail;

(2) greatly increased depth of focus enabling one to get useful magnification in three dimensions.

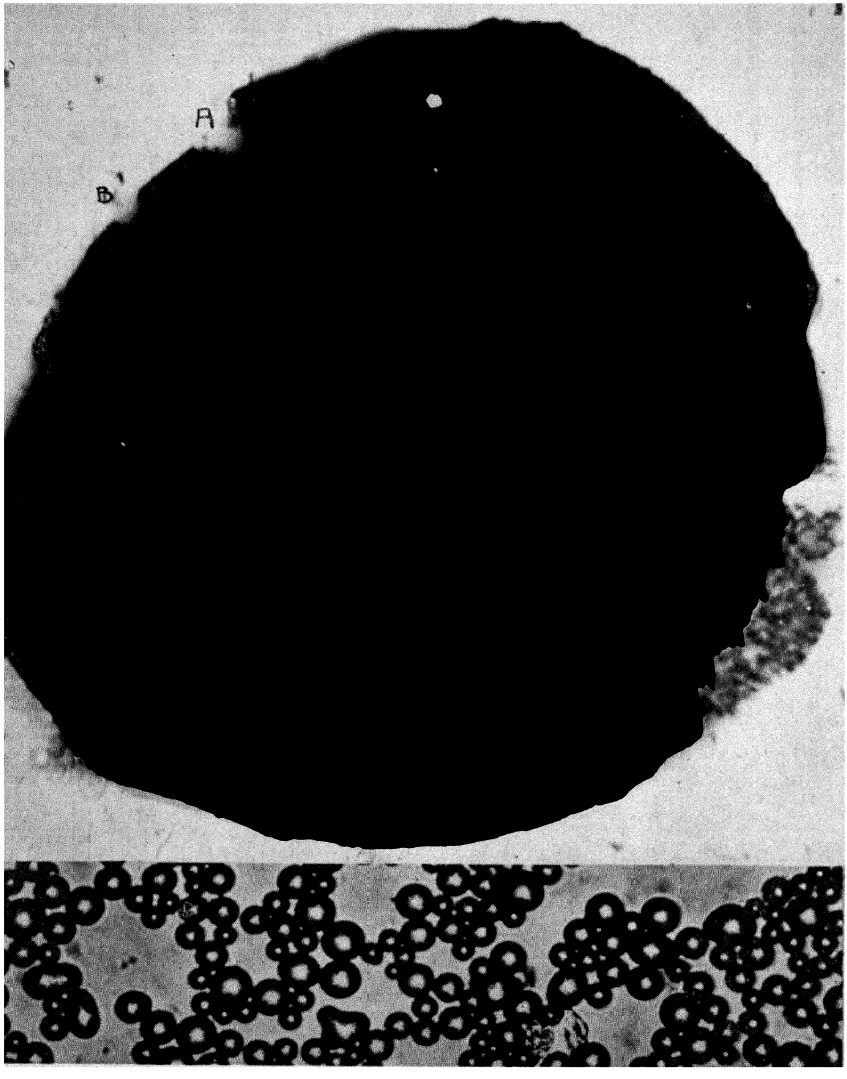
The disadvantages of the instrument are chiefly due to the fact that all specimens have ultimately to be exposed in a vacuum and consequently will have to undergo changes brought about by drying and evacuation. In addition, the micrograph cannot be taken without exposing the specimen to rather an intense electron beam for the considerable length of time required for focussing.

The electron bombardment may induce some changes; and under certain circumstances of mounting, the specimen may become electrically charged. As a consequence it is not advisable to rush into a rash interpretation of any particular micrograph. However, there is no doubt that the electron microscope has made a place for itself and gives promise of striking developments in the future.

Up to the present (1945) the magnetic electron microscope has been used extensively in many fields.

Fine Details of Natural Objects

The determination of fine details in the structure of various natural objects, such as diatoms, pollen dust, the trachea and the wings of insects was one of the earliest applications of the electron microscope. As diatom shells are common test objects for optical



Courtesy Columbian Carbon Co.

Above: Thiokol latex particle as seen in the electron microscope (×12,500)
Below: The same as seen through light microscope (×375).

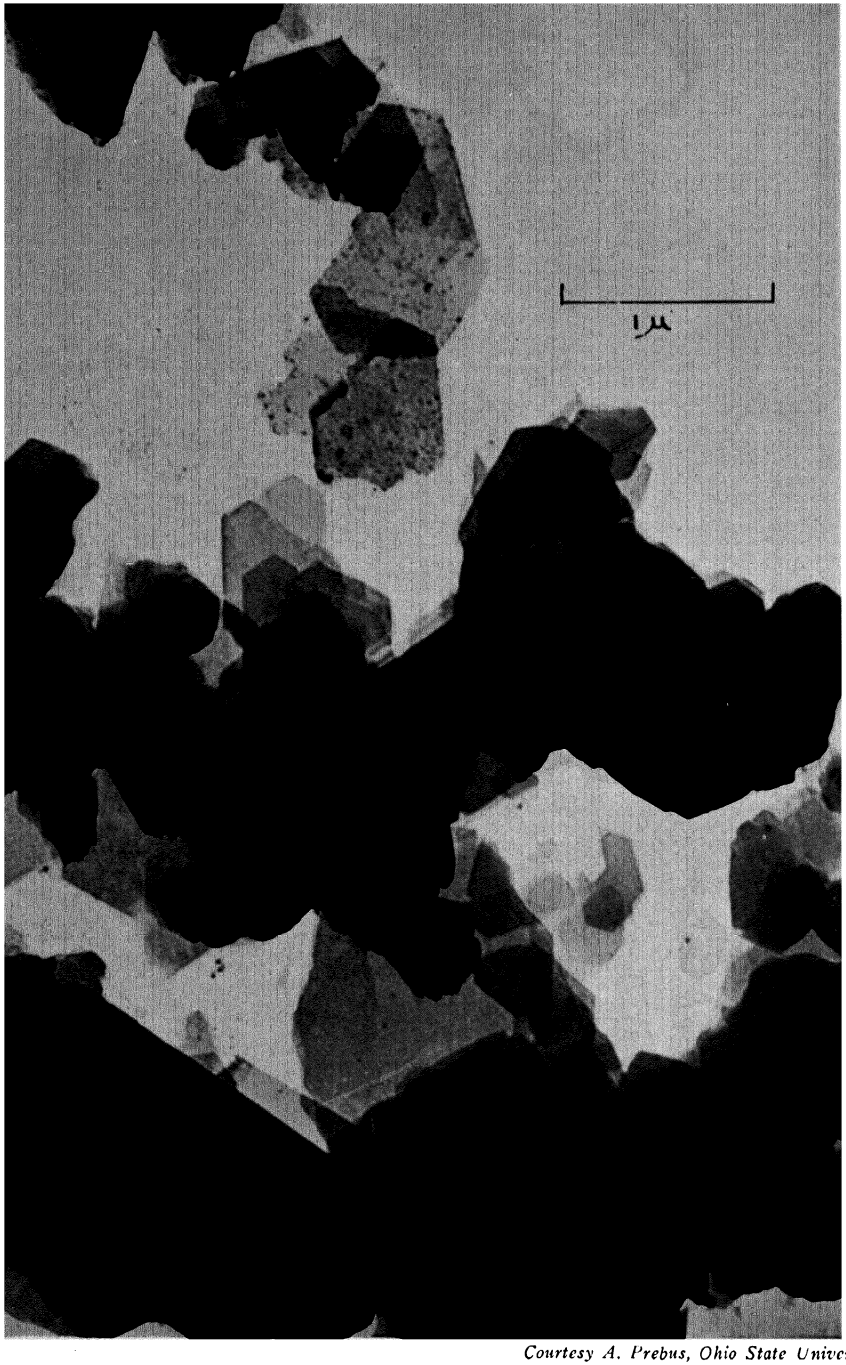
microscopes, it was natural that they should have been used for some of the first objects for these investigations. Illustrations of various kinds of diatoms are shown on pages 24, 38, 40, 76 and 234. The Department of Physics of the University of Toronto has had the kind coöperation of Dr. Paul S. Conger of Washington, D. C., who has supplied a great variety of diatoms for electron micrographs.

As shown in the picture of the wing of a midge (Frontispiece) the electron microscope has revealed many new, unexpected structures in animals and plants.

Sizes and Shapes of Small Particles

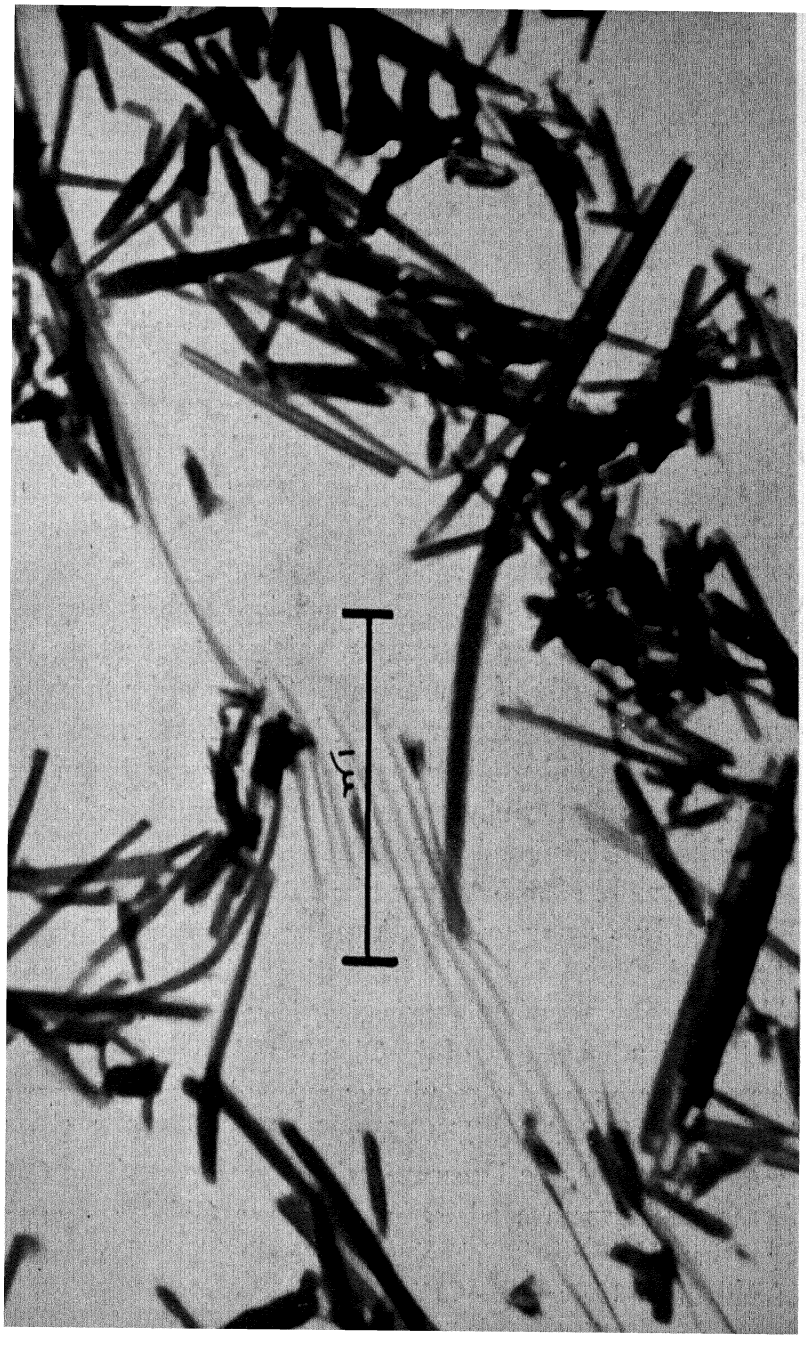
Carbon Black and Fillers. Historically, the first commercial application of the electron microscope was the determination of the size and shape of small particles, such as the particles of carbon black used for reinforcement in rubber, or the particles of pigments used in various paint products. Pioneer work in this field has been done in the laboratories of the Columbian Carbon Company of New York. Considerations raised by these carbon black pictures have revolutionized the theories of the role of rubber reinforcing agents. These particles take part in a physico-chemical reaction with the rubber, and the intensity of the effect depends on the total area of contact between the carbon particle surface and the rubber. These carbon particles are apparently spherical and some of them are as small as 40 mμ (4×10^{-6} cm) in diameter. If we should take a cube of sugar measuring one centimeter on a side and grind it into small spheres of this diameter, the surface exposed by the sugar would increase from 6 sq cm to over 800 sq ft. Thus we can easily see how important consideration of surface areas may be.

Clays. The study of various kinds of clay has been of very great interest to the soil chemist, *i.e.*, to agriculture, and to the colloid chemist who has been in contact with the many commercial applications of clay, *e.g.*, its use in ceramics, in china manufacture and for paper coating. A very great deal of attention has been given to the colloidal properties of clay and naturally one of the main branches of this study has had to do with the



Courtesy A. Prebus, Ohio State University

Kaolinite crystals (×29,000).



Courtesy A. Prebus, Ohio State University

Halloysite crystals (×44,000).

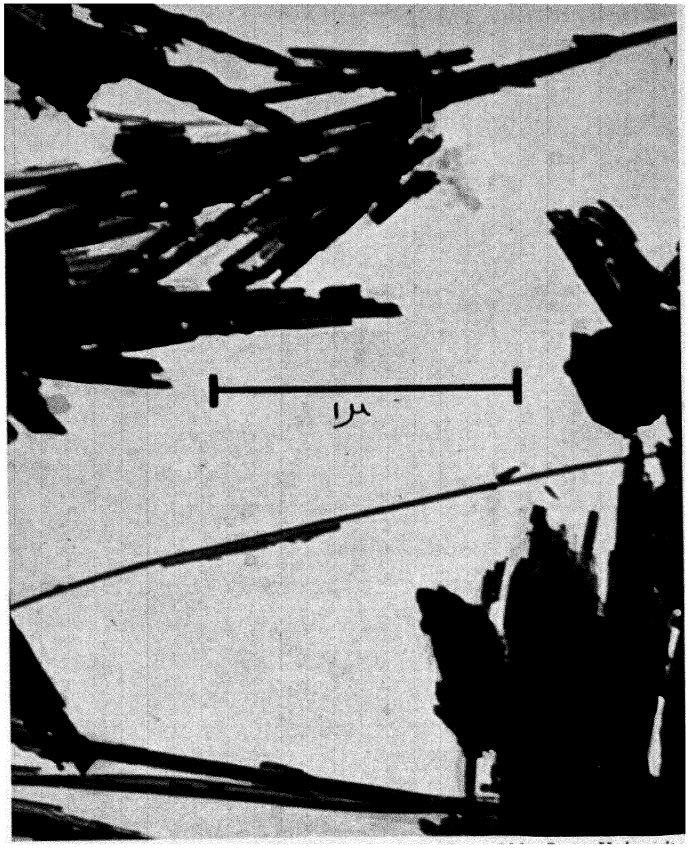
determination of the size and shape of the ultimate particles which go to make up the clay aggregate. Probably the main ingredients from this point of view are the clay minerals.

Specific study of clay minerals dates back to about 1930, although it was shown by C. S. Ross in 1927 that crystalline clay minerals occur in soils. As a result of later work it was established definitely that clay materials in general are crystalline. Attempts have been made to determine the size of plate-like crystals of clays by measurement of the limiting velocity of settling in water; but the formulas used, which were deduced from the formula applicable to small spheres (using Stokes' law), are not very convincing. On the other hand, x-ray diffraction and electron diffraction have been used to determine the crystal size and habit; these investigations of the fine minutiae of the crystal structure seldom led to any definitely acceptable interpretations.

With the advent of the electron microscope, it was soon realized that here is an instrument which is "particularly well adapted to the study of clay minerals; first, in order to characterize them by their appearance and, second, to assess, more exactly than has hitherto been possible, the contribution of their crystal habit to other physical and chemical properties." (Marshall, Humbert, Shaw and Caldwell).

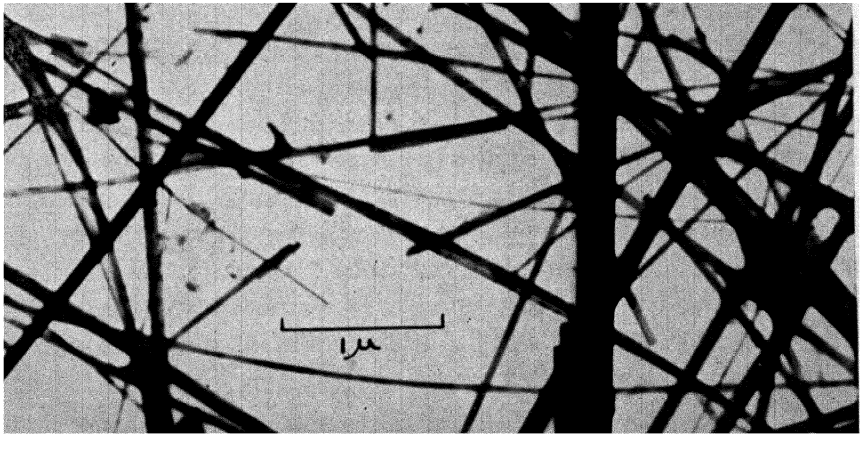
Micrographs of many forms of clay have been taken in the Research Laboratory of the American Cyanamid Company (Stamford, Conn.) and at the University of Toronto, but probably the most systematic investigations have been carried out in the Radiation Laboratory of the Ohio State University using the electron microscope built and operated under the direction of Professor A. F. Prebus. These investigations were carried on in co-operation with the Departments of Agronomy of the Ohio Agricultural Experimental Station (Wooster, Ohio), and of the Ohio State University (Columbus, O.), and with the Department of Soils of the University of Missouri.

As a result of these studies definite details of the structure of crystals in many commercially important clays have been determined. They report:



Courtesy A. Prebus, Ohio State University

Chrysotile asbestos (×40,000).



Courtesy American Cyanamid Co.

Asbestos Fibers (×21,000).

(1) Montmorillonite (San Diego, Calif.), illite (from Goose Lake, Ill., known commercially as grundite), beidillite (from Putnam silt loam, Missouri) and bentonite (from Rock River, Wyo.) consist of extremely thin plates, which have a very large specific area. In the first-named clay the plates are only about 1mμ thick.

(2) Kaolinite (an English China clay sample) and dickite (from Chihuahua, Mexico), also have plate-like crystals, but much thicker than those of the preceding classes.

(3) Nontronite (from Sandy Ridge, N. C.) and halloysite (from Maiden, N. C.) have lath-shaped crystals.

(4) Attapulgite (from Attapulgus, Ga.) and magnesium bentonite (from Hector, Calif.) are very fibrous. This also is the structure of asbestos in powdered asbestos. (Page 50.) The above workers conclude that fibrous or lathlike clay minerals are much commoner than formerly supposed.

"Highly characteristic features in the crystal habit of the different minerals are associated with their chemical and physical properties. Wide variations in particle shape can be closely correlated with extreme differences in the behavior of clays. The structures exposed by electron microscope studies are of more value for purposes of correlation of the physical properties of unfired clay. With proper interpretation, however, electron photomicrographs will also provide a satisfactory understanding of such properties as plasticity, hydration, green strength, and shrinkage.

"Plasticity results from (1) the interplay of the attractive force tending to hold the clay minerals together, (2) the thickness of the water film between the plates, and (3) the lubricating properties of the water film. Best working properties depend on the relative thickness of the water film to the strength of the force. As plasticity changes with structure variations, electron photomicrographs offer opportunity for valuable deductions from particle shape. In montmorillonite, the extreme thinness of plates and consequently the great number of water films indicate that the order of plasticity will be high. The extreme amount of surface area is also closely correlated with a high bonding power

and a high drying shrinkage. The structures of illite reveal quantities of surface intermediate in magnitude.

"The hexagonal plates of kaolinite are stable. Their low base-exchange capacity is attributed to their stability. . . . The relatively low amount of surface per unit mass explains the low values for bond strength, drying shrinkage, and general plastic properties.

"On hydration, a film of water envelops the exposed surface of the plates. Variations in amount and character of surfaces as exposed by the electron photomicrographs may explain the wide variations in swelling; low chemical stability of magnesium bentonite is closely correlated with the fibrous structure of this clay mineral."

Mine Dust. Drilling and blasting operations produce silica dust in the air of a mine. If this dust is breathed into the lungs over long periods of time the condition may develop into silicosis, which is a serious disease among miners. The drilling dust appears to be more harmful in its effect than the blasting dust, but no significant differences between the two could be discovered by ordinary methods. The electron microscope was used to examine the dusts and to determine whether any important differences did exist.

Meteorologists and public health officers have long been interested in the measurement of the size distribution of dust particles in normal and abnormal atmospheres. Various methods of capturing a sample of the dust have been tried; the earlier work depended on bubbling the dust-laden air through water and letting the dust settle on a microscope slide at the bottom of the liquid column, or on blowing a blast of dust-laden air against a glass plate to which the dust particles tend to cling.

Those interested in mine dusts in England developed a far more satisfactory collecting apparatus, the thermal precipitator, (Fig. 123.) The dust-laden air is drawn through the chamber past a thin metal wire which is heated electrically. For some reason, which is not entirely clear, the dust particles are repelled by the warm wire and deposited along the walls in quite a definite line. A small microscope slide (or the object holder of an

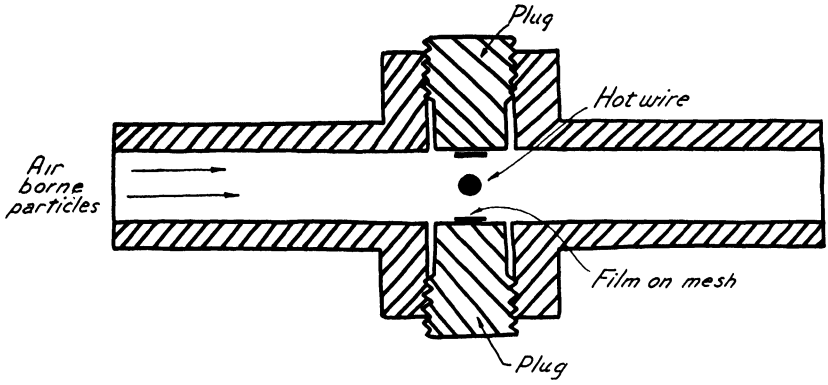


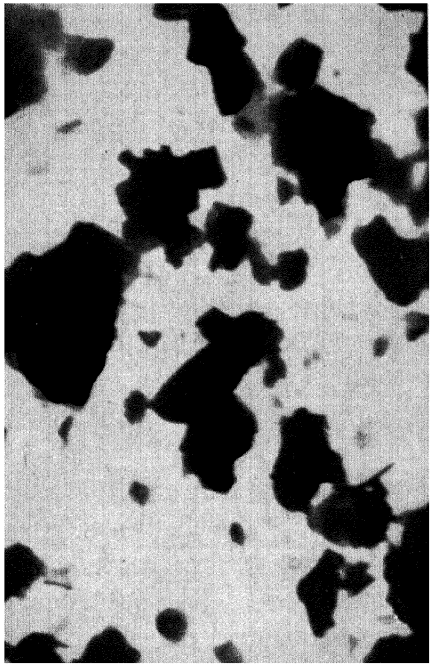
FIG. 123. Plan view of thermal precipitator.

electron microscope) is inserted in the position shown so as to have the dust particles deposited for observation. This apparatus clears the dust out of the air quite efficiently. With this thermal precipitator the dust sample can be taken right in the mine.

A series of electron micrographs are taken over the width of the thermal precipitator deposit, for several positions along its length. From these photographs, projected on a screen at $\times 50{,}000$ (5.0 cm = 1 μ), the particle sizes can be measured easily and the numbers in any particular size range can be counted.

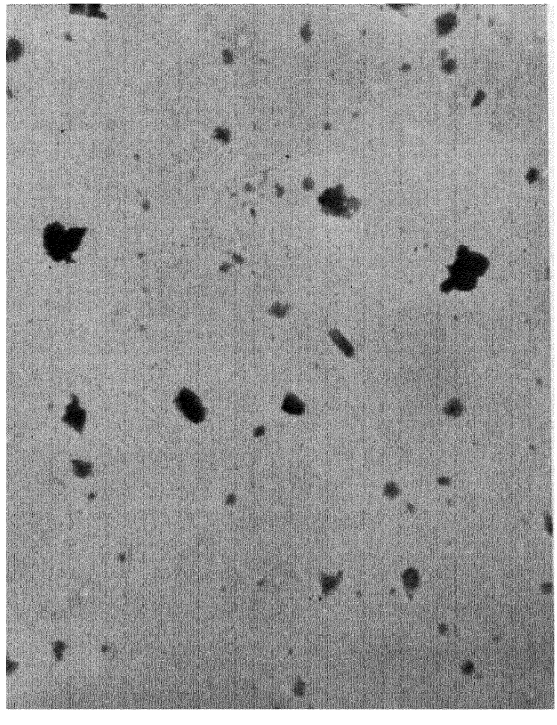
From these experiments it was concluded that the percentage of particles with diameters less than 0.20 μ was much greater in the drilling than in the blasting dust. About 50 per cent of the particles in the drilling dust were less than 0.10 μ in diameter; about 12 per cent of the particles from the blasting dust were of the smaller sizes. Optical microscope counts of samples taken on glass slides at the same time as the electron microscope samples were obtained gave good correlation in the range 0.10 to 2.0μ. The distributions of the dusts were very asymmetrical.

The use of the thermal precipitator as a piece of standard equipment for mounting aerosol samples for electronic investigation is an important mounting technique, especially when a good distribution of the particles under the conditions in which they *normally occur in the air* is desired.



Courtesy University of Toronto

Mine dust (blasting) ×14,000.



Courtesy University of Toronto

Mine dust (drilling) (×14,000).

Crystalline and Non-Crystalline Smoke Particles. The study of fine particles has a very important scientific interest entirely apart from commercial considerations. Plates on pages 120 to 126 show the contrast between the appearance of the small particles in the smokes consisting of the oxides of aluminum, magnesium, tungsten and zinc. In the case of aluminum, the particles are manifestly all spherical, while in all the others the structures of all the particles are definitely crystalline. In the nature of the case, the particles must have grown from the aggregations of molecules of the oxides; apparently here we see evidence of the struggle between the forces of crystallization and the forces of surface tension in the fashioning of the final particle.

In the pictures just mentioned the particles were deposited on a thin film (of collodion or formvar) but another technique used at Toronto has produced interesting results. Air laden with fine particles is drawn past a fine fiber (about one micron in diameter) stretched across the mesh holding the object. The particles stick to the fiber, as well as to one another, and an irregular layer of particles forms on the fibers. On pages 232 and 233 are shown pictures (1) of carbon particles and (2) of particles of sodium chloride resulting from atomizing a salt solution into air. In the case of the salt, the crystals have been built up by tracing an enlarged projection of the negative thrown on the wall. It is an interesting study to try to imagine how these crystals are held together in such an apparently precarious fashion. See also lens paper, page 98.

An additional picture is shown of carbon particles collected on fibers of three different diameters; it is quite noticeable that the smaller the fiber the greater the number of particles attached per unit of length. In each case the air sample was the same and the rate at which the air was drawing past the fiber was the same.

Formation of Silver Deposits in Photographic Emulsions

Investigations on the formation of the silver deposits in photographic emulsions were carried out in the research laboratory of the Eastman Kodak Company with the help of an electron micro-

scope built in that laboratory. A selection of the electron micrographs are reproduced here, with comments taken from a paper by C. E. Hall and A. L. Shoen. These results have revolutionized the theory of the photographic development processes.

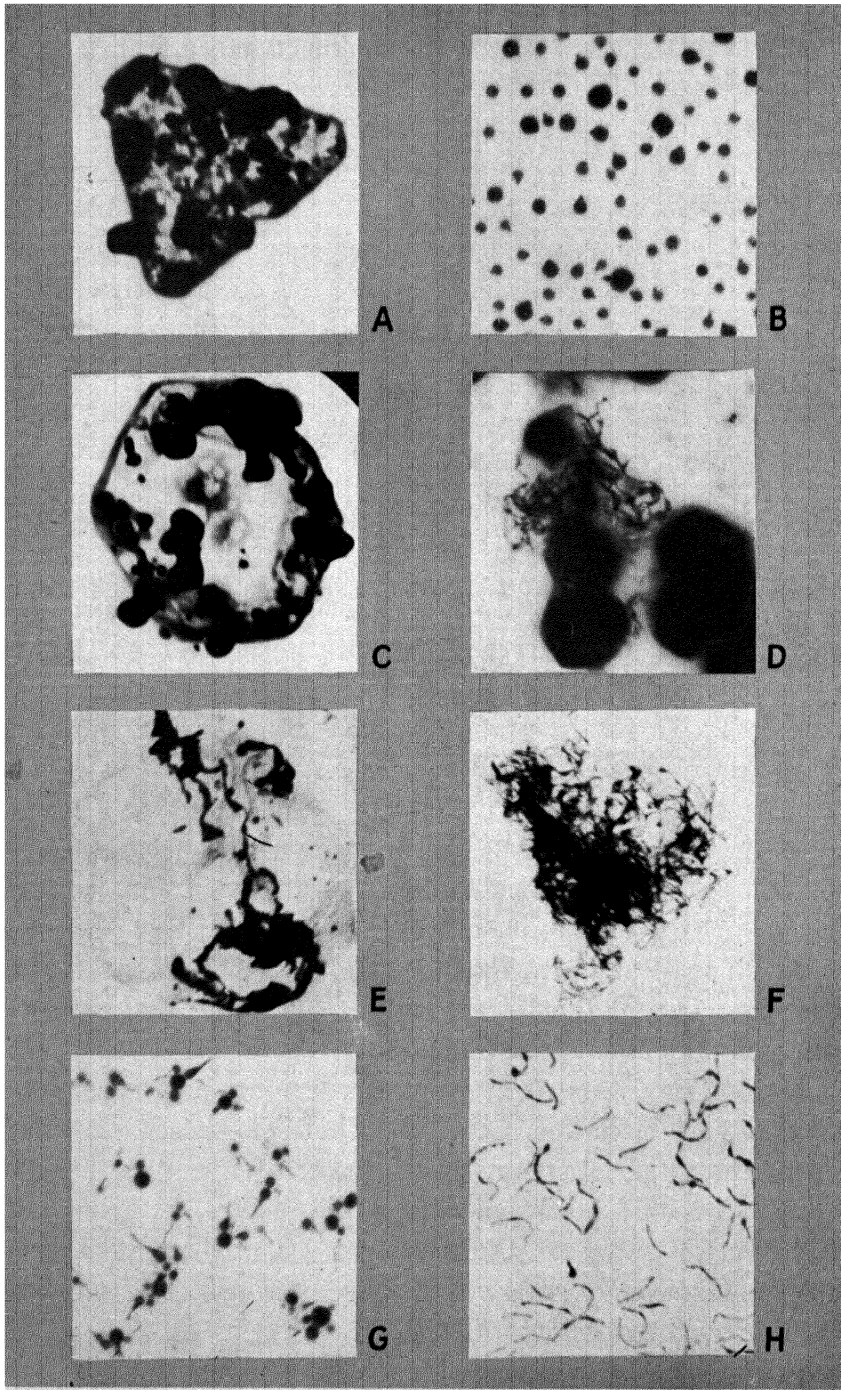
One of these plates, A (×21,500), is the picture of a single silver bromide crystal exposed to an intense electron beam for some time. At first such crystals are opaque to electrons and are therefore quite uniformly black in such a picture taken with the electron microscope. On being exposed to an electron beam for some time, these crystals begin to show transparent holes and cracks as in this figure. It is thought that this appearance is due to the migration of silver ions within the lattice of the crystal. The appearance of the crystals gradually changes while the exposure to the electron beam is prolonged, but in time a stable state is reached.

B (×30,000) is a picture of very small silver bromide crystals, known as Lippmann crystals: not developed or fixed. These would of course be quite invisible in the optical microscope.

C (×25,000) is the picture of a silver bromide crystal exposed to an electron beam, as for the crystal A, and then fixed. This crystal was exposed to an electron beam, while it was observed in the electron microscope. It was then taken from the electron microscope and washed in sodium thiosulphate solution. This dissolved the silver bromide away but left the silver, shown in black. It is to be noted that the reduced silver does not cover the cross-sectional view of the crystal uniformly; the free silver gathers about certain preferred points.

D (×25,000) shows a group of silver bromide crystals exposed to an intense light beam, then put into the developer for a very short time, but not fixed. Some of the silver bromide crystals, the solid black portions of the picture, have not been affected appreciably by the developer. The thread-like structures are filaments of silver, which have been reduced from silver bromide by the developer.

E (×25,000) shows crystals exposed to an intense light beam, then developed longer than those in D, but still only partially


A
B
C
D
E
F
G
H

Key to illustration on opposite page

A. Silver bromide crystal exposed to intense electron beam (×21,500).

B. Undeveloped Lippmann crystals (×30,000).

C. Silver bromide crystal exposed to electron beam. Fixed (×25,000).

D. Silver bromide crystals. Partially developed. Not fixed (×25,000).

E. Partially developed silver bromide crystal. Fixed (×25,000).

F. A silver grain developed in amidol (×25,000).

G. Undeveloped Lippmann crystals (×30,000).

H. Developed Lippmann crystals (×30,000).

developed and then fixed. A faint outline can be seen in the background where the original crystal has left its trace in the gelatin. There are many small particles of silver present, confirming the view that development starts at certain preferred centers, presumably at the latent-image centers.

F (×25,000) is the picture of a silver bromide grain which had been exposed to intense light and then developed on the electron microscope holder. Although this shows the kind of a silver deposit of which a developed silver grain is composed, it is not the same in general appearance as the grains developed on a photographic plate. In the latter the filaments are so closely packed that most of the grain is completely opaque with filamentary structure in evidence only around the edges.

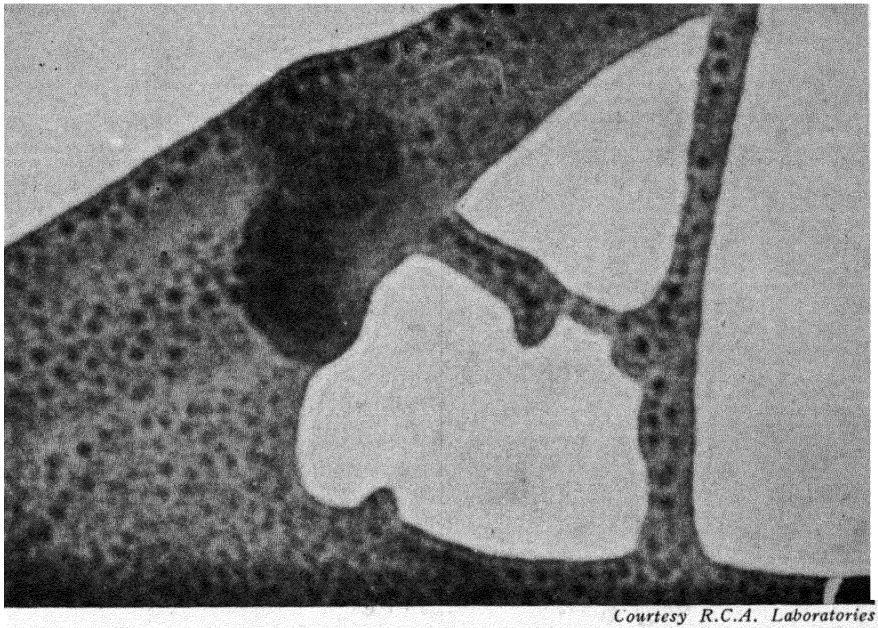
This particular crystal was developed in amidol. With the exception of pure paraphenylenediamine, all of the common chemical developers produce this typical filamentary structure with some secondary differences. Metol and amidol, for example, produce very fine filaments, whereas hydroquinone produces coarse filaments. The extent to which the filaments can wander away from the original crystal is influenced by the rigidity of the surrounding gelatin.

G (×30,000) shows Lippmann crystals exposed to light and partially developed but not fixed. The round dots are the silver bromide crystals: it will be noticed that each one has a projection forming.

H (×30,000) shows Lippmann crystals exposed, fully developed and fixed. Each small crystal has grown into a single filament of silver which is much longer and thinner than the original crystal.

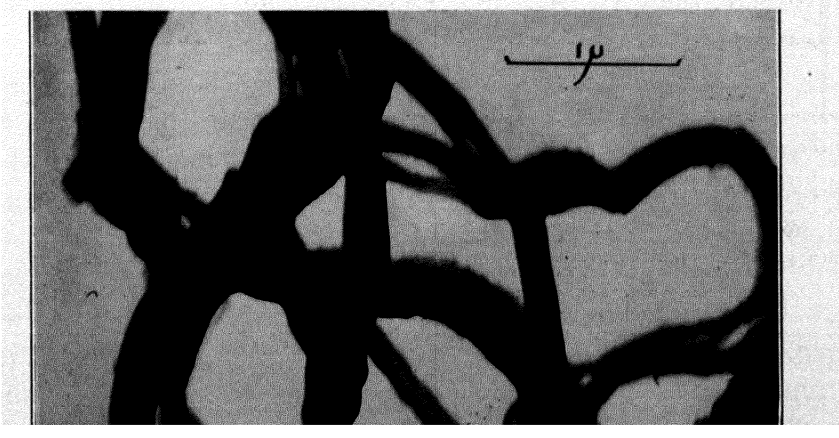
Molecules of Organic Materials

In the discussion of the properties of such solutions as proteins, colloid scientists have been driven to assign enormous values to molecular weights, and, consequently, a large size to such molecules. In fact, these scientists have great difficulty in agreeing on the definition of a molecule. The accompanying pic-



Courtesy R.C.A. Laboratories

Polymerized vinylchloride (×210,000).



Courtesy University of Toronto

Cuprene, a polymer of acetylene found in the presence of copper (×22,700),

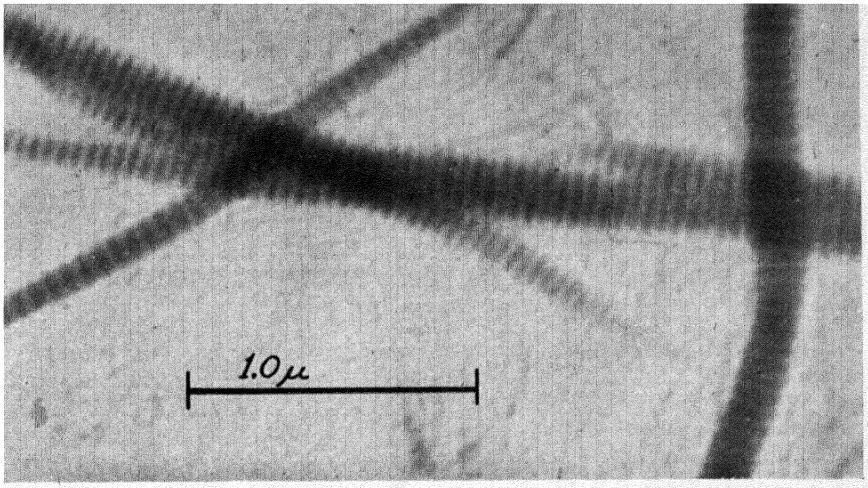
tures show various organic materials, but it is very hard to tell just what bearing these pictures have on our ideas of molecules of these substances.

Electron Micrographs of Fibrous Proteins.* "Structures reflecting the molecular organization of protein fibrils have been demonstrated with the electron microscope at the Massachusetts Institute of Technology. Fibrils of collagen, which is the chief protein constituent of tendon, skin and connective tissue generally, show a regular banded structure, as shown on page 269. The average value of the spacing (the distance between centers of consecutive *like* bands) is about 640 Å which is in agreement with x-ray diffraction measurements made by R. S. Bear. This banded structure is characteristic of collagen fibrils from different parts of the body and from different animals, and results from an alternation in density of the protein along the fiber axis. Finer detail within the fundamental period has been revealed by the use of heavy metal stains. The stains are preferentially adsorbed to produce at least five stained sub-bands within the fundamental period. (Å is another symbol for A.U.)

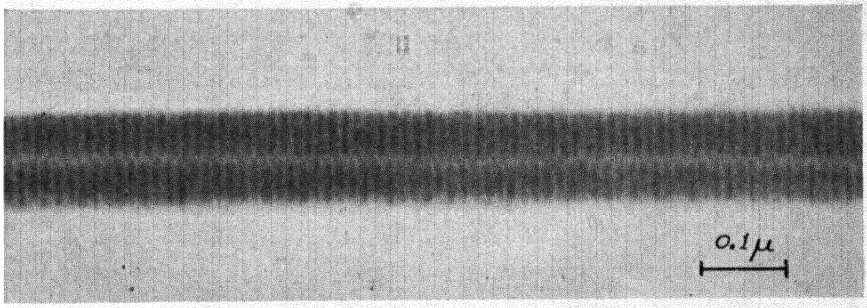
"Detailed structural patterns have also been demonstrated in protein fibrils from molluscan muscles by the same group. In this investigation the fibrils were treated with selective electron stains of high mass and molecular weight in order to improve the contrast in the electron image. An electron micrograph of typical fibrils from the adductor muscle of the clam, *Venus mercenaria*, is shown here also. In this case the electron stain was phosphotungstic acid. The stain combines with the protein at regular intervals along the fiber axis as a result of a periodicity in the protein structure. The average spacing as determined from some 200 fibrils was found to be 145 Å and the maximum deviation from this value was about 10 per cent.

"If the stain is applied in suitable amount, each cross band can be seen to consist of a series of equally spaced spots, as shown herewith. The fibrils are ribbon-like and usually dry during preparation with a flat side against the supporting film. Stained spots in consecutive cross bands are aligned at definite angles to

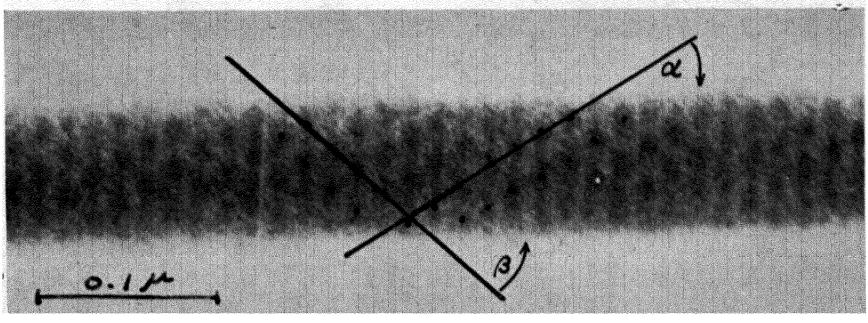
* Communicated by C. E. Hall.



Electron micrograph of collagen fibers from rat tail tendon (×37,500).



Portion of fibrils from adductor muscle of *Venus mercenaria* stained with phosphotungstic acid, showing stained cross bands (×110,000).



Courtesy C. E. Hall, Massachusetts Institute of Technology

Fibril from adductor muscle of *Venus mercenaria* showing two-dimensional lattice (×236,000).

the fiber axis as indicated by the angles α and β drawn on the electron micrograph. There is a definite relation between the angles α and β so that $\tan \alpha = \frac{3}{4} \tan \beta$. The disposition of spots in the cross bands and diagonals forms a remarkably perfect geometrical pattern which is shown diagrammatically in the plate. The pattern is laterally asymmetrical. If through any spot a line is drawn parallel to the fiber axis, it passes through a series of spots spaced five bands apart. The length of the unit cell is therefore $5 \times 144 = 720$ Å, as indicated in the plate. The lateral distance between spots is constant and is equal to about 193 Å.

"Earlier observations on the same material stained with osmic acid showed cross bands which were 360 Å apart in the fiber axis direction. Apparently in the case of osmic acid, the stain reacts with groups spaced one-half the fundamental axis period apart.

"Concurrent with the electron microscope study R. S. Bear has investigated the small angle x-ray diffractions from the same muscles. The x-ray pattern consists of a series of diffractions on the meridian and two row lines, one on either side of the meridian. From the layer line positions Bear concluded that the fundamental fiber axis period is 725 Å. The diffraction orders on the meridian are strong and their indices are multiples of five out to the 40th. This indicates a sub-period equal to one-fifth the fundamental period, or 145 Å. Thus the dimension of the fundamental period and the sub-period as obtained from x-ray diffraction data are in perfect agreement with those obtained from the electron micrographs.

"The distance between the row lines in the x-ray diagram indicates a lateral spacing of 325 Å, which does not correspond within experimental error to any distance measured in the electron micrographs. This lateral distance is undoubtedly related to the 193 Å lateral distance in the plate. A clarification of this aspect of the analysis is expected from further studies now in progress. In general the x-ray and electron microscope results are in remarkably good agreement; the discrepancy in the lateral period serves to emphasize the value of obtaining both types of information in a structural analysis of this nature."

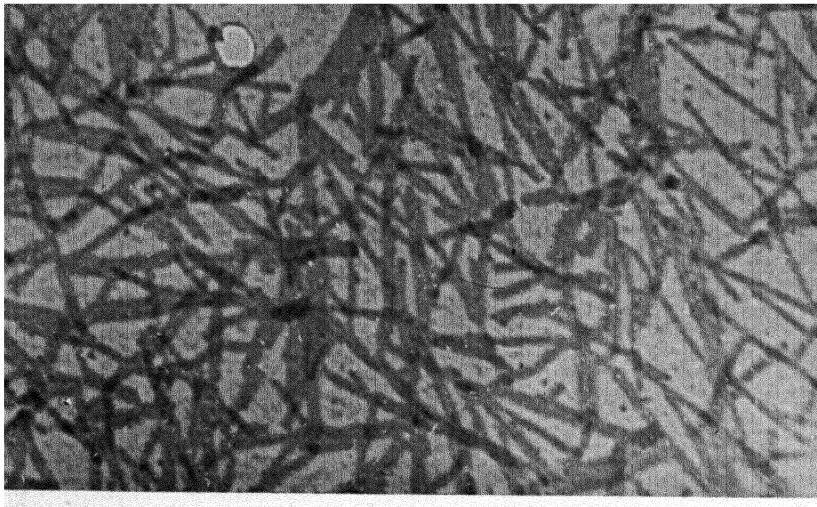
Application to Medicine

The electron microscope is undoubtedly destined to play an important role in medicine. Already a few research groups have undertaken systematic investigation of various medical problems. Naturally this work cannot be speeded up in its preliminary stages because the electron microscope reveals so many details which are entirely new that many pictures have to be taken under varying circumstances before even the most experienced worker can attempt to give a convincing interpretation. In the early stages of the application, pictures were taken of disease agents, many of which are below the range of optical microscopes. Even in the case of those which are visible in ordinary microscopes many new details of structure are made visible. It is not beyond the realm of probability that we may soon be able to make convincing studies of the life history of these minute individuals which serve such an important function in the human body, for good or ill.

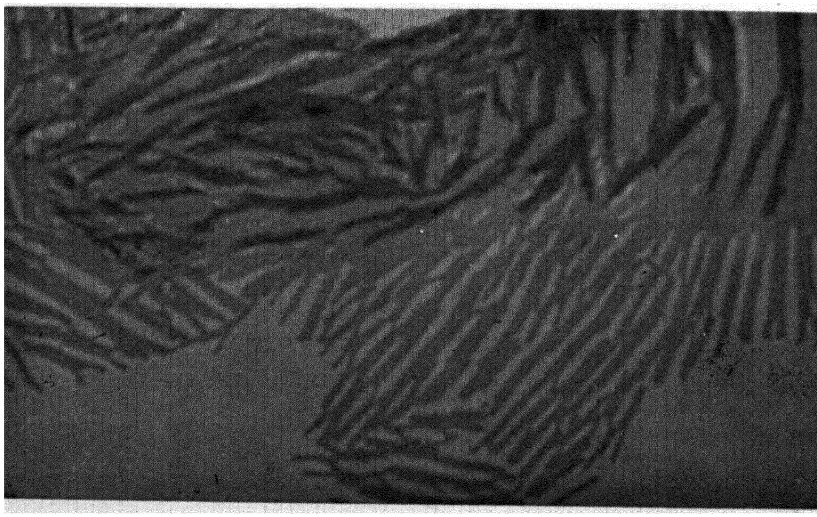
The earliest systematic work in this field in America was that undertaken at the RCA Laboratories,* first under L. Marton, and later, under James Hillier, in coöperation with W. M. Stanley and T. F. Anderson of the Rockefeller Institute for Medical Research and Stuart Mudd of the School of Medicine of the University of Pennsylvania. Recently the two latter investigators have been coöperating in Philadelphia, as Anderson is attached to the Johnson Foundation for Medical Physics at the University of Pennsylvania. Electron micrographs of a few bacteria were taken at Toronto when the work was begun there, but during the war years systematic medical investigations have yielded precedence to problems relating directly to the war.

"New possibilities for the study of the structure of bacteria, rickettsias, viruses, phage and of fine structure in tissue have been opened up by the electron microscope" (Mudd and Anderson).

*After the first few pictures of bacteria were taken by Dr. L. Marton at the RCA Laboratories, the RCA furnished the funds to the National Research Council for a Committee on Biological Applications of the Electron Microscope. This comprised about 17 specialists who worked according to a pre-arranged calendar at the RCA Laboratories with Dr. T. F. Anderson, the RCA Fellow on the Electron Microscope, National Research Council, 1940-42.



Tobacco mosaic (old preparation) (×50,000).



Courtesy RCA Laboratories

Tobacco mosaic (fresh preparation) (×50,000).

Already enough progress has been made in this field to enable us to classify the lines of future progress that have opened up. These may be listed as follows:

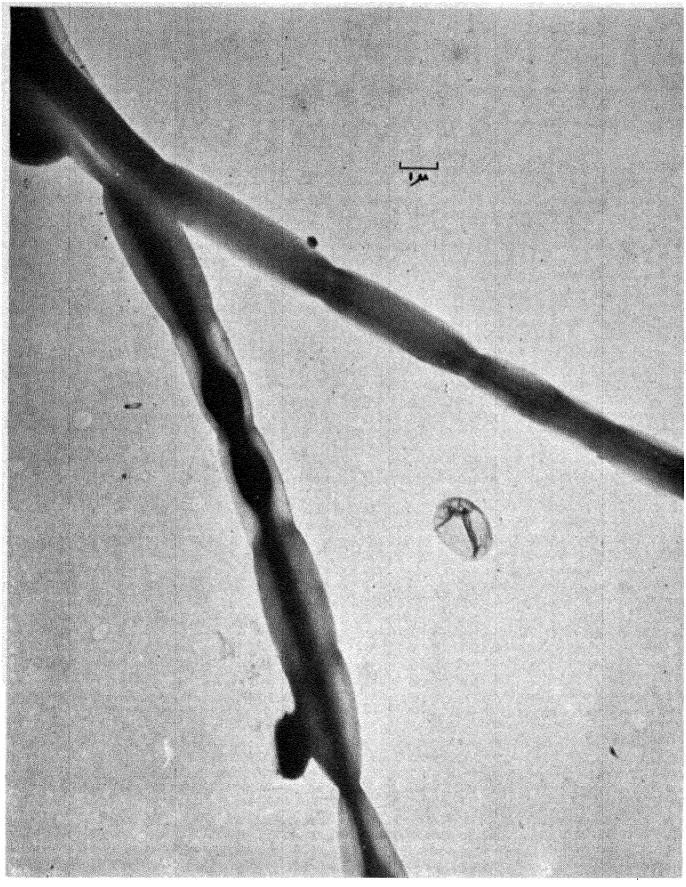
(a) The morphology of disease agents of various types.
(b) The interaction between disease agents and antibodies.
(c) The life history of a bacterium.
(d) The seat of biological chemical reactions induced by or in bacteria.
(e) Microtome sections.

There is great promise that, in time, sections may be cut thin enough by a microtome to be used as objects in the electron microscope. Special methods of staining also indicate future usefulness in this field.

Morphological

Size and Shape. The first new feature is that the electron microscope reveals the size and shape of individual disease agents not resolvable by the optical microscope. Stanley and Anderson have made a very complete study of the tobacco masaic virus. They point out that the limits of the small entity known as a virus have been sought by various methods—ultrafiltration through collodion membranes, microphotography with ultraviolet light using quartz or fluorite lenses, fluorescent microscopy, and special staining techniques—but for the very small specimens of virus the judgment of size (and shape) is dependent on more indirect evidence, such as rate of sedimentation (in the ultracentrifuge), diffusion, double refraction of a flowing stream containing the virus in suspension, viscosity of suspensions and x-rays. Most of the latter methods had been developed for work on colloidal solutions.

As a result of these various methods the tobacco mosaic virus was considered to be of a rod-like form about 12 mμ in diameter and 400 mμ long; a molecular weight of 40×10^6 was deduced, also from these experiments. Stanley and Anderson found from electron micrographs that the predominant unit in the suspension was rod-like, with a diameter of 15 mμ and a length of 280 mμ.



Courtesy Dr. Stuart Mudd

Bacillus anthracis (×4,800).

This is very good evidence of a continuity in measurement from the range of the ordinary microscope down to that of the electron microscope; it also indicates that the virus has not suffered any great change in being mounted in the vacuum chamber of the electron microscope.

Stanley and Anderson state as their considered opinion: "Although excellent micrographs of bacteria have been obtained by means of this apparatus and have proved of value in supplementing information already available, it would appear that the electron microscope will be of greatest value in the microscopy of objects having sizes between 5 and 250 mμ, a range not covered by the light microscope and one in which practically all viruses

have been found to fall. The electron microscope offers the possibility of securing micrographs of individual virus particles and thus of establishing their sizes and shapes with some precision. It should also be possible to determine the extent of the variation in the size and shape of a given virus and even perhaps learn something of the mechanism by means of which a virus particle is duplicated within the host and of the nature of the difference between strains of a given virus."

The Cell Wall and Flagella. Dr. Stuart Mudd and his coworkers have laid considerable stress on what electron micrographs show with regard to the cell wall. Their general conclusion is that bacteria possess a definite cell wall of substantial structure; this wall is in a sense independent of the protoplasmic contents which seem to be contained in a separate protoplasmic membrane. As a result of observation on *β-hemolytic streptococci* (Lancefield's Group A) they state that "taken together, the phenomena shown would seem very definitely to indicate that streptococcal cells do possess rigid outer membranes whose continuity accounts for the grouping in chains and which are differentiated from the inner protoplasm." Again as a result of photographs of *Bacillus subtilis*, *B.megatherium* and *B.anthracis*, they state that "these possess walls that are definite, solid morphological structures. An inner protoplasm may shrink away from this wall, or escape following injury, leaving the cell wall as a 'ghost,' which has essentially the shape of the intact cell. The flagella of the *B.subtilis* are continuous with the cell wall: the spores appear to be very dense, rigid bodies." Such micrographs as those of the pneumococcus (taken at Toronto), show very clearly the existence of a thick capsule about the central cell.

Structure in the Protoplasmic Contents. Micrographs of the tubercule bacillus taken at Toronto and other places give indication of dense spherical bodies in the protoplasmic contents of the cells. On page 286 are two micrographs of single cells of M.tuberculosis from the same medium, one perceptibly smaller than the other. In the larger bacillus four very distinct granular bodies are present, while in the smaller there are four corresponding centres of cloudiness, as though denser granular bodies were



Courtesy University of Toronto

Pneumococcus (×67,000) taken from the peritoneal cavity of a dead mouse.



Courtesy University of Toronto

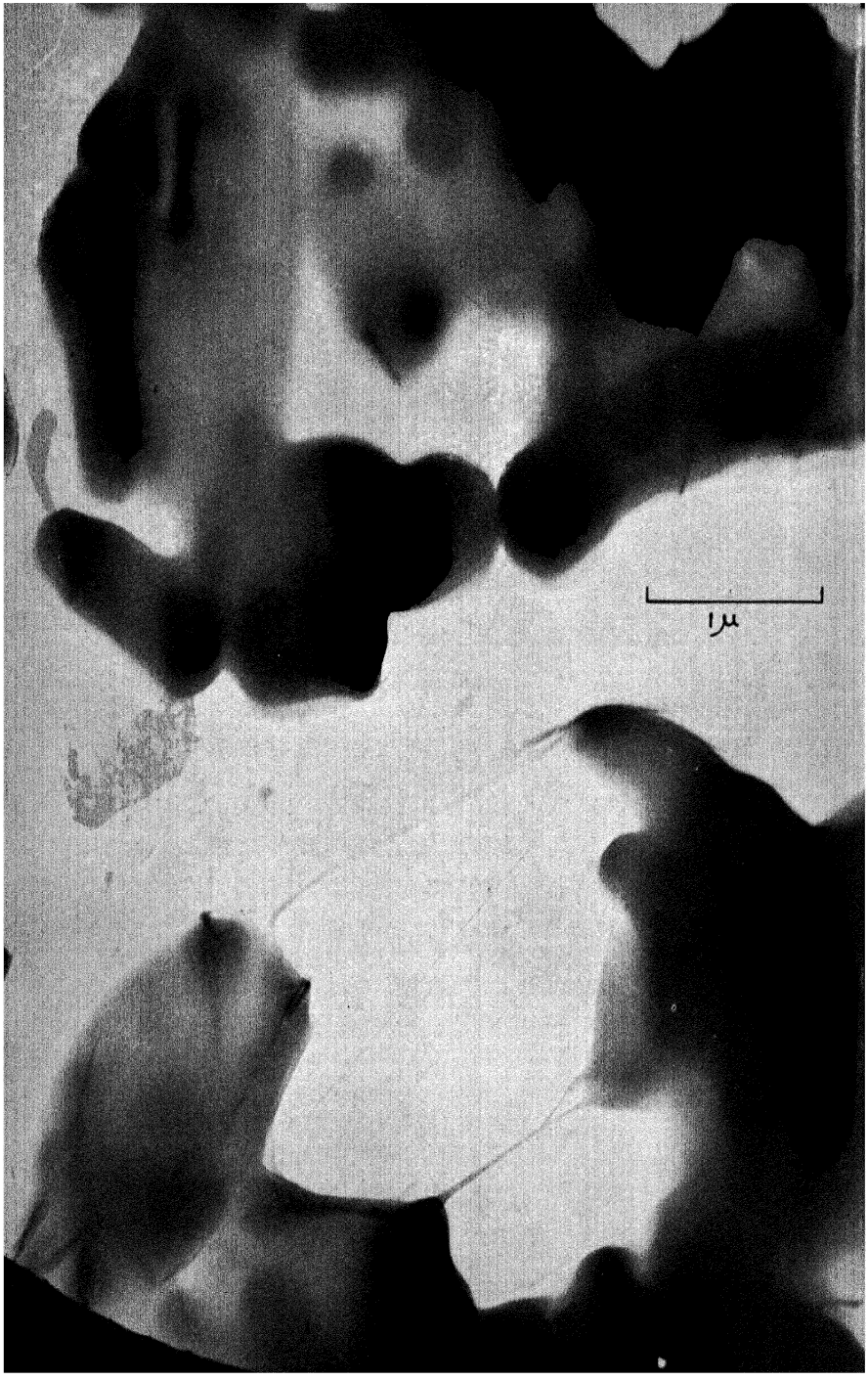
Pus cell with pneumococcus.

in process of formation. These may be examples of young and old germs.

Dr. Mudd and his colleagues have taken micrographs of the cells of *Mycobacterium tuberculosis* (hominis) and find that the cell wall appears to be very delicate. There were many granules in the field, a large number apparently adhering to the cell wall. "The thirteen largest of the black granules seen within the protoplasm range from 70 to 230 mμ in diameter." These granules have been recorded many times previously but no satisfactory interpretation has as yet been established.

The plate on page 238 "shows cells of *Vibrio schuylkiliensis*. Definite circumscribed granules are again seen within the protoplasm. The nineteen most definite of these range in diameter from 90 mμ to 230 mμ. In addition to having discrete granules, the whole bacterial protoplasm appears to be either finely or relatively coarsely granular; this appearance is in our experience rare and may be a coagulation artefact due to drying or to the electronic bombardment. The protoplasm is obviously shrunken away from the relatively 'transparent' cell wall in various cells."

Dr. Mudd concludes that "granules in bacterial protoplasm have been variously interpreted as nuclei or nuclear equivalents, reserve food material, reproductive elements, or otherwise, with-



Courtesy Dr. Stuart Mudd

Corynebacterium diphtheriae and Tellurium (×29,700).

out any of these interpretations having become established. The electron microscope shows fine structure within bacteria with clarity and detail not hitherto possible, and, when coördinated with cultural and cytologic procedures should contribute to eventual understanding of these structures."

It cannot be emphasized too strongly that electron micrographs alone will not solve everything about these small structures. Cooperative research in all bacteriological fields will be necessary.

As an example of similar morphological results in the coccus type of bacteria we may quote from the investigation of Knaysi and Mudd. "The cell of *Staphylococcus flavocyaneus* (page 250) contains one or more granules which have solubilities similar to nucleo-proteins and which often appear constricted or in pairs. In very young, actively growing cells, the granules demonstrable at high voltages are reduced in size and there is evidence that the nuclear material is then partially in solution. A strain of *Neisseria meningitidis* also shows granules which are insoluble in hot water and which are likely to be of nuclear nature.

"On the other hand, the cells of strains of *Neisseria gonorrhoeae*, *Staphylococcus aureus*, and *Streptococcus pyogenes*, strains 1048 M and C203M, appear homogeneous at all voltages" (*i.e.*, show no contrast even with electrons of high velocity).

Drs. Knaysi and Mudd here conclude that the results with the coccus cells "support the view that different bacteria may contain nuclear material in different states, and that the state of the nuclear material may change with the development of the cell."

Dr. Anderson and investigators at the Hospital of the Rockefeller Institute for Medical Research, New York, found "remarkable regularity in the morphology of the elementary body of vaccinia. The virus bodies apparently have internal structure and some sort of limiting membrane." Plates on page 280 show a micrograph of small-pox virus taken at Toronto.

Finally we may refer to the investigations of this group on bacteria of spirochete type. They reach the following conclusions:

"Electron micrographs of the Nichols-Hough, Kroo and Reiter cultured strains of *Treponema pallidum*, of treponemes of the virulent Nichols-Hough strain from a rabbit syphiloma, and of cultured strains of *Treponema macrodentium* and *Treponema microdentium* are presented and the morphology of the treponemal cells described.

"A delicate cell wall or periplast encloses the inner protoplasm of treponemata; this periplast may connect adjoining cells until transverse cell division is completed; thereafter it may extend beyond the cell protoplasm as a terminal filament. No evidence of a differentiated axial filament within the protoplasm is found.

"Flagella, often in groups of four, are found along the sides or near the ends of the cells of T. *pallidium* and T. *macrodentium*.

"Dense granules, 40 to 90 mμ in diameter are often found within the spirochetal protoplasm.

"Irregularly spheroidal, dense bodies, 150 to 500 mμ in diameter, are often found attached to the spirochetal cell, frequently near the end; such a dense body may be in close apposition to the outside of the spirochetal cell wall or may be connected to it by a short stalk. The evidence concerning these bodies seems to support the interpretation that they are asexual reproductive bodies."

Interaction between Bacteria and Antibodies

Electron micrographs have been used to give evidence of the nature of the interaction between bacteria and their environment: two examples of this will be given: (1) the action of antiserum on tobacco mosaic virus and (2) the action of bacteriophage.

Anderson and Stanley (in a coöperative investigation with the RCA Laboratories and the Department of Animal and Plant Pathology of the Rockefeller Institute for Medical Research, Princeton) have investigated the action of various substances on tobacco mosaic virus and report the following:

"Electron micrographs of tobacco mosaic virus deposited on a collodion film show that the molecules are about 280 mμ long and about 15 mμ wide.

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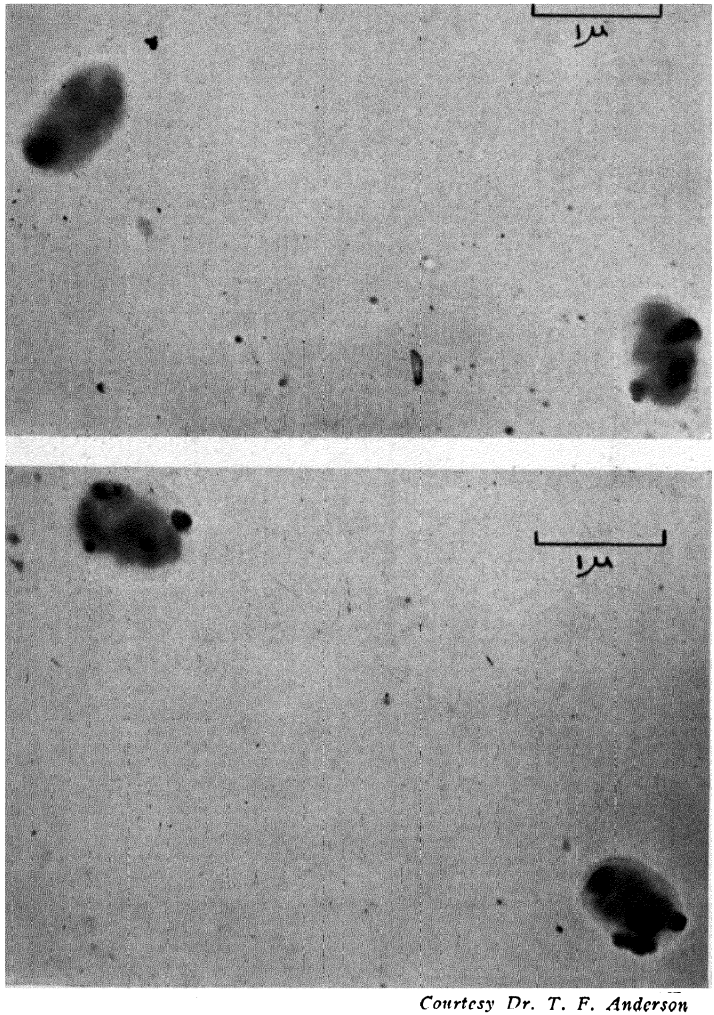
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Courtesy University of Toronto

Rickettsia (typhus) (×13,000). Apparently crystals are formed at edges of bacillu



Courtesy Dr. T. F. Anderson

Rickettsia-marine typhus (×16,000).

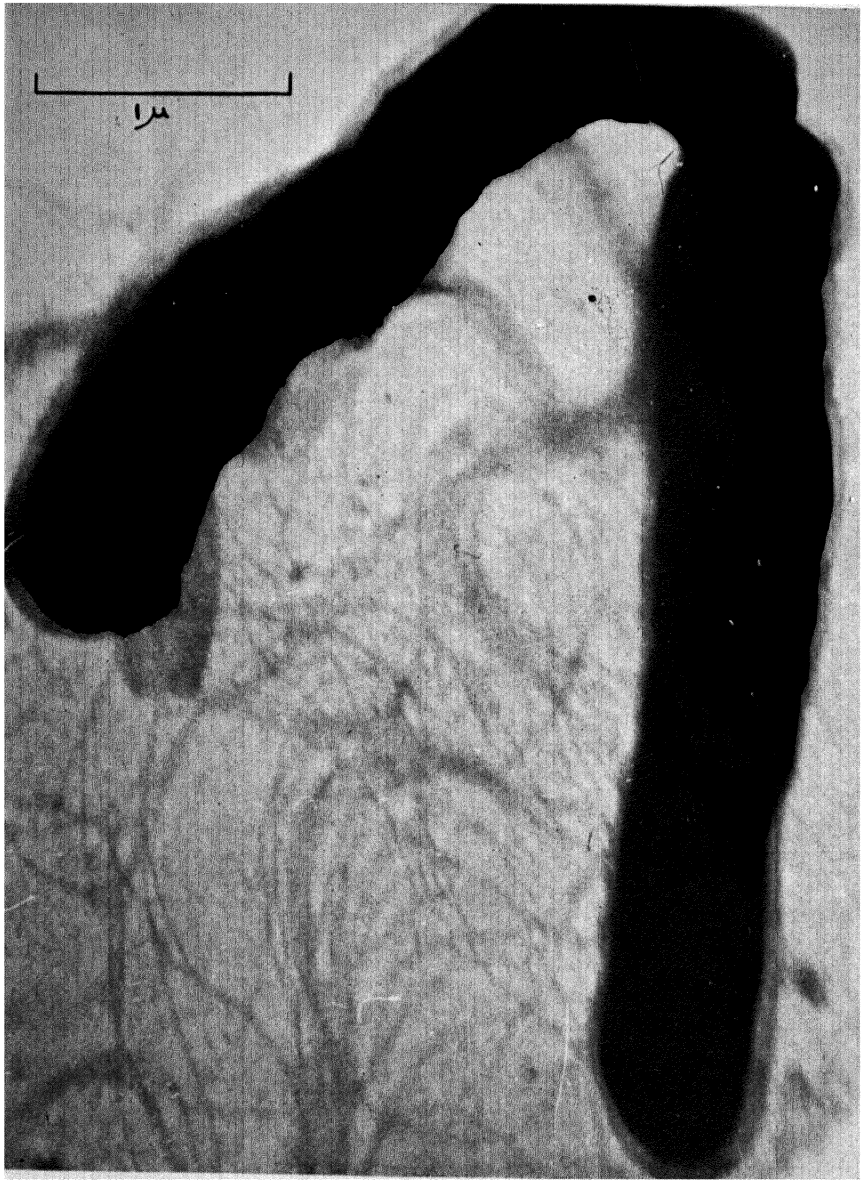
"Micrographs of a mixture of virus and normal rabbit serum show virus particles of normal size and indicate little or no absorption of particles from normal serum onto the virus molecules. Similar results were obtained with mixtures of tobacco mosaic virus with antisera to tomato bushy stunt, potato latent mosaic, and tobacco ring spot viruses.

"A mixture of tobacco mosaic virus and tobacco mosaic virus antiserum from rabbits, when dried on a collodion film an hour after mixing and examined by means of the electron microscope, shows particles about 60 mμ wide, about 300 mμ long, and having fuzzy profiles. The increase in particle width and the fuzzy appearance are regarded as indicating that the ends of asymmetrically shaped molecules from the serum react specifically with the antigen molecules. No reaction between anti-tobacco mosaic virus serum and bushy stunt virus was demonstrable.

"When the mixture of antigen and antiserum is applied to a collodion film several hours after mixing, an irregular framework of thickened antigen molecules may be seen. It is this framework which makes up the antigen-antiserum precipitate. The results demonstrate the usefulness of the electron microscope and of a large and distinctively shaped antigen such as tobacco mosaic virus in the study of the antigen-antibody reaction."

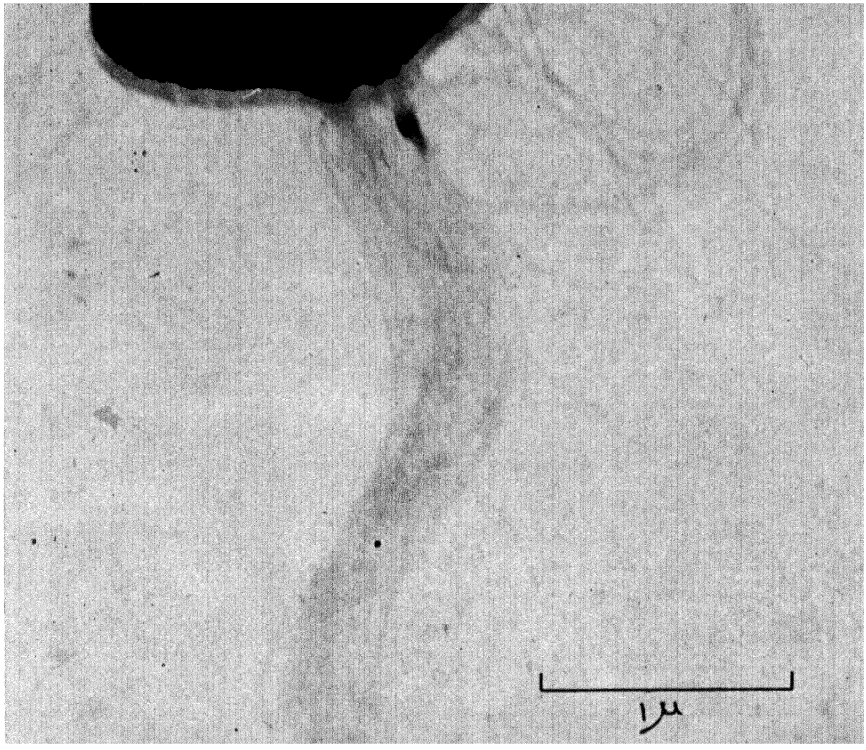
Luria and Anderson (in a coöperative investigation with the Bacteriological Research Laboratories of the Department of Surgery of Columbia University and the Research Laboratories of the Radio Corporation of America at Camden) have investigated the action of bacteriophages.

"Bacteriophages, or bacterial viruses, are a group of viruses reproducing in the presence of living bacterial cells. Bacteriophages are particulate, and convincing evidence exists that (1) one particle of phage is sufficient to originate the lysis of a bacterial cell; in the lysis, a variable number of new phage particles (an average of 100 or more) are liberated per cell; (2) the elementary particles of each phage strain seem to have a characteristic particle size as determined by any one of various indirect



Courtesy University of Michigan

Bacillus Novy (×34,200).

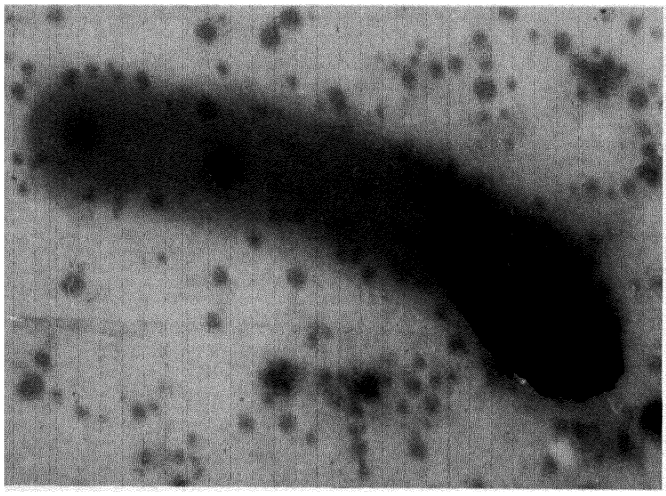


Courtesy University of Michiga

Bacillus Novy (×34,200). Continuation from end of previous pressure.

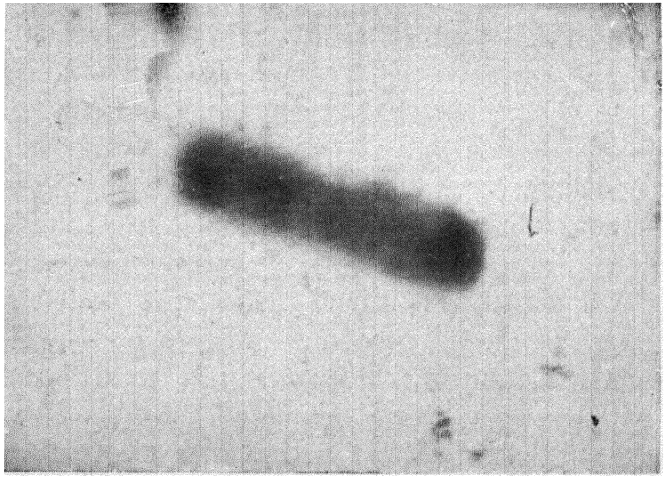
methods of investigation (ultrafiltration, radiosensitivity, diffusion), and diameters ranging from 10 to 100 mμ have been obtained for the various strains, depending on the method of investigation, although diffusion experiments occasionally yield still smaller values."

The results are reported as follows. With bacteriophage anti-coli PC the micrographs show "the constant presence of particles of extremely constant and characteristic aspect. They consist of a round "head," and a much thinner "tail," which gives them a peculiar sperm-like appearance. The "head" is not homogeneous but shows an internal structure consisting of a pattern of granules, distinguished by their higher electron scattering power. Deviations from the usual symmetrical internal pattern may be due to varying orientation of the particles or to other factors as yet unknown. The diameter of the head appears to be about 80 mμ; the tail is about 130 mμ long.



Courtesy University of Toronto

Tuberculosis bacillus (×31,400).



Courtesy University of Toronto

Tuberculosis bacillus (×26,400).
These two are from the same culture.

"When allowed to stand a few minutes in the presence of sensitive bacterial cells of *Escherichia coli*, PC, the particles described above are readily adsorbed. They appear to stick to the bacteria either by the head or by the tail. Other conditions remaining constant, the number of particles adsorbed on a bacterium increases with the time of contact, although it is difficult at the present time to differentiate between adsorption and reproduction of the particles on the cell wall. By allowing the phage to stay in contact with bacteria for a time of the order of the minimum time of lysis (21 minutes for PC phage, Delbrück and Luria) it is possible to observe bacterial cells extensively damaged, surrounded by a very large number of particles, probably newly formed."

Similar observations were made using bacteriophage anti-coli P28 and B—anti-staphylococcus 3K.

This is undoubtedly a very important field of research.

The Life History of a Bacterium

There is great hope that the electron microscope will enable us to trace the life history of various forms of bacteria, both in their undisturbed state and after they have been attacked by various drugs which have recently been applied so successfully. There is very little doubt that variations in the appearance of the protoplasmic contents of the cells and even the variations observed in the size of these cells will be found to depend on the life history of the organism.

The Seat of Biological Chemical Reactions induced by or in Bacteria; Special Staining Technique

We shall quote from a paper by Morton and Anderson (Department of Bacteriology, University of Pennsylvania, School of Medicine, Philadelphia and the RCA Laboratories, Camden, N. J.).

"Since the beginning of the science of bacteriology, investigators have pursued the study of the chemical reactions brought about by bacteria. As a result there has accumulated a tremendous mass of knowledge concerning the types of reactions in-

duced by bacteria, and the particular reactions which characterize various species. However, in all this work it has not been shown definitely whether the reactions in question take place exclusively on the cell surface, as some investigators maintain, or inside the cell, or both.

"With a powerful new tool, the electron microscope, now available, it was thought desirable to attempt to determine the site of some chemical reaction brought about by a bacterial cell. Since the electron microscope detects variations in density, such a reaction should involve as products large particles or crystals resolvable with the microscope; *i.e.*, the particles must have diameters of at least 50 Å (5 mμ). Another possibility would be to select for study reactions which involve substances which are capable of adsorbing particles or substances such as large protein molecules, organic compounds, or inorganic salts, any of which would give rise to a region of high density within or upon the cell. The addition of material to a suspension would, however, give rise to the possibility of the production of artefacts. We have consequently chosen for initial study a reaction of the first type, one brought about by an organism in a medium on which it produces an insoluble substance.

"The reaction chosen for study was discovered in 1900 by Klett. He observed that many microorganisms, including the diphtheria bacillus, when grown in or upon culture media containing tellurite or selenite salts, reduce them to the free metals. Conradi and Troch proposed a medium containing a tellurite salt for an aid in the diagnosis of *Corynebacterium diphtheriae*, because on this medium the colonies of this organism have a characteristic black color due to the reduced tellurium, and because the medium exerts a selective bacteriostatic effect, allowing the diphtheria bacillus to grow but inhibiting certain other microorganisms. Although Klett observed gray particles inside and outside the cells of *Bacillus anthracis* grown on tellurite media, it is not known where the reaction occurs in the case of C. *diphtheriae*.

"We have obtained micrographs with the electron microscope of cells from diphtherial colonies growing on blood ex-

tract agar and on potassium tellurite chocolate agar. The plate on Plate 278 shows unstained cells of C. *diphtheriae* from blood extract agar. The polar granules appear as black circles, while the remainder of the cell is light gray. Since, as previously mentioned, electron micrographs reveal differences in densities, this is to be interpreted as indicating that the polar granules are spheres or possibly plates of high density, while the remainder of the cell is of a relatively low density, in the dry state.

"Plates (not here) are of unstained cells grown on potassium tellurite chocolate agar. Inside the cells, and in addition to the polar granules, are seen minute needle-like crystals of high density. If these crystals are actually tellurium metal they should dissolve in the presence of an oxidizing agent such as bromine. To test this point, a drop of bromine water was added to 1 cc of a suspension of cells from black colonies on potassium tellurite chocolate agar. The black color of the mass of cells immediately disappeared: likewise, the needles were no longer observed in electron micrographs of cells so treated. Thus it appears highly probable that the black color is due to tellurium metal which exists, at least in part, in the needle-like forms shown in the pictures.

"More important than the identification of the crystals is the location of the site of the reduction of the tellurite. In a few exceptional cases crystals actually penetrated from inside outwards beyond the cell boundary, possibly during the drying of the preparation. In other cases the crystals distort the cell outline without penetrating. In no cases were crystals observed to lie wholly outside the cells. Since the majority of the crystals are contained wholly within the cells, it is to be inferred that the tellurite or tellurous ion is able to diffuse through the cell wall and is there reduced to tellurium metal which is precipitated inside the cells (see Plate, page 278).

"Similar crystals have been observed within cells of C. *xerosis* grown on tellurite chocolate agar."

Another application of tracing the chemical action is found in the development of special staining technique devised to show structural outlines more clearly. Mudd and Anderson report

on the effects of heavy-metal salts on individual bacterial cells. The plates, pages 157 and 158, gives an example of this work.

"The two pictures of *Vibrio comma* show the normal cells of the cholera vibrio and the cells after brief exposure to a lead salt. The last is particularly interesting because it illustrates the mechanism of injurious action. Evidently the salt diffuses through the cell wall, combines with the protoplasmic membrane, showing momentarily a dark line of lead compound; then the injured protoplasm begins to exude from the cell.

"The physical basis of contrast and image formation in electron micrography is considered in relation to the possibility of recording selective chemical effects on cell components. A technology of selective microchemical analysis, equivalent to differential staining, is suggested as practicable in electron micrography.

"Electron pictures of bacteria after exposure to salts of heavy metals have shown the bacterial inner protoplasm, but not the cell walls, to be selectively darkened; shrinkage, coagulation, or escape of protoplasm from the injured cells may result and are recorded in the electron micrographs.

"Recording of the action of germicidal agents on individual bacterial cells is indicated as one promising field of application of microchemical analysis with the aid of the electron microscope."

Microtome Sections

The first question asked by the medical investigators interested in the study of various abnormal growths is, "What is the prospect of using the electron microscope with thin sections such as made by a microtome?" The experimental difficulties are due to the fact that electron streams given by the ordinary accelerating fields (40 to 60 kilovolts) cannot penetrate sections as thick as the thinnest of those given by an ordinary microtome. If higher-velocity electrons are used they may penetrate everything and show little contrast. For 60 kv, sections should be less than 0.25μ in thickness, preferably 0.1μ.

Some progress has been made toward producing much thinner sections by A. G. Richards and co-workers (at the Zoological Laboratory, University of Pennsylvania). They have succeeded in producing sections 0.1μ thick and have published micrographs of striated muscle of the cockroach.

Stereoscopic Photography with the Electron Microscope

Everyone is more or less familiar with stereoptican views and their power to present to our vision a three-dimensional view of objects—in other words, their power to give the impression of depth to a picture. This, of course, presupposes that objects are in focus for our eyes for a considerable depth; any one object appears to be distinctly behind or in front of other objects in the picture. In everyday vision our eyes show the same power of "depth of focus"; one can look at an audience and see rows and rows of persons quite distinctly.

The focussing power of the electron microscope resembles that of the camera and the eye: objects are in focus for a relatively great distance, one behind another. Consequently, stereoscopic pairs of pictures can be taken of specimens in three dimensions by this microscope and viewed by means of the stereoscope in the ordinary way. This procedure is impossible with the ordinary high-power light microscope because it has extremely small depth of focus. Relatively speaking, if our eyes had a small depth of focus, we should have only one row of persons in an audience in focus; persons in all the other rows would be out of focus and therefore blurred and indistinguishable.

The making of stereoscopic pictures with the electron microscope is simple in conception, but requires considerable practice in accomplishment. After a picture is taken, the object is tilted through a small angle and a second picture of the same field is taken in the second position. These two pictures are used in the ordinary manner to give a stereoscopic view of the specimen. A typical pair of stereoscopic pictures is shown in the upper plate on page 232. These are pictures of carbon particles which have collected on a fine rubber fiber. Air laden with the carbon

particles was blown gently past the fiber. It is interesting to note the manner in which the particles build up one upon another.

A special object holder cartridge, designed by Hillier, is used

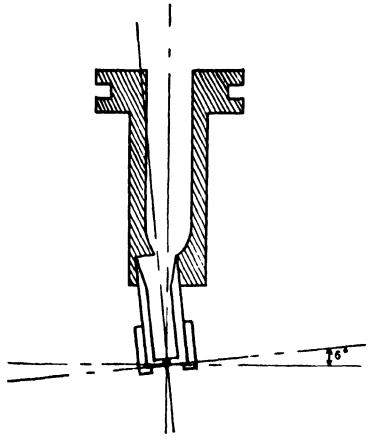


FIG. 124. The special object holder used for securing stereoscopic photographs in the electron microscope.

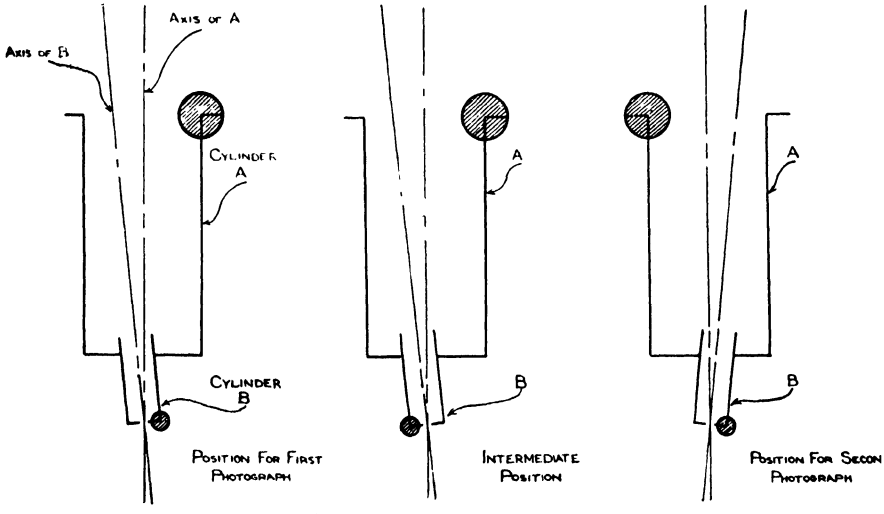
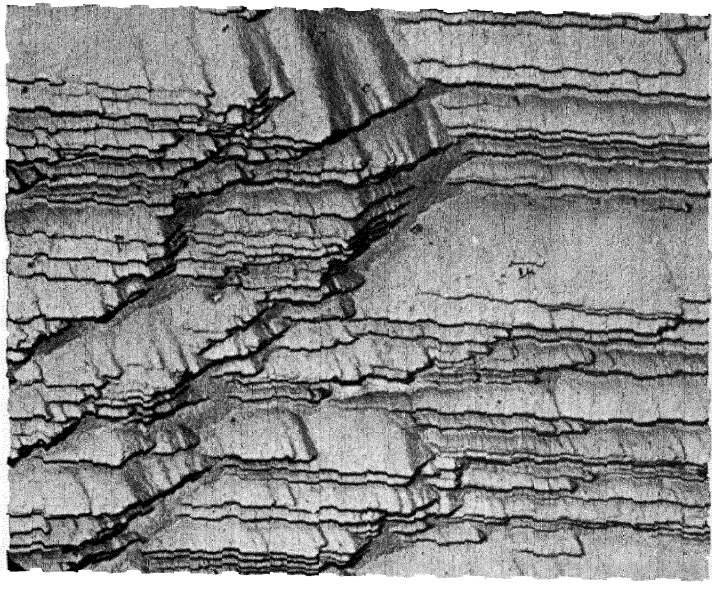


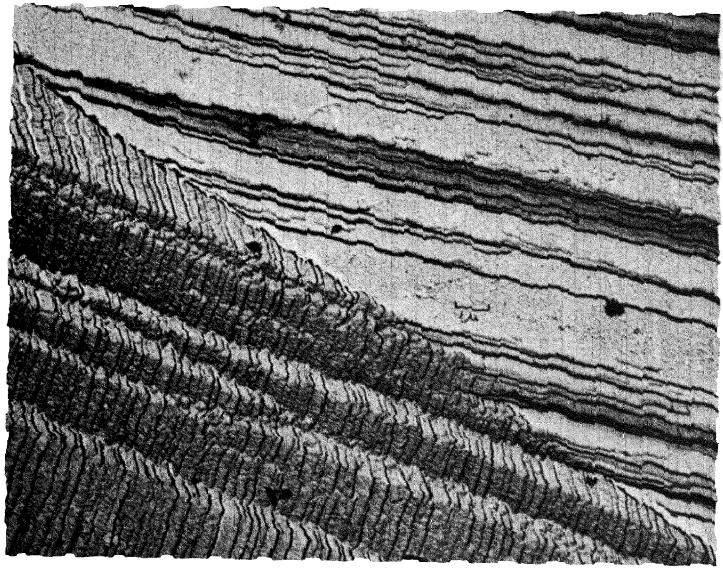
FIG. 125. Schematic drawings used to explain the use of the special object holder when obtaining a stereoscopic view with the electron microscope.

to secure these photographs, Fig. 124. The cartridge is composed of two cylinders, with the axis of the small one at an angle of 6° to that of the large one. The axis of the large cylinder is parallel to that of the microscope when the picture is being taken.



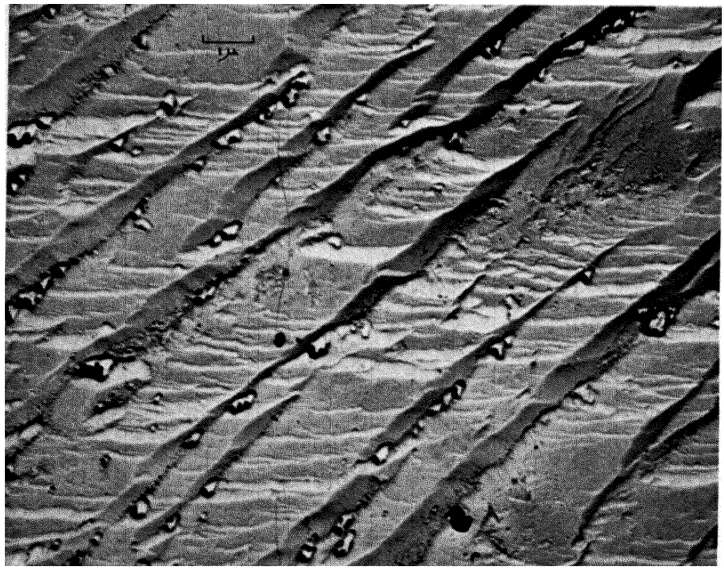
Courtesy Dow Chemical Co.

Crystallographic etch attack in a Mg-Al alloy. Polystyrene-silica replica (×4,500).



Courtesy Dow Chemical Co.

Twin boundary after crystallographic etch attack in Mg-Al alloy. Polystyrene-silica replica. (×4,500).



Courtesy Dow Chemical Co.

Surface of an etched quartz crystal. Calystyrene-silica replica (×6,900).

The object holder, which is a mesh of fine wire, is situated under a small metal cap at the end of the cartridge.

The working of the holder in taking stereoscopic views is shown in Fig. 125. Let it be assumed that a first photograph has been taken with the two cylinders marked A and B in the position indicated by the dots. After the first exposure of a chosen field has been taken, the holder is removed from the microscope and B is rotated through 180° to its intermediate position relative to A. The cartridge is then rotated through 180° as a unit until the cylinders occupy the final positions as shown in the third figure. The holder is returned to the microscope in this position and a second photograph is taken of the same field. By this procedure the object is tilted through 12° and the relative position of the object with respect to the beam is unaltered. Twelve degrees is the approximate angle subtended by the distance between normal human eyes at a distance of 25 cm from the eyes. This method of tilting the object by two rotations is necessary because it is unsatisfactory, mechanically, to attempt to

tilt the object directly, although such a direct tilting process would serve just as well if it could be done easily and accurately.

The hole in the lower end of the cylinder B has a diameter of 0.5 mm and it leaves 12 openings in the mesh uncovered to the electron beam. The operator can easily examine the 12 openings and with the aid of a map of the field can rediscover the particular field to be photographed the second time.

Surface Replicas

When microscopists came to the problem of obtaining a highly magnified view of the surface of an opaque substance, such as a metal, they had to develop a new method of illuminating the surface from above. In this way microphotography was applied to the study of etched surfaces of pure metals and alloys. The limitation as to resolving power due to the wave length of the light used was, of course, present also in this case. With the development of the electron microscope the question soon suggested itself, "Can this new instrument be applied to the surfaces of opaque materials?"

Taking the cue from microphotographic practice, various methods of trying to learn something of the detail of these surfaces by making use of electrons reflected from them have been attempted. The difficulties of interpretation of the results, inherent in all these methods, led to the suggestion of the use of replicas, *i.e.*, thin films to which the fine markings or defects of the metal surface can be transferred. For example, a solution of formvar may be poured on the surface so as to cover it with a thin skin when the solvent evaporates. The formvar penetrates all surface crevices and when the film sets it can be pulled off the metal surface. The film will be plain on one side and on the other will bear the contours which are the "negative" of those on the metal surface. The thickness of the film is such that the electrons penetrate the film, but differences in thickness would bring about differences in the blackening of the photographic plate.

The modern study of thin films goes back to the fundamental work of Langmuir at the General Electric Research Laboratory (Schenectady); Dr. Schaefer of this laboratory is a pioneer in the

production of surface replicas. Earliest suggestions of the application to the electron microscope are those of Mahl (oxide films on aluminum surfaces), and Schaefer and Harker (plastic films, *e.g.*, formvar).

At first only one film was produced. No matter how the film was applied to the surface, it had to be removed. This was done in various ways, *e.g.*, by stripping the film from the surface with the aid of a razor blade to pry it up at the start, or by dissolving away the original specimen in some solvent which did not attack the material of the film. Such a replica of course gave a surface which was a *negative* of the original surface.

It soon developed that positives provided a more satisfying object to photograph. These positives have been produced in several ways, two of which will be described.

(1) That of Zworykin and Ramberg (RCA) utilizes a negative of silver and a positive of collodion. "A thick layer of metal, e.g., silver, is evaporated in a vacuum chamber onto the surface to be studied. This metal film is stripped mechanically from the surface, yielding a negative metal replica of the surface. If too thin for the stripping process, the metal film may be reinforced by electroplating. Next, a dilute solution of the final replica material, e.g., a 1 per cent solution of collodion in amyl acetate, is flowed over the negative replica surface and is permitted to dry. Then the metal replica with the adhering thin film is immersed for several hours in a suitable solvent for the metal—2 to 3 normal nitric acid in the case of silver. At the end of this period the metal is completely dissolved and, after washing in distilled water, the residual positive replica film may be placed on the fine-mesh screen (*e.g.*, 250-mesh copper or stainless steel) which acts as the object support in the electron microscope."

(2) That of Heidenreich and Peck (Dow Chemical Company) utilizes instead a negative of polystyrene, and a positive of silica. "The technique developed is a two-step process in which the first replica is of molded polystyrene and the second, thin—film replica is evaporated silica. The formation of this molded plastic replica is simple in principle, consisting of simply making and impression of the original surface in a material which can be

readily handled in the remainder of the process. The second replica which is observed in the microscope was discovered by chance since the property which makes it suitable for this purpose was not predicted. This property is the high mobility of silica condensing from the vapor both upon polystyrene and upon the silica in its vitreous state. The silica films are themselves structureless to the electron microscope and electron diffraction shows them to be amorphous. They are easily removed from the styrene by the use of ethyl bromide solvent and washed free of any residual styrene."

The above workers found that the silica replicas gave very much clearer and more highly resolved pictures of surface inequalities than did such substances as formvar.

EPILOGUE

In any account of the state of progress in any scientific field where developments are so rapid as has been true of the electron microscope it is difficult to tell where to stop. Any stopping place is sure to be abrupt and every reader may be inclined to ask of an author, "Why did you stop there?"

A large number of these instruments are now in use and a new science of electron optics has come into being. One very substantial sign of the permanence of this development is the organization of a very active group of electron microscope specialists as the Electron Microscope Society of America.

This society was organized in November, 1942, as an Associate Society of both the American Institute of Physics and the American Association for the Advancement of Science. It was organized on the recommendation of a committee of three—Professor G. L. Clark (Illinois), Professor O. S. Duffendack (Michigan) and Dr. L. A. Matheson (Dow Chemical Company).

The first official meeting of the new society was held at Columbia University, January, 1944, and a second meeting in Chicago in the autumn of the same year. The Secretary-Treasurer of the Society is Dr. M. C. Banca, RCA Mfg. Co., Camden, New Jersey.

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A Bibliography of Electron Microscopy*

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I. BOOKS

Brüche, E. and Scherzer, O. *Geometrische Elektronenoptik.* J Springer, Berlin, 1934.

Marton, L. *Le microscope electronique et ses applications;* suivi de: **Henriot, E.,** *L'optique electronique des systèmes centrés.* Revue d'Optique, Paris, 1935.

Starks, H. J. H. The electron microscope. *Reports on progress in Physics*, **2**, 283-291. Physical Society of London, 1935.

Brüche, E. and Henneberg, W. Geometrische Elektronenoptik. *Ergebnisse der exakten Naturwissenschaften* **15**, 365–421. J. Springer, Berlin, 1936.

Busch, H. and Brüche, E. *Beitrage zur Elektronenoptik.* J. A. Barth, Leipzig, 1937.

Klemperer, O. *Electron Optics.* Cambridge University Press, Cambridge, 1939.

Myers, L. M. *Electron Optics.* Chapman and Hall, London, 1939.

Ardenne, M. von. *Elektronen Übermikroskopie.* J. Springer, Berlin, 1940.

AEG Forschungs-Institut. *Jahrbuch.* Sonderheft: Übermikroskop. J. Springer, Berlin, 1940.

Klemperer, O. Electron microscopes of high magnification. *Reports on progress in physics* **7**, 107-129. Physical Society of London, 1940.

Borries, B. von and Ruska, E. Microscopy of high resolving power by means of fast electrons. *Ergebnisse der exakten Naturwissenschaften* **19**, 237-322. J. Springer, Berlin, 1941.

Brüche, E. and Recknagel, A. *Elektronengeräte, Prinzipien und Systematik.* J. Springer, Berlin, 1941.

Anderson, T. F. The study of colloids with the electron microscope. In Kraemer, E. O., ed. *Advances in colloid science*, Vol. 1., pp. 353-390. Interscience, New York, 1942.

Burton, E. F. and Kohl, W. H. *The electron microscope.* Reinhold, New York, 1942.

Marton, L. The electron microscope in biology. *Annual review of biochemistry*, Vol. 12, pp. 587-614. Annual Reviews Inc., Stanford University.

Ramsauer, C. (editor), *Das freie Elektron in Physik und Technik.* J. Springer, Berlin, 1940.

Ramsauer, C. *Elektronenmikroskopie. Bericht über Arbeiten des A E-G-Forschungs-Instituts 1930 bis 1941.* Second edition. J. Springer, Berlin, 1942.

Hawley, G. G. *Seeing the invisible*, Knopf, New York, 1945.

II. EMISSION MICROSCOPY

Brüche, E. and Johannson, H. Cinematography of oxide cathodes using the electron microscope. *Ann. d. Physik* **15**, 145–166 (1932).

* Journal of Applied Physics, **14**, 522–531 (1943) and **15**, 575–579 (1944).

Brüche, E. and Johannson, H. New investigations of cathodes with the electron microscope. *Phys. Zeits.* 33, 898-899 (1932).

Knoll, M., Houtermanns, F. G., and Schulze, E. Emission distribution at glow cathodes with the magnetic microscope. *Zeits. f. Physik* 78, 340-362 (1932).

Brüche, E. and Johannson, H. Crystallographic investigations with the electron microscope. *Zeits. f. techn. Physik* 14, 487–488 (1933).

Brüche, E. Electron microscopical reproduction by means of photoelectric electrons. *Zeits. f. Physik* 86, 448–450 (1933).

Johannson, H. Electron optical immersion objective. *Ann. d. Physik* 18, 385–413 (1933).

Knoll, M. and Lubszinsky, G. Electron microscope pictures with secondary electrons. *Phys. Zeits.* 34, 671–674 (1933).

Richter, E. F. Electron microscope observations of the migration of emitting material on oxide cathodes. *Zeits. f. Physik* 86, 697–709 (1933).

Ruska, E. Formation of pictures of surfaces irradiated by electrons in the electron microscope. *Zeits. f. Physik* 83, 492–497 (1933).

Benham, W. E. Demonstration of low voltage electron microscope using electrostatic focusing. *J. E. E., J.* 75, 388–390 (1934).

Calbick, C. J. and Davisson, C. J. Electron microscope, *Phys. Rev.* 45, 764 (1934).

Brüche, E. The electron microscope and its application in particular to the study of thin layers on metals. *Kolloid Zeits.* 69, 389–394 (1934).

Brüche, E. and Knecht, W. Electron-optical observation of the transformation of iron at temperatures between 500° and 1000°C. *Zeits. f. techn. Physik* 15, 461–463 (1934).

Brüche, E. and Knecht, W. Note on attaining high resolution with the electron optical immersion objective. *Zeits. f. Physik* 92, 462–466 (1934).

Johannson, H. Immersion objective for electron microscopes. *Ann. d. Physik* 21, 274–284 (1934).

Knecht, W. Combined light and electron microscope. *Ann. d. Physik* 20, 161-182 (1934).

Brüche, E. The electron-optical image of structures and its interpretation in the emission ratio of barium-nickel cathodes. *Zeits. f. Physik* 98, 77-107 (1935).

Brüche, E. and Knecht, W. Electron-optical observation of the α-γ transformation in iron. *Zeits. f. techn. Physik* 16, 95–98 (1935).

Brüche, E. and Mahl, H. On the emission image of thoriated tungsten and thoriated molybdenum. I. *Zeits. f. techn. Physik* 16, 623–627 (1935).

Dosse, J. and Knoll, M. Electron distribution at focus of x-ray tubes with electron microscope. *Arch. f. Elektrot.* 29, 729-730 (1935).

Kemnitz, G., Knoll, M., and Walcher, W. Electron concentration by concave hot cathode surfaces with the electron microscope. *Zeits. f. Physik* 96, 612–619 (1935).

Mahl, H. Electron-optical image formation with emitting wires. *Zeits. f. Physik* 98, 321–322 (1935).

Schenk, D. Distribution of emission over a crystalline heated cathode. *Ann. d. Physik* 23, 240–254 (1935).

Behne, R. Characteristics of the immersion objective for image formation with fast electrons. *Ann. d. Physik* 26, 372–384 (1936).

Behne, R. Contribution to the knowledge of the electron-optical immersion lens, II. *Zeits. f. Physik* 101, 521–526 (1936).

Behne, R. Photography of foils with the electron-optical immersion objective. *Ann. d. Physik* 26, 385–397 (1936).

Brüche, E. and Mahl, H. On the emission image of thoriated tungsten and thoriated molybdenum, II. *Zeits. f. techn. Physik* 17, 81–84 (1936).

Brüche, E. and Mahl, H. On the emission image of thoriated tungsten and thoriated molybdenum, III. *Zeits. f. techn. Physik* 17, 262–266 (1936).

Heinze, W. and Wagener, S. The processes in the activation of oxide cathodes. *Zeits. f. techn. Physik* 17, 645–653 (1936).

Mahl, H. Influence of oxygen on glow emission investigated by the electron microscope. *Zeits. f. techn. Physik* 17, 653–656 (1936).

Burgers, W. G. Direct observation of structural changes at high temperature with the electron microscope. *Zeits. f. Metallkunde* **29**, 250–251 (1937).

Burgers, W. G. and van Amstel, J. J. A. P. Electron-optical observation of metal surfaces. Parts I and II. *Physica* **4**, 5-22 (1937).

McMillen, J. H. and Scott, G. H. A magnetic electron microscope of simple design. *Rev. Sci. Instruments* **8**, 288–290 (1937).

Burgers, W. G. and van Amstel, J. J. A. P. Electron-optical observation of the transition of α- into β- zirconium. *Nature* **141**, 330 (1938).

Mahl, H. Electron-optical examination of electronic and ionic emissions of wires. *Zeits. f. Physik* **108**, 771–776 (1938).

Meschter, E. An electron microscope for studying thermal and secondary electron emission. *Rev. Sci. Instruments* **9**, 12–15 (1938).

Scott, G. H. and Packer, D. M. The localization of minerals in animal tissues by the electron microscope. *Science* **89**, 227–228 (1938).

Scott, G. H. and Packer, D. M. The electron microscope as an analytical tool for the localization of minerals in biological tissues. *Anat. Rec.* **74**, 17–30 (1939).

Scott, G. H. and Packer, D. M. An electron microscope study of magnesium and calcium in striated muscle. *Anat. Rec.* **74**, 31–46 (1939).

Scott, G. H. An electron microscope study of calcium and magnesium in smooth muscle. *Proc. Soc. Exp. Biol. and Med.* **45**, 30–31 (1940).

Fox, G. W. and Bailey, F. M. Measurement of cathode emission by use of the electron microscope. *Phys. Rev.* **59**, 174–178 (1941).

Boersch, H. Increase of resolution of the emission electron microscope. *Naturwiss.* **30**, 120 (1942).

Boersch, H. Improvement of the resolving power of the emission electron microscope. *Zeits. f. techn. Physik* **23**, 129–130 (1942).

Brüche, E. The limit of resolution of the emission electron microscope. *Kolloid Zeits.* **100**, 192–206 (1942).

Dosse, J. and Müller, H. O. The resolving power of the emission electron microscope. *Zeits. f. Physik* **119**, 415–422 (1942).

Huber, H. and Wagener, S. X-ray and electron optical study of crystal structure of alkali earth oxide mixtures. *Zeits. f. techn. Physik* **23**, 1–12 (1942).

Mahl, H. An experiment in emission microscopy with electrostatic lenses. *Zeits. f. techn. Physik* **23**, 117–119 (1942).

Mecklenburg, W. Electrostatic emission electron microscope. *Zeits. f. Physik* **120**, 21–30 (1942).

Recknagel, A. Resolving power of the emission electron microscope. *Zeits. f. Physik* **120**, 331-362 (1943).

III. TRANSMISSION TYPE MICROSCOPE

Knoll, M. and Ruska, E. The electron microscope, *Zeits. f. Physik* **78**, 318–339 (1932).

Marton, L. and Nuyens, M. Geometrical electron optics. *Wis-en Natuurkundig Tijdschrift* **6**, 159–170 (1933).

Marton, L. Electron microscopy of biological objects. I. *Bull. Acad. Roy. de Belg., Cl. des Sciences* **20**, 439–446 (1934).

Ruska, E. Advances in building and performance of the magnetic electron microscope. *Zeits. f. Physik* **87**, 580–602 (1934).

Ruska, E. Magnetic objective for the electron microscope. *Zeits. f. Physik* **89**, 90–128 (1934).

Sommerfeld, A. and Scherzer, O. Description of an electron microscope. *Münich. Med. Wochenschr.* **81**, 1859–1860 (1934).

Knoll, M. The electron microscope. *Zeits. f. Ärztl. Fortbild.* **32**, 644–678 (1935).

Marton, L. Electron microscopy of biological objects. III. *Bull. Acad. Roy. de Belg., Cl. des Sciences* **21**, 606–617 (1935).

Fritz, R. The electron microscope. *Rev. Gen. des Sciences* **47**, 338–342 (1936).

Martin, L. C., Whelpton, R. V., and Parnum, D. H. A new electron microscope. *Journ. Sci. Instruments* **14**, 14–24 (1937).

Borries, B. von and Ruska, E. Development and present efficiency of the electron microscope. *Wiss. Veröffent. Siemens-Werke* **17**, 99–106 (1938).

Nuttall, A. K. An electron microscope for high magnifications. *Metro-Vickers Gaz.* **17**, 256–259 (1938).

Ardenne, M. von. An electrostatic high voltage lens of short focal distance. *Naturwiss.* **27**, 614–615 (1939).

Ardenne, M. von. Single crystal fluorescent screens for supermicroscopy. *Zeits. f. techn. Physik* **20**, 235–239 (1939).

Borries, B. von and Ruska, E. Development and efficiency of the Siemens ultramicroscope. *Z. f. wiss. Mikroskop.* **56**, 317–333 (1939).

Borries, B. von and Ruska, E. An electron supermicroscope for research institutes. *Naturwiss.* **27**, 577–582 (1939).

Brüche, E. and Haagen, E. A new simple supermicroscope and its application to bacteriology. *Naturwiss.* **27**, 809–811 (1939).

Burton, E. F., Hillier, J., and Prebus, A. A report on the development of the electron microscope at Toronto. *Phys. Rev.* **56**, 1171–1172 (1939).

Mahl, H. The electrostatic electron microscope. *Zeits. f. techn. Physik* **20**, 316–317 (1939).

Martin, L. C. The electron microscope. *J. Roy, Microscop. Soc.* **59**, 217-231 (1939).

Martin, L. C., Parnum, D. H., and Speak, G. S. Report on experimental work on the development of the electron microscope. *J. Roy. Microscop. Soc.* **59**, 203–216 (1939).

Prebus, A. and Hillier, J. Construction of a magnetic electron microscope of high resolving power. *Canad. J. of Research* **17**, 49–63 (1939).

Ardenne, M. von. Results of a new electron ultramicroscope. *Naturwiss.* **28**, 113–127 (1940).

Ardenne, M. von. Stereo-ultramicroscopy with the universal electron microscope. *Naturwiss.* **28**, 248–252 (1940).

Ardenne, M. von. A universal electron microscope for bright field, dark field and stereoscopic use. *Zeits. f. Physik* **115**, 339-368 (1940).

Borries, B. von, and Ruska, E. The effect of the potential difference on the supermicroscopic image. *Zeits. f. Physik* **116**, 249–256 (1940).

Kinder, E. and Pendzich, A. A new magnetic lens of short focal length. *Jahrbuch AEG-Forsch., Sonderheft, Übermikroskop* **7**, 23–26 (1940).

Kinder, E. A new high-potential ultramicroscope. *Zeits. f. techn. Physik* **21**, 222–223 (1940).

Mahl, H. The electrostatic electron ultramicroscope. *Jahrbuch AEG-Forsch., Sonderheft, Übermikroskop* **7**, 43–56 (1940).

Martin, L. C. Ultraviolet and electron microscopy. *Nature* **146**, 288–292 (1940).

Marton, L. A new electron microscope. *Phys. Rev.* **58**, 57–60 (1940).

O'Daniel, H. and Radczewski, O. E. Electron microscopy and electron-diffraction study on the same specimen of highly dispersed minerals. *Naturwiss.* **28**, 628–630 (1940).

Marton, L., Banca, M. C., and Bender, J. F. A new electron microscope. *RCA Rev.* **5**, 232–243 (1940).

Prebus, A. Improved pole piece construction of the objective lens of a magnetic electron microscope. *Canad. J. of Research* **18**, 175–177 (1940).

Ruska, E. Electron diffraction patterns recorded in the supermicroscope. *Wiss. Veröffentl. Siemens-Werke, Werkstoff-Sonderheft* 372–379 (1940).

Ruska, H. Supermicroscopy. *Ned. T. Natuurk.* **7**, 179–191 (1940).

Zworykin, V. K. An electron microscope for the research laboratory. *Science* **92**, 51–53 (1940).

Ardenne, M. von. Electron ultramicroscopy with accessory probe for production of electron diffraction diagrams with very limited field of view. *Zeits. f. Physik* **117**, 515–523 (1941).

Hillier, J. and Vance, A. W. Recent developments in the electron microscope. *Proc. Inst. Radio Engrs.* **29**, 167–176 (1941).

Hughes, A. L. The magnetic electron lens. *Amer. J. Phys.* **9**, 204–207 (1941).

Vance, A. W. Stable power supplies for electron microscopes. *RCA Rev.* **5**, 293–300 (1941).

Zworykin, V. K., Hillier, J., and Vance, A. W. An electron microscope for practical laboratory service. *Trans. Am. Inst. Elect. Engrs.* **60**, 157-162 (1941).

Ardenne, M. von, Schiebold, E., and Gunther, F. Fine beam electron diffraction in the universal electron microscope. *Zeits. f. Physik.* **119**, 352–365 (1942).

Ardenne, M. von. Further development of the universal electron microscope. *Phys. Zeits.* **43**, 11-15 (1942).

Bachman, C. H. and Ramo, S. Simplified electron microscope. *Phys. Rec.* **62**, 494 (1942).

Hillier, J., Baker, R. F., and Zworykin, V. K. A diffraction adapter for the electron microscope. *J. of Applied Physics* **13**, 571–577 (1942).

Bachman, C. H. and Ramo, S. Electrostatic electron microscopy. I. *J. of Applied Physics* **14**, 8–18 (1943).

Bachman, C. H. and Ramo, S. Electrostatic electron microscopy. II. *J. of Applied Physics* **14**, 69–76 (1943).

Bachman, C. H. and Ramo, S. Electrostatic electron microscopy. III. *J. of Applied Physics* **14**, 155–160 (1943).

Bachman, C. H. Simplified electron microscopy. *Electronics* **16**, 78–81; 195–200 (1943).

Zworykin, V. K. Electron microscope: most recent research tool. *Electronics* **16**, 146–147; 254 (1943).

Ardenne, M. von. The resolving power of photographic emulsions for electron beams. *Zeits. f. Physik* **114**, 379 (1939).

Borries, B. von and Ruska, E. Technique of the Siemens electron microscope. *Siemens Zeits.* **20**, 217–227 (1940).

Ardenne, M. von. Electron microscopy at elevated temperatures with the universal electron microscope. *Kolloid Zeits.* **97**, 257–272 (1941).

Brüche, E. The development of the electron microscope with electrostatic lenses. *V.D.I.* **85**, 221–229 (1941).

Lundgren, E. H. The electron microscope. *Tek Tid. Uppl. A-c, Kemi* **71**, 20–35 (1941).

Boersch, H. Construction and possibilities of application of an electron microscopical arrangement. *Phys. Zeits.* **43**, 515–520 (1942).

Frey, F. Orientation marks on sample holders for the electron microscope. *Zeits. f. techn. Physik* **23**, 82 (1942).

Frey, F. Application and construction of a plateholder for two exposures with the Siemens electron microscope in its normal construction. *Zeits. f. techn. Physik* **23**, 176–177 (1942).

Matthias, A. Remark on the origin of the electron microscope. *Phys. Zeits.* **43**, 129–130 (1942).

Prebus, A. The electron microscope. *Ohio State Univ. Eng. Exp. Sta. News* **14**, 3 (1942).

Ruska, E. Taking of photographs with the electron microscope at high pressures. *Kolloid Zeits.* **100**, 212–219 (1942).

Ardenne, M. von. Electron microcinematography with the universal electron microscope. *Zeits. f. Physik* **120**, 397–412 (1943).

Brüche, E. The development of the electron microscope. *Phys. Zeits.* **44**, 176–180 (1943).

Mahl, H. and Pendzich, A. Electron-mirror microscope: a new electron microscope. *Zeits. f. techn. Physik* **24**, 38–42 (1943).

Rüdenberg, R. The early history of the electron microscope. *J. Appl. Phys.* **14**, 434–436 (1943).

Zworykin, V. K. and Hillier, J. A compact high resolving power electron microscope. *J. Appl. Phys.* **14**, 658–673 (1943).

IV. OPTICS OF THE TRANSMISSION TYPE ELECTRON MICROSCOPE

Davisson, C. J. and Calbick, C. J. Electron lenses. *Phys. Rev.* **38**, 585 (1931).
Davisson, C. J., and Calbick, C. J. Electron lenses. *Phys. Rev.* **42**, 580 (1932).
Knoll, M. and Ruska, E. Contribution to geometrical electron optics. I. *Ann d. Physik* [5] **12**, 607–640 (1932).
Knoll, M. and Ruska, E. Contribution to geometrical electron optics. II. *Ann. d. Physik* [5] **12**, 461–661 (1932).
Ruska, E. and Knoll, M. The magnetic concentration coil for fast electrons. I. *Zeits. f. techn. Physik* **12**, 389–399 (1932).
Ruska, E. and Knoll, M. The magnetic concentration coil for fast electrons. II. *Zeits. f. techn. Physik* **12**, 448 (1932).
Henneberg, W. The resolving power of the electron microscope for transparent objects. *Zeits. f. Instrumentenk.* **55**, 300-305 (1935).
Stabenov, G. Magnetic electron lens without image rotation. *Zeits. f. Physik* **96**, 612–619 (1935).
Boersch, H. On the primary and secondary image in the electron microscope. I. *Ann. d. Physik* **26**, 631-644 (1936).
Boersch, H. On the primary and secondary image in the electron microscope. II. *Ann. d. Physik* **27**, 75-80 (1936).
Marton, L. Some considerations concerning the resolving power in electron microscopy. *Physica* **3**, 959-967 (1936).
Ardenne, M. von. The image errors of the electron microscope caused by electron scattering in the object and their relation to each other. *Zeits. f. Physik* **11**, 152–157 (1938).
Ardenne, M. von. Limits of the resolving power of the electron microscope. *Zeits. f. Physik* **108**, 308–338 (1938).
Borries, B. von, and Ruska, E. Image formation in the supermicroscope. *Zeits. f techn. Physik* **19**, 402–407 (1938).
Ardenne, M. von. Chromatic errors in the electron microscope. *Zeits. f. Physik* **113**, 257–259 (1939).
Ardenne, M. von. Intensity and resolving power of the electron microscope. *Zeits. f. Physik* **112**, 744–753 (1939).
Borries, B. von, and Ruska, E. Properties of the supermicroscopical image formation *Naturwiss.* **27**, 281–287 (1939).
Borries, B. von, and Ruska, E. The resolving power of the supermicroscope. *Zeits f. techn. Physik* **20**, 225–235 (1939).
Hillier, J. Effects of chromatic error on the electron microscope. *Canad. J. of Research*, **A17**, 64–69 (1939).
Ardenne, M. von. Determination of the resolving power of electron microscope. *Phys. Zeits.* **42**, 72-74 (1941).
Ardenne, M. von. Testing of short focus electron lens. *Zeits. f. Physik* **117**, 602–611 (1941).
Hillier, J. A discussion of the fundamental limit of an electron microscope. *Phys. Rev.* **60**, 743–745 (1941).
Marton, L. and Schiff, L. I. Determination of object thickness in electron microscopy. *J. of Applied Physics* **12**, 759–765 (1941).
Ruska, E. Lenses for electron microscopes of high resolving power. *Archiv. f. Elektrotechn.* **36**, 431–454 (1942).
Schiff, L. I. Ultimate resolving power of the electron microscope. *Phys. Rev.* **61**, 721–722 (1942).
Savchenko, F. The dependence of certain optical parameters on the electric and geometric parameters of electric immersion lens. *Zhurnal Tekhnicheskoi Fiziki, Moscow*, **9**, 2211–2219 (1939).
Borries, B. von and Ruska, E. The influence of electron interferences on the image formation of crystals in the electron microscope. *Naturwiss.* **28**, 366–367 (1940).
Dosse, J. Theoretical and experimental investigation of electron emitters. *Zeits. f. Physik* **115**, 530–556 (1940).

Ardenne, M. von. Supplement to the papers: "The testing of electron lenses of short focal length" and "a 200-kv universal electron microscope with an object screen." *Zeits. f. Physik* **118**, 384–388 (1941).

Glaser, W. and Lammel, E. For which electromagnetic fields is Newton's image equation valid? *Ann. d. Physik* **40**, 367–384 (1941).

Glaser, W. On the distribution of the ampere-turn density of a given magnetic field produced by a cylindrical coil. *Zeits. f. Physik* **118**, 264–268 (1941).

Ardenne, M. von. The faithful representation of the structures close to the limit of resolution with the light microscope and the electron microscope. *Kolloid Zeits.* **100**, 206–211 (1942).

Bertram, S. J. Calculation of axially symmetric fields. *J. Appl. Phys.* **13**, 496–502 (1942).

Boersch, H. The influence of crystal lattice interferences on the imaging in the electron microscope. *Zeits. f. Physik* **118**, 706–713 (1942).

Copeland, P. L. Thin electrostatic lenses for electrons. *Am. J. Phys.* **10**, 236–246 (1942).

Craggs, J. D. The electrostatic focusing of high speed ion and electron beams. *J. Appl. Phys.* **13**, 772–786 (1942).

Glaser, W. Electron-optical imaging with distorted rotational symmetry. *Zeits. f. Physik* **120**, 1–15 (1942).

Boersch, H. Edge diffraction of electrons. *Phys. Zeits.* **44**, 32–38 (1943).

Boersch, H. Fresnel diffraction in the electron microscope. *Phys. Zeits.* **44**, 202-211 (1943).

Glaser, W. Image formation and resolving power of the electron microscope from the point of view of wave mechanics. *Zeits. f. Physik* **121**, 647–667 (1943).

Wendt, G. The dioptrics of electron optical instruments with arbitrarily curved optical axis. *Zeits. f. Physik* **120**, 720–741 (1943).

Marton, L. and Hutter, R. G. E. The transmission type of electron microscope and its optics. *Proc. I.R.E.* **32**, 3–12 (1944).

Marton, L. and Hutter, R. G. E. On apertures of transmission type electron microscopes using magnetic lens. *Phys. Rev.* **65**, 161–167 (1944).

Opatowski, I. Refractive index in electron optics. *Phys. Rev.* **65**, 54–55 (1944).

V. IMAGE DEFECTS

Busch, H. Calculation of the trajectory of cathode rays in electromagnetic fields of axial symmetry. *Ann. d. Physik* **81**, 974–993 (1926).

Busch, H. On the action of the concentration coil in Braun tubes. *Arch. f. Elektrot.* **18**, 583–594 (1927).

Picht, J. Theory of geometrical optics for electrons. *Ann. d. Physik* **15**, 926–964 (1932).

Glaser, W. Geometrical optics of electron rays. *Zeits. f. Physik* **80**, 451–464 (1933).

Glaser, W. Geometrical electron optics of the axial symmetrical electromagnetic field. *Zeits. f. Physik* **81**, 647–686 (1933).

Glaser, W. Optical imagery by mechanical systems and the optics of nonhomogeneous isotropic media. *Ann. d. Physik* **18**, 557–586 (1933).

Glaser, W. Theory of the electron microscope. *Zeits. f. Physik* **83**, 104–122 (1933).

Johannson, H. and Scherzer, O. Electric electron condensing lens. *Zeits. f. Physik* **80**, 183–192 (1933).

Posener, L. Theory of the electron microscope. *Zeits. f. Physik* **80**, 813–818 (1933).

Scherzer, O. Theory of electric electron condensing lenses. *Zeits. f. Physik* **80**, 193–202 (1933).

Diels, K. and Knoll, M. Proof of the aberrations of an electron lens by point imagery. *Zeits. f. techn. Physik* **16**, 621–623 (1935).

Glaser, W. Theory of image defects of an electron microscope. *Zeits. f. Physik* **97**, 171–201 (1935).

Wallauschek, R. and Bergmann, P. Theory of electron microscope using purely magnetic fields. *Zeits. f. Physik* **94**, 329–347 (1935).

Scherzer, O. On some defects of electron lenses. *Zeits. f. Physik* **101**, 593–603 (1936).
Scherzer, O. The weak electric single lens of least spherical aberration. *Zeits. f. Physik* **101**, 23–26 (1936).
Diels, K. and Wendt, G. Eight third-order aberrations of magnetic electron lenses. *Zeits. f. techn. Physik* **18**, 65–69 (1937).
Rebsch, R. and Schneider, W. Spherical aberration of weak electron lenses. *Zeits. f. Physik* **107**, 138–143 (1937).
Rogowski, W. Defects in electron images. *Arch. f. Elektrot.* **31**, 555–593 (1937).
Rebsch, R. Theoretical resolving power of the electron microscope. *Ann. d. Physik* **31**, 551–560 (1938).
Scherzer, O. The theoretically attainable resolving power of the electron microscope. *Zeits. f. Physik* **114**, 427–434 (1939).
Voit, H. Third-order electron-optical abberations. *Zeits. f. Instrumentenk.* **59**, 71–82 (1939).
Glaser, W. Chromatic aberration in electron lenses. *Zeits. f. Physik* **116**, 56–57 (1940).
Glaser, W. On a magnetic field free from spherical aberration. *Zeit. f. Physik* **116**, 19–33 (1940).
Rebsch, W. and Glaser, W. Aperture error of electron lenses. *Zeits. f. Physik* **116**, 729–735 (1940).
Dosse, J. Optical constants of strong electron lenses. *Zeits. f. Physik* **117**, 722–753 (1941).
Dosse, J. Precise computation of unsymmetrical field form $H=H_0/1+(z/a)^2$. *Zeits. f. Physik* **117**, 316–321 (1941).
Glaser, W. Precise computation of magnetic lenses with the field form $H=H_0/1+(z/a)^2$. *Zeits. f. Physik* **117**, 285–315 (1941).
Kompfner, R. On a method of correcting the spherical error of electron lenses, especially those employed with electron microscopes. *Phil. Mag.* **32**, 410–416 (1941).
Recknagel, A. Theory of electrical electron microscope which is self-illuminating. *Zeits. f. Physik* **177**, 689–708 (1941).
Plass, G. N. Electrostatic electron lenses with a minimum of spherical aberration. *J. of Applied Physics* **13**, 49–55 (1942).
Ramberg, E. G. Variation of the axial aberrations of electron lenses with lens strength. *J. of Applied Physics* **13**, 582–594 (1942).
Ardenne, M. von. On the magnitude of the aperture defect in the electron microscope. *Zeits. f. techn. Physik* **20**, 289–290 (1939).
Dosse, J. Supplement to the paper: "Optical characteristics of strong electron lenses." *Zeits. f. Physik* **118**, 375–383 (1941).
Gobrecht, R. Experimental investigations of spherical aberration in electrostatic lenses. *Arch. f. Elektrotechn.* **35**, 672–685 (1941).
Scherzer, O. The lower limits of focal distance and of chromatic defect of magnetic electron lenses. *Zeits. f. Physik* **118**, 461–466 (1941).
Plass, G. N. Errata: Electrostatic electron lenses with a minimum of spherical aberration. *J. Appl. Phys.* **13**, 524 (1942).
Boersch, H. Secondary images in electron microscopy. *Zeits. f. Physik* **121**, 746–754 (1943).

VI. ELECTRON SPEEDS ABOVE 100 KV

Marton, L. The electron microscope in biology. *Acta Union Internat. Contre Cancer* **4**, 221–238 (1939).
Ardenne, M. von. 200-kv universal electron microscope with an object screen. *Zeits. f. Physik* **117**, 657–688 (1941).
Müller, H. O. and Ruska, E. A supermicroscope for 220-kv beam potential. *Kolloid Zeits.* **95**, 21–25 (1941).
Zworykin, V. K., Hillier, J., and Vance, A. W. A preliminary report on the development of a 300-kv magnetic electron microscope. *J. of Applied Physics* **12**, 738–742 (1941).

Ardenne, M. von. Supplement to the papers: "The testing of electron lenses of short focal length" and "A 200-kv universal electron microscope with an object screen." *Zeits. f. Physik* **118**, 384–388 (1941).

VII. DIFFERENT RELATED INSTRUMENTS

Johnson, R. P. and Shockley, W. Investigation of thermionic filaments with a simple electron microscope. *Phys. Rev.* **48**, 973 (1935).

Wehnelt, A. and Schilling, W. Electron microscope examination of the electron emission of cold metals. *Zeits. f. Physik* **98**, 286–287 (1935).

Johnson, R. P. and Shockley, W. An electron microscope for filaments: emission and adsorption by tungsten single crystals. *Phys. Rev.* **49**, 436–440 (1936).

Müller, E. W. Electron microscopical observations of field emittors. *Zeit. f. Physik* **106**, 541–550 (1937).

Ardenne, M. von. The electron scanning microscope. *Zeits. f. techn. Physik* **19**, 407–416 (1938).

Ardenne, M. von. Electron scanning microscope—theoretical fundamentals. *Zeits. f. Physik* **109**, 553–573 (1938).

Johnson, R. P. Simple electron microscopes. *J. of Applied Physics* **9**, 508-516 (1938).

Boersch, H. The electron shadow microscope. I. *Zeits. f. techn. Physik* **20**, 346–350 (1939).

Zworykin, V. K., Hillier, J., and Snyder, R. L. A scanning electron microscope. *A. S. T. M. Bull.* 117, 15–23 (1942).

Ruthemann, G. Discrete energy losses of fast electrons in solids. *Naturwiss.* **29**, 648 (1941).

Haefer, R. Field electron microscopic observations on tungsten points. *Zeits. Krist.* **104**, 1–10 (1942).

Ruthemann, G. Electron retardation at x-ray levels. *Naturwiss.* **30**, 145 (1942).

Hillier, J. On microanalysis by electrons. *Phys. Rev.* **64**, 318–319 (1943).

Müller, E. W. Resolving power of the field electron microscope. *Zeits. f. Physik* **120**, 270–282 (1943).

Müller, E. W. Velocity distribution of electrons for field emission. *Zeits. f. Physik* **120**, 261–269 (1943).

VIII. APPLICATIONS OF THE TRANSMISSION TYPE MICROSCOPE

Borries, B. von, and Ruska, E. Images of films in transmission by means of the electron microscope. *Zeits. f. Physik* **83**, 187–193 (1933).

Marton, L. The electron microscope; first attempts at its application to biology. *Ann. et Bull. de la Soc. Roy. des Sciences Med. et Nat. de Bruxelles* [5-6] **92**, 106 (1934).

Marton, L. Electron microscopy of biological objects. *Phys. Rev.* **46**, 527–528 (1934).

Marton, L. Electron microscopy of biological objects. *Nature* **133**, 911 (1934).

Borries, B. von, and Ruska, E. Electron microscope and its uses. *V. D. I.* **79**, 519–524 (1935).

Driest, E. and Müller, H. O. Electron micrographs of chitin substances. *Z. f. wiss. Mikrosk.* **52**, 53–55 (1935).

Marton, L. The electron microscope and its applications. *Rev. d'Optique* **14**, 129–145 (1935).

Marton, L. The electron microscope and its applications especially in biology. *2ème Congrès Nat. d. Sciences, Bruxelles* **2**, 928-933, 1935.

Marton, L. Electron microscopy of biological objects. II. *Bull. Acad. Roy. de Belg., Cl. des Sciences* **21**, 553-564 (1935).

Saupe, E. Use of electron microscope and diffraction in biology and pathology. *Frankfurt. Z. f. Path.* **47**, 485–516 (1935).

Krause, F. Electron-optical pictures of diatoms with the magnetic electron microscope. *Zeits. f. Physik* **102**, 417-422 (1936).

Marton, L. The electron microscope. *Rev. Microbiol. Appl.* **3**, 117–124 (1936).

Marton, L. Electron microscopy of biological objects. IV. *Bull. Acad. Roy. de Belg., Cl. des Sciences* **22**, 1336–1344 (1936).

Beischer, D. and Krause, F. Electron microscope in colloid investigations. *Naturwiss.* **25**, 825–829 (1937).

Krause, F. The electron microscope and its use in biology. *Naturwiss.* **25**, 817–825 (1937).

Luft, F. Practical uses of electron optics. *Rontgenpraxis* **9**, 384–394 (1937).

Marton, L. Electron microscopy of biological objects. V. *Bull. Acad. Roy. de Belg., Cl. des Sciences* **23**, 672–678 (1937).

Beischer, D. Determination of size of crystals in metal and metal oxide smokes by means of Röntgen- and electron-diffraction diagrams and electron photomicrographs. *Zeits. Elektrochem.* **44**, 375-385 (1938).

Borries, B. von, Ruska, E., and Ruska, H. Bacteria and virus as seen in the ultramicroscope, with introduction to technology of ultramicroscopy. *Klin. Wochenschr.* **17**, 921–925 (1938).

Borries, B. von, Ruska, E., and Ruska, H. Photographs of bacteria with the supermicroscope. *Wiss. Veröffent. Siemens-Werke* **17**, 107–111 (1938).

Borries, B. von, Ruska, E., and Ruska, H. Status of the supermicroscope. *V. D. I.* **82**, 937-941 (1938).

Eitel, W. H., Müller, H. O., and Radczewski, O. E. Examination of clay minerals with the ultramicroscope. *Ber. Deut. Keram. Ges.* **20**, 165–180 (1938).

Krause, F. Examination of viruses by the electron microscope. *Naturwiss.* **26**, 122 (1938).

Marton, L. A note on the article: "Practical uses of electron optics," by Fritz Luft. *Röntgenpraxis* **10**, 352–353 (1938).

Beischer, D. and Krause, F. The electron microscope in colloid chemistry. *Angew. Chem.* **51**, 331–334 (1938).

Ruchardt, E. New developments in electron microscopy and their results. *Münch. Med. Wochenschr.* **85**, 1832–1837 (1938).

Ardenne, M. von. Possibility of examining living substances with electron microscopes. *Zeits. f. techn. Physik* **20**, 239–242 (1939).

Frank, F. and Ruska, H. Examination of the blue structure of bird feathers with the electron microscope. *Naturwiss.* **27**, 229–230 (1939).

Friess, H. and Müller, H. O. Smokes and dusts in the electron microscope. *Gasmaske* **11**, 1–9 (1939).

Kausche, G. A., Pfankuch, E., and Ruska, H. Examination of plant viruses with the high power electron microscope. *Naturwiss.* **27**, 292–299 (1939).

Kausche, G. A. and Ruska, H. The structure of the "crystalline aggregates" of tobacco mosaic virus proteins. *Biochem. Z.* **303**, 221–230 (1939).

Kausche, G. A. and Ruska, H. Supermicroscopic investigation of the adsorption of the metal colloids on proteins. *Kolloid Zeits.* **89**, 21-26 (1939).

Krause, F. Use of the electron microscope in biology and medicine. *Arch. Exp. Zellforsch.* **22**, 668–672 (1939).

Marton, L. On the sensitivity of photographic emulsions for electrons between 50 and 100 kv. *Phys. Rev.* **56**, 290 (1939).

Müller, H. O. The supermicroscope in medicine. *Med. Klinik* **35**, 1041–1043 (1939).

Piekarski, G. and Ruska, H. Supermicroscopic pictures of bacterial flagellae. *Klin. Wochenschr.* **18**, 383–386 (1939).

Piekarski, G. and Ruska, H. Supermicroscopical investigations of bacteria with particular reference to the so-called nucleoids. *Arch. Mikrobiol.* **10**, 302–321 (1939).

Radczewski, O. E., Müller, H. O., and Eitel, W. The hydration of tricalcium aluminate. *Naturwiss.* **27**, 837–838 (1939).

Radczewski, O. E., Müller, H. O., and Eitel, W. Supermicroscopical investigation of the hydration of lime. *Zement* **28**, 693–697 (1939).

Radczewski, O. E., Müller, H. O., and Eitel, W. The hydration of tricalcium silicate. *Naturwiss.* **27**, 807 (1939).

Ruska, H. Supermicroscopic demonstration of organic structure. *Arch. Exp. Zellforsch.* **22**, 673–680 (1939).

Ruska, H., Borries, B. von, and Ruska, E. The importance of the supermicroscope in virus research. *Arch. Ges. Virusforsch.* **1**, 155 (1939).

Wolpers, C. and Ruska, H. Structural investigations of the clotting of blood. *Klin. Wochenschr.* **18**, 1077–1111 (1939).

Ardenne, M. von. Analysis of the structure of highly and very highly illuminated silver bromide grains with the universal electron microscope. *Z. Angew. Photogr.* **2**, 14–20 (1940).

Ardenne, M. von, and Beischer, D. Examination of the fine structure of high-molecular compounds with the universal electron microscope. I. The structure of β-polyoxymethylene crystals. *Zeits. f. phys. Chem.*, [B] **45**, 465–473 (1940).

Ardenne, M. von, and Beischer, D. Examination of the fine structure of high-molecular compounds with the universal electron microscope. II. The morphology of rubber and Buna. *Kautschuk* **16**, 55-60 (1940).

Ardenne, M. von, Endell, K., and Hoffmann, E. Examination of finest fractions of bentonite and cement with the universal electron microscope. *Ber. Deut. Keram. Ges.* **21**, 209–227 (1940).

Ardenne, M. von. Images of minute particles, especially of molecules, by means of the universal electron microscope. *Zeits. f. phys. Chem.* [A] **187**, 1-12 (1940).

Ardenne, M. von, and Beischer, D. Investigation of catalysts with the universal electron microscope. *Angew. Chem.* **53**, 103–107 (1940).

Ardenne, M. von, and Beischer, D. Investigation of metal oxide smokes with the universal electron microscope. *Zeits. Elektrochem.* **46**, 270–277 (1940).

Ardenne, M. von. Occurrence of black lines in electron microscope images of crystal lamellae. *Zeits. f. Physik* **116**, 736-738 (1940).

Ardenne, M. von. Stage vibrator for electron microscopes. *Kolloid Zeits.* **93**, 158-163 (1940).

Borries, B. von, and Kausche, G. A. Determination of the size and shape distribution of colloidal gold by means of the supermicroscope. *Kolloid Zeits.* **90**, 132–141 (1940).

Borries, B. von, and Ruttmann, W. Metallographic investigations of steel, cast iron, and brass by means of the supermicroscope. *Wiss. Veroffentl. Siemens-Werke, Werkstoff-Sonderheft* 342-362 (1940).

Borries, B. von. Higher resolving power at the formation of images of surfaces by the supermicroscope. *Zeits. f. Physik* **116**, 370–378 (1940).

Burton, E. F., Hillier, J., and Prebus, A. Contribution of the electron microscope to medicine. *Canad. M. A. Jour.* **42**, 116–119 (1940).

Columbian Carbon Company Research Laboratories. The particle size and shape of colloidal carbon as revealed by the electron microscope. *Columbian Colloidal Carbons* **2**, 5–53 (1940).

Eitel, W. and Schusterius, C. The determination of the efficient surfaces of clay particles with the supermicroscope. *Chem. Erde* **13**, 322–335 (1940).

Eitel, W. and Schusterius, C. The interpretation of electron microscope pictures for the determination of clay grain distribution. *Naturwiss.* **28**, 300–303 (1940).

Eitel, W. and Radczewski, O. E. The characteristics of the clay mineral montmorillonite as shown by the supermicroscope. *Naturwiss.* **28**, 397–399 (1940).

Eitel, W. and Gotthardt, E. Stereophotographic measurement of the thickness of very small crystals by electron microscope observation. *Naturwiss.* **28**, 367 (1940).

Frühbrodt, E. and Ruska, H. Research on the structure of bacteria, especially of bacterium membranes and capsules. *Arch. Mikrobiol.* **11**, 137–154 (1940).

Husemann, E. and Ruska, H. Making glycogen molecules visible. *J. Prakt. Chem.* **156**, 1–10 (1940).

Husemann, E. and Ruska, H. Making visible the molecules of *p*-iodobenzoyl-glycogen. *Naturwiss.* **28**, 534 (1940).

Jakob, A. and Mahl, H. Application of the supermicroscope in bacteriology, especially for experiments with capsules. *Jahrbuch AEG-Forsch., Sonderheft, Übermikroskop* 7, 77–87 (1940).

Jakob, A. and Mahl, H. Structure of bacteria, in particular capsulation of anarobiae by means of the electrostatic supermicroscope. *Arch. Exp. Zellforsch.* 24, 87–104 (1940).

Kausche, G. A. and Ruska, H. The identification of tobacco mosaic virus molecules in the chloroplast of virus-infected plants. *Naturwiss.* 28, 303 (1940).

Kausche, G. A. Investigations on the problem of biological characterization of phytopathogenic virus proteins. *Arch. Ges. Virusforsch.* 1, 362–372 (1940).

Kausche, G. A. The mechanism of the gold-sol reaction of the protein of tobacco mosaic and potato-X-virus. *Biol. Zentr.* 60, 179–199 (1940).

Kausche, G. A. and Ruska, H. The problem of the structure of the chloroplast. *Naturwiss.* 28, 303-304 (1940).

Kausche, G. A. Results and problems of experimental plant virus research. *Ber. Deut. Botan. Ges.* 58, 200–222 (1940).

Koch, L. and Lehmann, A. Supermicroscopical investigation of rolled aluminum surfaces. *Wiss. Veröffentl. Siemens-Werke, Werkstoff-Sonderheft*, 363-371 (1940).

Lembke, A., Ruska, H., and Christophersen, J. Comparative microscopical and supermicroscopical observations on the infective agent of tuberculosis. *Klin. Wochenschr.* 19, 217–220 (1940).

Mahl, H. Application of the supermicroscope in colloid chemistry and metallurgy. *Jahrbuch AEG-Forsch., Sonderheft. Übermikroskop* 7, 67–76 (1940).

Mahl, H. Determination of the orientation of single crystals of aluminum by means of the supermicroscope. *Metallwirtschaft* 19, 1082–1085 (1940).

Mahl, H. The electrostatic electron microscope and some applications in colloid chemistry. *Kolloid Zeits.* 91, 105–117 (1940).

Mahl, H. Metallurgical researches with the electrostatic ultramicroscope. *Zeits. f. techn. Physik* 21, 17–18 (1940).

Mahl, H. A plaster-cast method for supermicroscopical investigation of metal surfaces. *Metallwirtschaft* 19, 488–491 (1940).

Meldau, R. Fine dusts in the submicroscopic field. *V. D. I.* 84, 103–106 (1940).

Middel, V., Reichmann, R., and Kausche, G. A. Supermicroscopic investigation of the structure of bentonites. *Wiss. Veröffentl. Siemens-Werke, Werkstoff-Sonderheft* 334–341 (1940).

Pfankuch, E. and Kausche, G. A. Ultramicroscopic examination of bacteriophages. *Naturwiss.* 28, 46 (1940).

Radczewski, O. E., Müller, H. O., and Eitel, W. Supermicroscopic investigation of the beginning of precipitation of calcium carbonate from aqueous solutions. *Zentr. Mineral. Geol.* 8–19 (1940).

Ruska, H. Making visible the bacteriophage lysis in the supermicroscope. *Naturwiss.* 28, 45–46 (1940).

Ruska, E. and Müller, H. O. Progress in reproduction of electron irradiated surfaces. *Zeits. f. Physik* 116, 366–369 (1940).

Ruska, H. The structure of cellulose fibers. *Kolloid Zeits.* 92, 276–285 (1940).

Ruska, H. and Wolpers, C. The structure of "liquor-fibrin." *Klin. Wochenschr.* 19, 695 (1940).

Ruska, H. and Kretschmer, M. Supermicroscopic investigation of the degradation of cellulose fibers. *Kolloid Zeits.* 92, 163–166 (1940).

Ruska, H. and Frühbrodt, E. Supermicroscopy as a method of investigation. *Biologe* 9, 69–75 (1940).

Ruska, H. Visibility of bacteriophage cultures in the ultramicroscope. *Naturwiss.* 28, 45–46 (1940).

Trurnit, H. and Friedrich-Freksa, H. The electron-microscopical investigation of "tomato mosaic virus Dahlem 1940." *Biol. Zentr.* 60, 546–556 (1940).

Zahn, H. Experiments on the supermicroscopy of wool. *Melliand Textilberichte* 21, 505–508 (1940).

Anderson, T. F. and Stanley, W. M. A study of the reaction between the tobacco mosaic virus and its antiserum by means of the electron microscope. *J. Biol. Chem.* **139**, 339–344 (1941).

Ardenne, M. von. Electron microscopy of living tissue. *Naturwiss.* **29**, 521–523 (1941).

Ardenne, M. von, and Friedrich-Freksa, H. Germination of the spores of the bacillus vulgatus from photographs in the 200-kv universal electron microscope. *Naturwiss.* **29**, 523–528 (1941).

Barnes, R. B. and Burton, C. J. Metallic smokes as test objects in electron microscopy. *Ind. Eng. Chem.*, News Ed. **19**, 965–967 (1941).

Beischer, D. Newer methods for investigating the structure of colloidal systems. *Kolloid. Zeits.* **96**, 127–135 (1941).

Borries, B. von, and Janzen, S. Image of finely machined technical surfaces in the supermicroscope. *V. D. I.* **85**, 207–211 (1941).

Hall, C. E. and Schoen, A. L. Application of the electron microscope to the study of photographic phenomena. *J. Opt. Soc. Am.* **31**, 281–285 (1941).

Hass, G. and Kehler, H. Investigations on the electrolytically produced and annealed layers of aluminum oxide by means of electron interference and measurements in the supermicroscope. *Kolloid Zeits.* **97**, 27-35 (1941).

Hass, G. and Kehler, H. On a temperature resistant durable carrier for electron interference and electron-microscope investigations. *Kolloid Zeits.* **95**, 26–29 (1941).

Humbert, R. P. and Shaw, B. Studies of clay particles with the electron microscope. *Soil Science* **52**, 481–487 (1941).

Knoll, M. Evidence for built-up layers of iron oxide with the electron microscope. *Phys. Zeits.* **42**, 120–122 (1941).

Kregel, E. A. et al. A technique for electron-microscopic examination of encapsulated bacteria. *Science* **94**, 592 (1941).

Marton, L. The electron microscope. *J. Bact.* **41**, 397–413 (1941).

Marton, L., McBain, J. W., and Vold, R. D. Electron microscope study of curd fibres of sodium laurate. *J. Am. Chem. Soc.* **63**, 1990–1993 (1941).

Mehl, R. F. The structure and rate of formation of pearlite. *Trans. Am. Soc. Metals* **29**, 813–862 (1941).

Menke, W. Investigations of the fine structure of protoplasm with the universal electron microscope. *Protoplasma* **35**, 115 (1941).

Morton, H. E. and Anderson, T. F. Electron-microscopic studies of biological reactions. I. Reduction of potassium tellurite by Coryne-bacterium diphtheriae. *Proc. Soc. Exp. Biol. Med.* **46**, 272–276 (1941).

Mudd, S. and Anderson, T. F. Demonstration by the electron microscope of the combination of antibodies with flagellar and somatic antigens. *Journ. of Immunology* **42**, 251–266 (1941).

Mudd, S., Polevitzky, K., Anderson, T. F., and Chambers, L. A. Bacterial morphology as shown by the electron microscope. *J. Bact.* **42**, 251–264 (1941).

Mudd, S. and Lackman, D. B. Bacterial morphology as shown by the electron microscope. *J. Bact.* **41**, 415–420 (1941).

Mudd, S. The electron microscope. *Frank. Inst. J.* **231**, 496–498 (1941).

Müller, F. H. Fiber production, fiber characteristics, and molecular structure. *Phys. Zeits.* **42**, 123–129 (1941).

Schmieder, F. Electron microscopic investigation of the relation between covering quality and grain size of pigments. *Kolloid Zeits.* **95**, 29–33 (1941).

Shaw, B. T. and Humbert, R. P. Electron micrographs of clay minerals. *Soil. Sci. Soc. Am. Proc.* **6**, 146–149 (1941).

Stanley, W. M. and Anderson, T. F. A study of purified viruses with the electron microscope. *J. Biol. Chem.* **139**, 325–338 (1941).

Wallner, F. E. and Schiebold, E. Contribution to the interpretation of supermicroscopical pictures of fibrous specimens. *Kolloid Zeits.* **97**, 36–37 (1941).

Wesch, L. Electron-optical properties of Lenard phosphors. *Ann. d. Physik* **40**, 249–294 (1941).

Zworykin, V. K. and Ramberg, E. G. Surface studies with the electron microscope. *J. of Applied Physics* **12**, 692–695 (1941).

Anderson, T. F. and Richards, A. G. Electron microscope studies of some structural colors of insects. *J. of Applied Physics* **13**, 748-758 (1942).

Ardenne, M. von. Reaction-chamber supermicroscopy by means of the universal electron microscope. *Zeits. f. phys. Chemie*, [B] **52**, 61–71 (1942).

Baker, R. F., Ramberg, E. G., and Hillier, J. The photographic action of electrons in the range between 40 and 212 kilovolts. *J. of Applied Physics* **12**, 450–456 (1942).

Barnes, R. B. and Burton, C. J. The electron microscope and its uses. *A. S. T. M. Bull.* **116**, 34–41 (1942).

Brown, O. J., Jr. and Smith, W. R. Relation of paint properties to surface areas of carbon black. *Ind. and Eng. Chem.* Ind. Ed. **34**, 352-355 (1942).

Burton, C. J., Barnes, R. B., and Rochow, T. G. The electron microscope: calibration and use at low magnifications. *Ind. and Eng. Chem.* Ind. Ed. **34**, 1429–1436 (1942).

Clark, G. L., Bernays, P. M., and Tordella, J. P. Progress in lime investigation with x-rays and electron microscope. *Nat. Lime Assoc. Proc. 24th Annual Convention*, May, 1942.

Clark, G. L., Barnes, M. R., and Baylor, E. R. A study of lampbrush chromosomes by the electron microscope. *Science* **95**, 250 (1942).

Eisenhut, O. and Kuhn, E. Light microscopic and electron microscopic investigations of native and artificial cellulose fibers. *Angew. Chem.* **55**, 198–206 (1942).

Frampton, L. V. The size and shape of the tobacco mosaic virus protein particle. *Science* **95**, 232–233 (1942).

Green, R. H., Anderson, T. F., and Smadel, J. E. Morphological structure of the virus of vaccinia. *J. Exp. Med.* **75**, 651–656 (1942).

Hall, C. E., Jakus, M. A., and Schmitt, F. O. Electron microscope observations of collagen. *J. Am. Chem. Soc.* **64**, 1234 (1942).

Hamly, D. H. and Watson, J. H. L. Electron and optical microscope interpretation of the wall of *pleurosigma angulatum*. *J. Opt. Soc. Am.* **32**, 433-442 (1942).

Heidenreich, R. D. Electron reflections in MgO crystals with the electron microscope. *Phys. Rev.* **62**, 291–292 (1942).

Hillier, J. and Baker, R. F. The observation of crystalline reflections in electron microscope images. *Phys. Rev.* **61**, 722–723 (1942).

Luria, S. E. and Anderson, T. F. The identification and characterization of bacteriophages with the electron microscope. *Proc. Natl. Acad. Sci.* **28**, 127–130 (1942).

Marshall, C. E., Humbert, R. P., Shaw, B. T., and Caldwell, O. G. Studies of clay particles with the electron microscope. II. The fractionation of beidellite, nontronite, magnesium bentonite, and attapulgite. *Soil Science* **54**, 149–157 (1942).

Marton, L. Applications of the electron microscope in colloid chemistry. *Jour. Phys. Chem.* **46**, 1023–1032 (1942).

Marton, L. and McBain, J. W. The electron microscope and its developments. *Chemical Products* **5**, 61-67 (1942).

Morton, H. E. and Anderson, T. F. Some morphologic features of the Nichols strain or *treponema pallidum* as revealed by the electron microscope. *Am. J. Syph. Gono. and Ven. Dis.* **26**, 565-573 (1942).

Mudd, S., Polevitzky, K., Anderson, T. F., and Kast, C. Bacterial morphology as shown by the electron microscope. III. Cell wall and protoplasm in a strain of fusobacterium. *J. Bact.* **44**, 361-366 (1942).

Mudd, S., Polevitzky, K., and Anderson, T. F. Bacterial morphology as shown by the electron microscope. IV. Structural differentiation within the bacterial protoplasm. *Arch. Path.* **34**, 199-207 (1942).

Mudd, S. and Anderson, T. F. Selective staining for electron microscopy: the effects of heavy metal salts on individual bacterial cell. *J. Exp. Med.* **76**, 103–108 (1942).

Mueller, H. and Sakmann, B. W. Electro-optical properties of colloids. *J. Opt. Soc. Am.* **32**, 309–317 (1942).

Picard, R. G. Studies on the structure of thin metallic films by means of the electron microscope. Dissertation, U. of Michigan, 1942. (Manuscript)

Richards, A. G., Jr. and Anderson, T. F. Electron micrographs of insect trachaea. *J. N. Y. Ento. Soc.* **50**, 147–167 (1942).

Richards, A. G., Jr. and Anderson, T. F. Electron microscope studies of insect cuticle with a discussion of the application of electron optics to this problem. *J. Morph.* **71**, 135–183 (1942).

Richards, A. G., Jr. and Anderson, T. F. Further electron microscope studies on arthropod trachaea. *J. N. Y. Ento. Soc.* **50**, 245–247 (1942).

Richards, A. G., Jr., Anderson, T. F., and Hance, R. T. A microtome sectioning technique for electron microscopy illustrated with sections of striated muscle. *Proc. Soc. Exp. Biol. and Med.* **51**, 148–152 (1942).

Rosenblatt, M. B., Fullam, E. F., and Gessler, A. E. Studies of mycobacteria with the electron microscope. *Amer. Rev. of Tuberculosis* **46**, 587–598 (1942).

Schaefer, V. J. New methods for preparing surface replicas for microscopic observation. *Phys. Rev.* **62**, 495–496 (1942).

Schaefer, V. J. and Harker, D. Surface replicas for use in the electron microscope. *J. of Applied Physics* **13**, 427–433 (1942).

Schmitt, F. O., Hall, C. E., and Jakus, M. A. Electron microscope investigations of the structure of collagen. *J. Cell. and Comp. Physiol.* **20**, 11–53 (1942).

Scott, G. H. and Anderson, T. F. A study of connective tissue with the electron microscope. *Anat. Rec.* **82**, 445 (1942).

Sears, G. R. and Kregel, E. A. Application of the electron microscope to the problems of the pulp, paper and paperboard industry. *Paper Trade Jour.* **114**, 43–49 (1942).

Sharp, D. G., Taylor, A. R., Beard, D., and Beard, J. W. Electron micrography of the western strain equine encephalomyelitis virus. *Proc. Soc. Exp. Biol. and Med.* **51**, 206–207 (1942).

Sharp, D. G., Taylor, A. R., Beard, D., and Beard, J. W. Study of the papilloma virus protein with the electron microscope. *Proc. Soc. Exp. Biol. and Med.* **50**, 205–207 (1942).

Shaw, B. T. The nature of colloidal clay as revealed by the electron microscope. *Jour. Phys. Chem.* **46**, 1032–1043 (1942).

Stanley, W. M. and Anderson, T. F. Electron micrographs of protein molecules. *J. Biol. Chem.* **146**, 25–30 (1942).

Taylor, A. R., Sharp, D. G., Beard, D., and Beard, J. W. Electron micrography of the eastern strain equine encephalomyelitis virus. *Proc. Soc. Exp. Biol. and Med.* **51**, 332–334 (1942).

Umbreit, W. W. and Anderson, T. F. A study of thiobacillus thiooxidans with the electron microscope. *J. Bact.* **44**, 317-320 (1942).

Wergin, W. What does electron microscopy reveal regarding the structure of cellulose fibers? *Kolloid Zeits.* **98**, 131–141 (1942).

Wiegand, W. B. and Ladd, W. A. Colloidal carbon as revealed by the electron microscope. *Rubber Age* **50**, 431–436 (1942).

Wile, U. J., Picard, R. G., and Kearny, E. B. The morphology of *spirochaeta pallida* in the electron microscope. *J. Am. Med. Assoc.* **119**, 880–881 (1942).

Alexander, L. T., Faust, G. T., Hendricks, S. B., Isley, H., and McMurdie, H. F. Relationships of the clay minerals halloysite and endellite. *Am. Miner.* **28**, 1–18 (1943).

Barnes, R. B. and Burton, C. J. The electron microscope and cellulose. *Ind. and Eng. Chem.* Ind. Ed. **35**, 120–125 (1943).

Chambers, L. A. and Henle, W. Studies on the nature of the virus of influenza: I. The dispersion of the virus of influenza A in tissue emulsions and in extra-embryonic fluids of the chick. *J. Exp. Med.* **77**, 251–264 (1943).

Chambers, L. A., Henle, W., Lauffer, M. A., and Anderson, T. F. Studies on the nature of the virus of influenza: II. The size of the infectious unit in influenza A. *J. Exp. Med.* **77**, 265–276 (1943).

Heidenreich, R. D. and Peck, V. G. Fine structure of metallic surfaces with the electron microscope. *J. of Applied Physics* **14**, 23–29 (1943).

Mahl, H. and Stranski, J. N. The behavior of aluminium in metallographic etching. *Naturwiss.* **31**, 12–17 (1943).

Plotz, H., Smadel, J. E., Anderson, T. F., and Chambers, L. A. Morphological structure of *rickettsiae*. *J. Exp. Med.* **77**, 355–358 (1943).

Richards, A. G., Jr., Steinbach, H. B., and Anderson, T. F. Electron microscope studies of squid giant nerve axoplasm. *J. Cell. and Comp. Phys.* **21**, 129–137 (1943).

Zworykin, V. K. Electron microscope in chemistry. *Electronics* **16**, 190–196 (January, 1943).

Ardenne, M. von. The wedge sectioning method for producing microtome cuts of less than 10^{-3} mm thickness for purposes of electron microscopy. *Zeits. f. wissensch. Mikr.* **56**, 8–23 (1939).

Ardenne, M. von. Experiments in photographing the virus of the hoof and mouth disease by means of the universal electron microscope. *Naturwiss.* **28**, 531–532 (1940).

Mahl, H. Electron microscope images of objects by transmitted radiation and of metal surfaces. *Zeits. angew. Photogr.* **2**, 58–63 (1940).

Radczewski, O. E., Müller, H. O., and Eitel, W. Electron microscopic investigations of the hydration of lime. *Veröffentl. Kaiser Wilhelm-Inst. Silikatforsch.* **10**, 139–142 (1940).

Ruska, H. Significance and results of the electron microscope. *Siemens Zeits.* **20**, 228–234 (1940).

Ardenne, M. von. Experiments on making visible molecular roughness of crystal edges inclined to the lattice planes in the universal electron microscope. *Naturwiss.* **29**, 780–781 (1941).

Ardenne, M. von and Weber, H. H. Electron microscopic investigations of the muscle protein "myosin." *Kolloid Zeits.* **97**, 322–325 (1941).

Endell, J. Significance of the electron microscope for identifying the microstructure of clays. *Tonind. Ztg.* **65**, 69–72 (1941).

Henneberg, W. Electron microscope, supermicroscope and metallography. *Stahl u. Eisen* **41**, 769–777 (1941).

Koch, L. and Lehmann, A. Electron microscope investigation of smooth aluminum surfaces. *Aluminium* **23**, 304-309 (1941).

Mahl, H. The electrostatic electron microscope and some results from the metallurgical field. *Zeits. f. Metallk.* **33**, 68–73 (1941).

Mahl, H. Electron microscopic detection of metallic precipitation by the replica method. *Metallwirtschaft* **20**, 983-986 (1941).

Mahl, H. The damaging of cellulose fibers by radiation in the electron microscope. *Kolloid Zeits.* **96**, 7–10 (1941).

Meldau, R. and Teichmüller, M. The morphology of finest lead-oxide sublimates. III. *Zeits. f. Elektrochem.* **47**, 630-634 (1941).

Meldau, R. and Teichmüller, M. The morphology of finest lead-oxide sublimates. IV. *Zeits. f. Elektrochem.* **47**, 634–636 (1941).

Ruska, H. Technique and research results of electron microscopy. *Vierteljrsch. d. Naturf. Ges. Zürich* **86**, 20–21 (1941).

Ardenne, M. von. Recent research on the universal electron microscope. *Forschng. u. Fortschr.* **18**, 32–35 (1942).

Ardenne, M. von. On an electron microscopic investigation of the structure of reflection reducing layers and on the determination of the dimensions of such layers. *Zeits. angew. Photogr.* **4**, 15–16 (1942).

Borries, B. von. On the intensity relations in the electron microscope. I. The blackening of photographic plates by electron beams. *Phys. Zeits.* **43**, 190–204 (1942).

Borries, B. von. On the intensity relations in the electron microscope. II. Magnification, graininess, and resolving power of electron exposed photographic plates. *Zeits. angew. Photogr.* **4**, 3–4 (1942).

Borries, B. von. On the intensity relations in the electron microscope. III. Suitability and limits of sensitivity of photographic plates for electron microscope pictures. *Zeits. f. Physik* **119**, 498–521 (1942).

Duffek, V. and Mahl, H. The electron microscope representation of metallic surfaces by the replica process without injury to the surface of the sample. *Arch. Eisenhüttenw.* **16**, 73–76 (1942).

Fischer, H. and Kurz, F. Electron microscope images of anodic oxide films on aluminum and their growth. *Korros. und Metallschutz* **18**, 42–50 (1942).

Gotthardt, E. Stereoscopic measurements of objects with the electron microscope. *Zeits. f. Physik* **118**, 714–717 (1942).

Gundermann, J. and Külz, H. Observations on zinc black by means of the electron microscope. *Kolloid Zeits.* **98**, 287–289 (1942).

Haam, E. von and Schuh, M. Cytologic studies with the electron microscope. *J. Tech. Methods* **22**, 75–80 (1942).

Heidenreich, R. D. and Peck, V. G. Electron microscope study of surface structure. *Phys. Rev.* **62**, 291–293 (1942).

Mahl, H. The electron microscopic representation of surfaces with the replica method. *Naturwiss.* **30**, 207–217 (1942).

Mahl, H. and Pawlek, F. Electron microscopic structural investigations of non-alloyed steels. *Arch. Eisenhüttenw.* **16**, 219–222 (1942).

Mahl, H. and Pawlek, F. Electron microscopic investigation of Al alloys. *Zeits. f. Metallk.* **34**, 232–236 (1942).

Müller, H. O. Measurement of the depth of electron microscopic objects. *Kolloid Zeits.* **99**, 6-28 (1942).

Müller, H. O. and Pasewaldt, C. W. Observations on the fine structure of the test diatom *Pleurosigma angulatum* W.Sm. and stereoscopic pictures with the electron microscope. *Naturwiss.* **30**, 55–60 (1942).

Rawlins, T. E. Recent evidence regarding the nature of viruses. *Science* **96**, 425–426 (1942).

Roberts, E. A. The structure of chloroplasts, chromoplasts, leucoplasts, and carotin "crystals" and their relationship to cellulose "particles" and colloidal carbon. *Am. J. of Botany* **29**, Suppl. p. 16 (1942).

Rüdiger, O. Use of beryllium for electron microscopic replica foil. *Naturwiss.* **30**, 279 (1942).

Semmler-Alter, E. Electron microscope investigation of martensite in different tempering stages in steel with 0.24 per cent carbon. *Arch. Eisenhüttenw.* **16**, 223–225 (1942).

Smakula, A. Remark on the paper of M. von Ardenne, "On an electron-microscopic investigation of the structure of reflection reducing layers and the determination of such layers." *Zeits. angew. Photogr.* **4**, 15–16 (1942).

Tiselius, A. and Gard, S. Electron microscopic observations on poliomyelitis virus preparations. *Naturwiss.* **30**, 728–731 (1942).

Winterfeld, E. von. The universal electron microscope. Recent results of electron microscopy. *Messtechn.* **18**, 98–102 (1942).

Ardenne, M. von. Suitability of gelatine-free photographic film for electron microscopy. *Zeits. f. Physik* **121**, 1-6 (1943).

Ardenne, M. von and Beischer, D. Electron microscope photographs of fine reaction layers on crystals of metal oxide smokes. *Kolloid Zeits.* **102**, 127–131 (1943).

Baker, R. F., Ramberg, E. G., and Hillier, J. Erratum: The photographic action of electrons in the range between 40 and 212 kilovolts. *J. Appl. Phys.* **14**, 39 (1943).

Barrett, C. S. Metallography with the electron microscope. *Metals Technology* **10**, 1–19 (1943).

Bole, G. A. and Loomis, G. A. Some physical procedures used in ceramic research. *J. Appl. Phys.* **14**, 443–450 (1943).

Bragg, L. Seeing ever-smaller worlds. *Nature* **151**, 545–547 (1943).

Burton, E. F. Electron microscope studies of the capture of airborne particles by single fibers. *Nature* **152**, 540 (1943).

Fullam, E. F. Magnification calibration of the electron microscope. *J. Appl. Phys.* **14**, 677–683 (1943).

Gard, S. Purification of poliomyelitis viruses. Experiments on murine and human strains. *Acta Med. Scandinavica, Supplementum* 143 (1943).

Gard, S. Electron microscope observations on purified poliomyelitis virus preparations. II. A contribution to the question of the epidemiology of infantile paralysis.. *Klin. Wochenschr.* **22**, 315–318 (1943).

Gard, S. Electron microscope observations on purified poliomyelitis virus preparations. III. A comparison with the results of physico-chemical experiments. *Arch. Ges. Virusforschung* (1943). An abstract of this article was published in *Arkiv för Kemi*, Stockholm, 17/B. I. (1943).

Glaser, R. W. and Stanley, W. M. Biochemical studies on the virus and the inclusion bodies of silkworm jaundice. *J. Exp. Med.* **77**, 451–466 (1943).

Gölz, E. Electron microscopic fine structure of fractured glass surfaces. *Zeits. f. Physik* **120**, 773–777 (1943).

Gölz, E. Surface electron microscopy of glass and ceramics by the replica method. *Zeits. f. techn. Physik* **24**, 8–11 (1943).

Green, H. and Fullam, E. F. Some applications of the high resolving power of the electron microscope. *J. Appl. Phys.* **14**, 332–340 (1943).

Harker, D. and Schaefer, V. J. Metallography by electron microscope. *Metal Prog.* **43**, 68–69 (1943).

Heidenreich, R. D. Interpretation of electron micrographs of silicon surface replicas. *J. Appl. Phys.* **14**, 312–320 (1943).

Henle, W. and Henle, G. Interference of inactive virus with the propagation of virus of influenza. *Science* **98**, 87–89 (1943).

Hock, C. W. and McMurdie, H. F. Structure of the wool fiber as revealed by the electron microscope. *J. Res. Nat. Bur. Stand., Wash.*, **31**, 229–236 (1943).

Johnson, F. H., Zworykin, N., and Warren, G. A study of luminous bacterial cells and cytolysates with the electron microscope. *J. Bact.* **46**, 167–185 (1943).

Jungeblut, C. W. and Bourdillon, J. Electronmicrography of murine poliomyelitis virus preparations. *J. Am. Med. Ass.* **123**, 399–402 (1943).

Kinder, E. Magnesium oxide crystals in the electron microscope. *Naturwiss.* **31**, 149 (1943).

Knaysi, G. and Mudd, S. The internal structure of certain bacteria as revealed by the electron microscope. A contribution to the study of the bacterial nucleus. *J. Bact.* **45**, 349–359 (1943).

Linke, F. Condensation nuclei made visible in the electron microscope. *Naturwiss.* **31**, 230–231 (1943).

Luria, S. E., Delbruck, M. and Anderson, T. F. Electron microscope studies of bacterial viruses. *J. Bact.* **46**, 57–77 (1943).

Marx, T., Klemm, W., and Smekal, A. Electron microscope studies of scratches. *Naturwiss.* **31**, 143–144 (1943).

Morton, H. E. and Anderson, T. F. The morphology of *Leptospira icterohemorragiae* and *L. canicola* as revealed by the electron microscope. *J. Bact.* **45**, 143–146 (1943).

Mudd, S. Changes in the bacterial cell brought about by the action of germicides and antibacterial substances as demonstrated by the electron microscope. *Am. J. Public Health* **33**, 167-168 (1943).

Mudd, S., Heinmets, F., and Anderson, T. F. The pneumococcal capsular swelling reaction studied with the aid of the electron microscope. *J. Exp. Med.* **78**, 327–332 (1943).

Mudd, S., Polevitzky, K., and Anderson, T. F. Bacterial morphology as shown by the electron microscope. V. *Treponema pallidum, T. macrodentium, and T. microdentium. J. Bact.* **46**, 15–24 (1943).

Mudd, S., Heinmets, F., and Anderson, T. F. Bacterial morphology as shown by the electron microscope. VI. Capsule, cell wall, and inner protoplasm of pneumococcus, type III. *J. Bact.* **46**, 205–211 (1943).

O'Brien, H. C. and McKinley, G. M. New microtome and sectioning method for electron microscopy. *Science* **98**, 455–456 (1943).

Picard, R. G. and Duffendack, O. S. Studies on the structure of thin metallic films by means of the electron microscope. *J. Appl. Phys.* **14**, 291–305 (1943).

Preckshot, G. W., DeLisle, N. G., Cottrell, C. E., and Katz, D. L. Asphaltic substances in crude oils. *Am. Inst. of Mining and Metal, Engrs. Petroleum Division Section, Transactions* **151**, 188–205 (1943).

Quarrell, A. G. Electron microscope and its application to engineering problems. *Engineer* **176**, 499–502; 526–528 (1943).

Schmidt, R. W. Oxidation of metal powders in electron microscopic investigations. *Kolloid Zeits.* **102**, 15–17 (1943).

Seeman, H. Migratory schlieren in electron optical pictures of single crystals, especially molybdenum oxide. *Naturwiss.* **31**, 415–416 (1943).

Seymour, F. J. Electron microscope, fertility, and gynecology. *M. Woman's J.* **50**, 151 (1943).

Sharp, D. G., Taylor, A. R., Beard, D., and Beard, J. W. Morphology of the Eastern and Western strains of the virus of equine encephalomyelitis. *Arch. Path.* **36**, 167–176 (1943).

Sjöstrand, F. Electron-microscopic examination of tissues. *Nature* **151**, 725–726 (1943).

Sliepcevich, C. M., Gildart, L., and Katz, D. M. Crystals from Portland cement hydration; an electron microscope study. *Industr. and Engr. Chem., Ind. ed.*, **35**, 1178–1187 (1943).

Taylor, A. R., Sharp, D. G., McLean, I. W., Jr., Beard, D., Beard, J. W., Dingle, J. H., and Feller, A. E. Purification and character of the swine influenza virus. *Science* **98**, 587–589 (1943).

Taylor, A. R., Sharp, D. G., Beard, D., Beard, J. W., Dingle, J. H., and Feller, A. E. Isolation and characterization of influenza virus A (PR 8 Strain). *J. Immun.* **47**, 261–282 (1943).

Weiss, L. J. Electron micrographs of bacteria medicated with penicillin. *Proc. Indiana Acad. Sci.* **52**, 27–29 (1943).

Weiss, L. J. Electron micrographs of rickettsiae of typhus fever. *J. Immun.* **47**, 353–357 (1943).

Wile, W. J. and Kearney, E. B. The morphology of *Treponema pallidum* in the electron microscope; demonstration of flagella. *J. Am. Med. Ass.* **122**, 167-168 (1943).

Zworykin, V. K. Applications of the electron microscope in metallurgy. *Trans. Am. Inst. Mining Met. Engrs., Inst. Metals Div.*, Tech. Pub. No. 1594, 1–25 (1943).

Fuller, M. L., Brubaker, D. G., and Berger, R. W. Mounting of pigments for electron microscopy. *J. Appl. Phys.* **15**, 201 (1944).

Martin, D., Baylor, M. R. B., and Clark, G. L. A preliminary electron microscope study of the active deposit from radiothorium. *Science* **99**, 185 (1944).

Melnick, J. L. Detection with the electron microscope of rod-shaped particles in stools or normal and poliomyelitic individuals. *J. Immun.* **48**, 25–28 (1944).

Sharp, D. G., Taylor, A. R., McLean, I. W., Jr., Beard, D., Beard, J. W., Feller, A. E., and Dingle, J. H. Isolation and characterization of influenza virus B (Lee Strain). *J. Immun.* **48**, 129–153 (1944).

Addenda

Abrams, I. M. and McBain, J. W. A Closed Cell for Electron Microscopy. *J. Applied Physics* **15**, 607–609 (1944).

Barrett, C. S. The Electron Microscope in Metallurgical Research. *J. Applied Physics* **15**, 691–696 (1944).

Benson, I. G. Electron Microscopy. *General Electric Review* **47**, 6 (Dec., 1944).

Calbick, C. J. Historical Background of Electron Optics. *J. Applied Physics* **15**, 685–690 (1944).

Claude, A. and Fullam, E. F. An Electron Microscope Study of Isolated Mitochondria. *J. Exp. Med.* **81**, 51–62 (1945).

Crane, H. R. Direct Centrifugation on Electron Microscope Specimen Films. *Rev. Sci. Instruments* **15**, 253 (Oct., 1944).

Goddard, L. S. The Computation of Electron Trajectories in Axially Symmetric Fields. *Proc. Phys. Soc.* **56**, 372 (1944).

Goddard, L. S. and Klemperer, O. Electron Ray Tracing through Magnetic Lenses. *Proc. Phys. Soc.* **56**, 378 (1944); **57**, 63 (1945).

Hall, C. E., Hauser, E. A., LeBeau, D. S., Schmitt, F. O., and Talalay, P. Natural and Synthetic Rubber Fibres. *Ind. Eng. Chem.* **36**, 634 (July, 1944).

Hambraeus, G. and Rånby, B. Electron Microscope Investigations of Precipitates of Cellulose Nitrates. *Nature* **155**, 200 (1945).

Heidenreich, R. D. Techniques in Applied Electron Microscopy. *J. Opt. Soc. Am.* **35**, 139 (1945).

Heidenreich, R. D. and Sturkey, L. Crystal Interference Phenomena in Electron Microscope Images. *J. Applied Physics* **16**, 97–105 (Feb., 1945).

Hillier, J. and Baker, R. F. Microanalysis by Means of Electrons. *J. Applied Physics* **15**, 663–677 (1944).

Katz, D. L. and Beu, K. E. Nature of Asphaltic Substances. *Ind. Eng. Chem.* **37**, 195–200 (1945).

Keller, F. and Geisler, A. H. Extending Microscopic Examination of Metals. *J. Applied Physics* **15**, 696–704 (1944).

Ladd, W. A. Electron Microscope Studies of Colloidal Carbon in Vulcanized Rubber. *Ind. Eng. Chem. (Anal. Ed.)* **16**, 642–644 (1944).

Levy, G. B. Dark Field Illumination in Electron Microscopy. *J. Applied Physics* **15**, 623–625 (1944).

Marton, L. Stereoscopy with the Electron Microscope. *J. Applied Physics* **15**, 726–727 (1944).

Marton, L. and Hutter, R. G. E. Optical Constants of a Magnetic Type Electron Microscope. *Proc. I. R. E.* **32**, 546–552 (1944).

Marton, L. A 100-kv Electron Microscope. *J. Applied Physics* **16**, 131 (1945).

Picard, R. C. Studies with the Electron Microscope Diffraction Adapter. *J. Applied Physics* **15**, 678–684 (Oct., 1944).

Porter, K. R., Claude, A., and Fullam, E. F. A Study of Tissue Culture Cells by Electron Microscopy. *J. Exp. Med.* **81**, 233–246 (1945).

Powers, D. H. Effect of Synthetic Resins on Cellulose and Protein Fibers. *Ind. Eng. Chem.* **37**, 188–193 (1945).

Williams, R. C. and Wyckoff, R. W. G. The Thickness of Electron Microscopic Objects. *J. Applied Physics* **15**, 712–716 (1944).

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