THE ELECTRON MICROSCOPE

By PROF. WILLIAM V. HOUSTON

Starting from the fundamental principle of the ordinary microscope, Dr. Houston has developed the theory underlying the electron microscope in a simple, logical, and concise fashion. Applications and limitations encountered with both types of instruments are described.

To many people the microscope is the symbol of science. It is a popular symbol and it is an appropriate symbol, in spite of the fact that many physicists, chemists and engineers that claim membership in the ranks of science may never have learned to use it.

Science is based upon the analysis of matter or phenomena into parts. The objective for twenty-five centuries has been the discovery and description of "ultimate" parts. The Greeks called them atoms, and although atom has a somewhat different significance today, science is still looking for some sort of an ultimate constituent of matter.

The miscroscope was the first tool by means of which a real study could be made of objects too small to be seen with the naked eye. From its crude beginning some 300 years ago it has been developed into an instrument that is a credit to the inventive skill and analytical ability of those that have worked on it. The modern optical microscope is an instrument that approaches the "theoretical limit" of its performance.

An optical miscroscope is not of much use in the study of objects smaller than about 1/100,000 of an inch, but that has not stopped such investigation. Atoms and molecules are a thousand times smaller than the smallest object that can be seen in a microscope, and yet they have been extensively studied. Electrons and protons are still tremendously smaller than these, and yet they also have been intensively investigated and a great deal is known about them. These investigations have been by indirect methods. A great variety of experiments has been carefully studied to give the properties of the atoms, molecules, electrons, protons, etc., that are regarded as the constituents of matter. This type of work is a glorified puzzle. The conclusions hinge on the careful fitting together of a vast number of clues, sometimes apparently contradictory clues; and there is always the logical possibility that a newly discovered fact may seriously upset some of the conclusions.

In spite of the perfection of the optical miscroscope, and the success of the indirect method on very small particles, there is a range of sizes in which neither of them can be effectively applied. The indirect method has not been sufficient in the study of particles larger than molecules, and the optical microscope cannot reveal much about a particle unless it contains a very large number of molecules. This unknown region contains the particles studied by the colloid chemist by indirect means, and it contains the objects to which the biologist wishes to attribute much behavior that cannot be understood in terms of the visible parts of cells. It is one of the attractive frontiers of science that has recently been penetrated by means of the electron miscroscope.

The limitation on the performance of a microscope is set by its resolving power. This is its ability to distinguish, and to separate, two points on the object. Although a popular description of a microscope is often given in terms of its magnification, such a description is not always significant. It is of no value to produce a very large image if the outlines are blurred and the details are lost. In fact, magnification can always be produced. A simple method is simply to use one microscope to examine the image produced by another. The resultant magnification would then be the product of the magnifications of the two instruments, and might be very large. Whether this process would produce a sharp final image in which more detail can be seen than in the first depends on the two resolving powers.

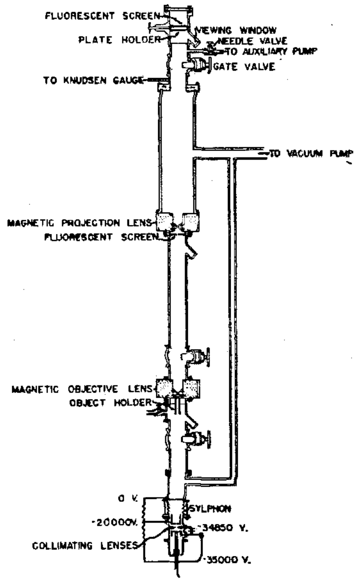

Fig. 1: **Outline Sketch of Dr. Houston's Electron Microscope in the Norman Bridge Laboratory.**

The resolving power of an optical system depends on a variety of things. The first may be said to be the precision of manufacture. If the lenses are poorly made, the resolving power will be poor. There are other limitations, however, that are more difficult to remove. These are associated with the fact that light of different colors is refracted differently by lenses, and the fact that simple lenses do not produce perfect images. These difficulties, caused by chromatic and spherical aberration, can be reduced in importance by careful design and the use of lens combinations. In fact, the skill of lens designers and manufacturers is such that the lens errors are now a negligible factor in limiting the performance of the best optical microscopes.

There still remains, however, a fundamental limit set by the nature of light itself. The simple theories of optical instruments are based on geometrical optics, in which light rays are used as idealizations of the paths along which the light travels. To get an exact theory it is necessary to take into account the wave properties of the light, and to calculate the amplitude of the waves at various points in the field. Such a calculation shows that the most perfect lens system can never separate, or "resolve", two points on the object that are closer together than about half a wave-length of the light used. For visible light this means that the resolving power is limited to about 1/100,000 of an inch. Details much smaller than this cannot be revealed by an optical microscope working with visible light, no matter how excellently it is designed and constructed.

The obvious solution to this difficulty is the use of shorter wavelengths, and microscopes have been constructed that use ultraviolet light. But the gain in this way is small, because light of less than about half the wavelength of visible light is absorbed by air and there is great difficulty in constructing the proper lenses, as glass is opaque to ultraviolet light. For many years people have dreamed of a microscope using X-rays, but as yet no very practical method of focussing them has been devised, and it has remained for the development of the field of electron optics to point the way to a significant improvement in resolving power.

The term "electron optics" arose after it was discovered that electrons and light have more similar properties than was at first realiezd. It had been known for a long time that electrons travel in straight lines when uninfluenced by any outside force and that they travel in curved paths through electric and magnetic fields. These paths correspond entirely to the light rays in ordinary geometrical optics, and by suitable design of the electric and magnetic fields the electrons can be brought to a focus similar to that of the light rays. Here is sufficient basis for a geometrical electron optics, and a basis for the construction of microscopes using electrons instead of light. But the analogy goes farther. Not only is there a geometric electron optics but the detailed study of the electron motion requires the solution of a wave problem. To know the details of electronic behavior one must take the wave properties into account and, as in the optical case, this sets a limit to the resolving power that can be attained with an electron microscope. Fortunately, the electrons have a very short wavelength and a wavelength that depends upon the velocity. The equation is $l = h/mv$, where l is the wavelength in centimeters, m is the mass in grams, and v is the velocity of the electrons in cm/sec. h is known as Planck's constant and has a value of about 6.6×10^{-27}. The mass of an electron is about 9×10^{-28} grams. Hence $l = 7.3/v$ but v is a large quantity. It is almost impossible to handle electrons whose velocity is much less than 10^{8} cm per sec. so that l is pratically always a thousand times smaller than the wavelength of visible light.

Another way to express the wavelength of an electron is in terms of the potential difference used to produce its velocity. This leads to $l = (12/\sqrt{v}) \times 10^{-8}$ where v is the potential difference in volts. This shows that the wavelength can be made almost as small as desired by increasing the potential difference used to accelerate them. In any case, with potential differences of several thousand volts the wavelengths are very small.

After the recognition of the essential similarity between electron optics and ordinary optics, the problem was to devise an apparatus that would control the electrons in the same way that the lenses of an optical microscope control the light.

The problem has been solved in a number of ways that are very similar to each other. The drawing gives an outline sketch of the apparatus built in the Norman Bridge Laboratory. The ordinary microscope requires a source of light and the electron microscope requires a source of electrons. In the instrument shown this is a hot filament. An ordinary microscope uses a condensing lens or mirror to concentrate the light on the object. In the electron micrscope this purpose is served by a series of electrodes maintained at suitable potentials. These produce such an electric field that the electrons are caused to move in paths that bring them to a focus on the object to be examined.

One of the major problems in microscopy is the proper preparation and mounting of the object. When these are small and transparent, they can be placed on a glass slide through which visible light passes easily. However, electrons will not penetrate a piece of glass, and some other support must be used. A common solution of the problem makes use of a very thin film of collodion. The electrons pass through this, not because of any particular transparency to electrons that it exhibits, but merely because it is thin. The stopping power for electrons depends essentially on the number of grams per square cm of film. Collodion is convenient because it can be made into very thin films by allowing a solution of it to spread out on the surface of water.

Fig. 2: **A shot of Optical Rouge taken with the instrument of Fig. 1 Magnification: 16,500 diameters.**

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this radio training is for communications of all types and services and also for the more advanced and highly specialized application of ultra-high frequency detection technique.

EDUCATION FOR VICTORY

The many instances which could be cited of benefits which have resulted from these Defense Training Courses are impressive. Many students have thus been able to enter in very useful and advantageous capacities industries with which they had had no previous experience or connection. Some very significant developments with widespread effects through large industries have evolved from the participation of various supervisors in industry in these courses as instructors. The time and effort which has been so sincerely applied to these courses by the many students enrolled have represented very definite and productive contributions to the national welfare.

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The same situation arises when the electrons come to the object. The number of electrons transmitted at a given point depends on the thickness in terms of grams per square cm. For that reason most electron microscope pictures appear to be shadows. The electrons pass around the object but penetrate it to only a very slight degree. Only when the thickness of object varies over a small range and is such as to permit some transmission of electrons at all points, can a gradation of blackness be produced in the image.

The light that passes through the object in an ordinary microscope must be brought to a focus to give the image. In the same way, the electrons that pass through the object must be focussed to produce the image. The objective lens produces an image with a magnification of almost 100 at the focus of the projection lens. This projection lens again focuses the electrons into a further enlarged second image at the photographic plate. These lenses are magnetic lenses that consist of a coil of wire surrounded by a steel armor. The armor has a small opening in it so that the lines of force bulge out into the electron path over only a very short distance. In this distance the focussing takes place. The focal length of such a lens depends on the current passing through it so that the process of getting correct positions of object and photographic plate is replaced by a simple adjustment of the current.

Much of the complication of an electron microscope is due to the fact that fairly high voltages must be used for accelerating the electrons, and that the whole electron path must be in a high vacuum. The vacuum must be so good that the electrons make no collisions during the whole distance of some six feet from the filament to the photographic plate. This requires continuous pumping with high speed pumps as well as arrangements of valves by means of which the object and the photographic plates can be inserted and removed.

The voltages used vary from a few thousand to over a hundred thousand. A high voltage produces fast electrons that will penetrate a greater thickness of matter, but lower voltages show a better contrast in the image. Above all it is necessary to hold the voltage constant within a few volts. For this purpose, fairly elaborate voltage regulators must be used, and this is one of the major problems of construction.

The electron microscopes of today are only in the beginning of their development, and they are far from realizing the theoretically attainable resolving power. This makes it an attractive field of study for the engineer and physicist, while the field of study opened up by its applications promises to close the gap between the visible and the molecular ranges of size.