

The Electron Microscope as an Illustration of the Wave Nature of the Electron

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Introduction

The transmission electron microscope uses principles that originated in light microscopy and which therefore rely on the properties of waves. We will illustrate these principles using the electron microscope.

The Wave Nature of the Electron

Light has been shown to have particle like properties when it is absorbed, as for example, in the photoelectric effect. Electrons, which are normally thought of as particles, have a wave-like character in their propagation and show all of the phenomena normally associated with waves. Wavelike phenomena include interference and diffraction. The electron microscope provides an ideal opportunity to illustrate the wave-like character of the electron. In fact, the very operation of the electron microscope relies on the properties of waves.

The Electron Lens

The electron is one of a family of particles called the *Leptons*. Leptons are fundamental particles which do not appear to be made up of other constituent particles. In this respect they are different to the particle family called *Baryons*, which includes the neutron and the proton. The neutron and the proton have a fine structure which is made out of *quarks* and *gluons*. The electron is a negatively charged lepton. The negative charge of the electron enables us to focus a parallel beam of electrons to a point and thereby produce a lens. An electron lens is shown in Figure 1.

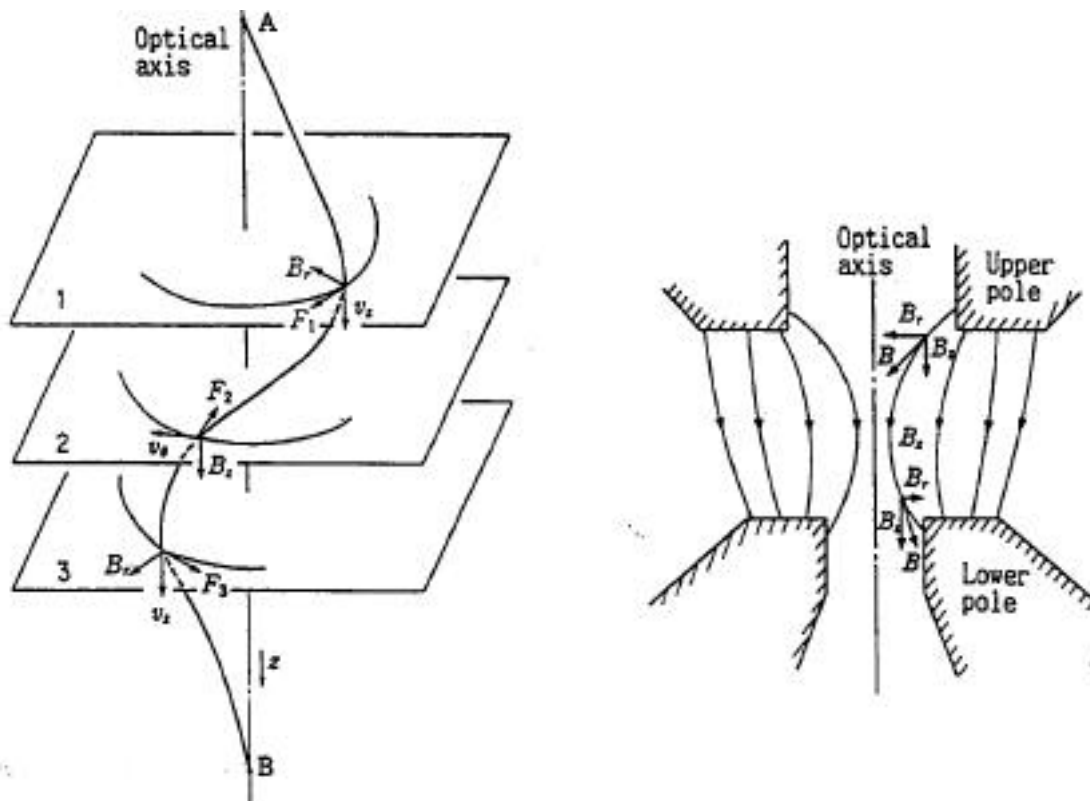


Figure 1. The Illustration on the left shows how a magnetic field (B) deflects an electron travelling with velocity (v) by means of the magnetic force (F). Note that the plane containing the optical axis and the electron trajectory is rotated at the image point B, compared to the object point A. The lens is shown schematically on the right.

Two magnetic pole pieces produce a converging region of magnetic field, which deflects an electron leaving the object at A at an angle to the optical axis, and brings it back onto the axis at the image position B. This electron lens is similar to the ones used in the electron microscope. An additional (and sometimes unfortunate), property of this lens is that it rotates the image. A useful property which a light lens does not have, is that the focal length can be changed by altering the magnetic field strength in the pole pieces, by a simple adjustment of the current through the field windings. In this way, the magnification of images in the electron microscope can be adjusted quickly and easily.

The electron lens has more imperfections or *aberrations* than a light and a glass lens for light, and this has important implications for the resolution of the electron microscope.

A comparison between the electron microscope and the optical microscope

Both the electron microscope and the optical microscope share common features. The diagram in Figure 2 below shows ray diagrams for the electron microscope.

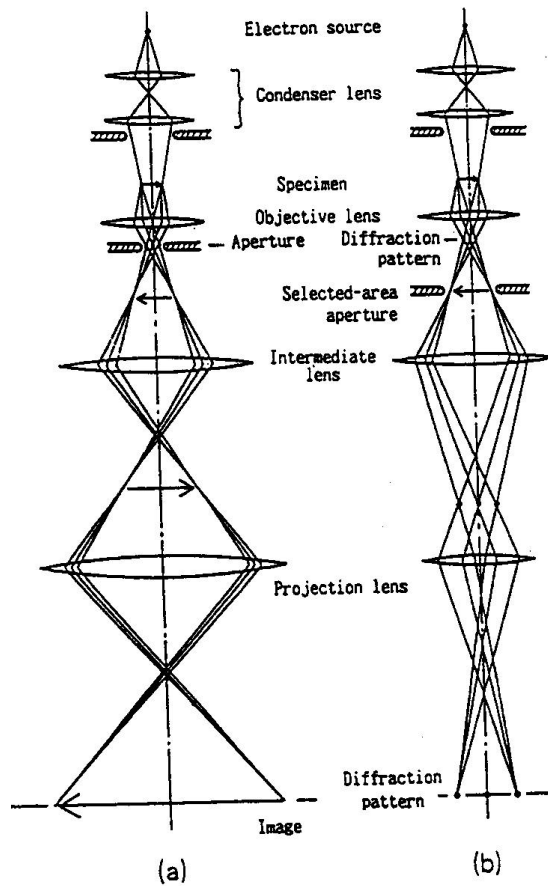


Figure 2 The electron paths in the electron microscope operating in imaging mode (left) and diffraction mode (right)

In the electron microscope, the source of electrons is a heated filament of tungsten, from which the electrons are emitted or “boiled off”. In advanced forms of the electron microscope the source is very bright and is made from a sharp metal tip from which electrons are drawn out by an electric field. In the light microscope, the light source is an incandescent filament. The first lens in both microscopes is the condenser lens, which forms an almost parallel illumination of the specimen. The next lens is the objective lens, the most important lens in the microscope. The objective lens forms a diffraction pattern of the object, since rays which leave the object parallel to each other are brought together in a plane called the “back focal plane”. In addition, further along the column, an image of the specimen is formed. The rest of the microscope can be thought of as serving either to magnify the diffraction pattern or the image formed by the objective lens. In the electron microscope the image is viewed first on a fluorescent screen where the electron image is converted into a light image, which is viewed in turn by a camera or the eye. In the optical microscope, the image can of course be viewed directly by a camera or the eye.

Resolution

The electron wave is much shorter than the light waves of visible light. We can estimate the benefits for resolution that might be gained by using these very short waves by considering the object to be a diffraction grating with a spacing of d as illustrated in Figure 3. Information concerning the spacing of the rulings in the grating is conveyed in the diffracted beams, but not the straight-through beam which occurs for any grating, and does not depend on the spacing. More information is conveyed by the microscope the larger the number of the diffracted beams which are accepted by the objective lens, but we will be able to detect the periodicity of the grating with minimum resolution when only the smallest angle of diffracted beam, known as the first order diffracted beam, is transmitted by the objective. The angle of the first order diffraction is given by the standard formula for a diffraction grating:

$$\sin \theta = \frac{\lambda}{d}$$

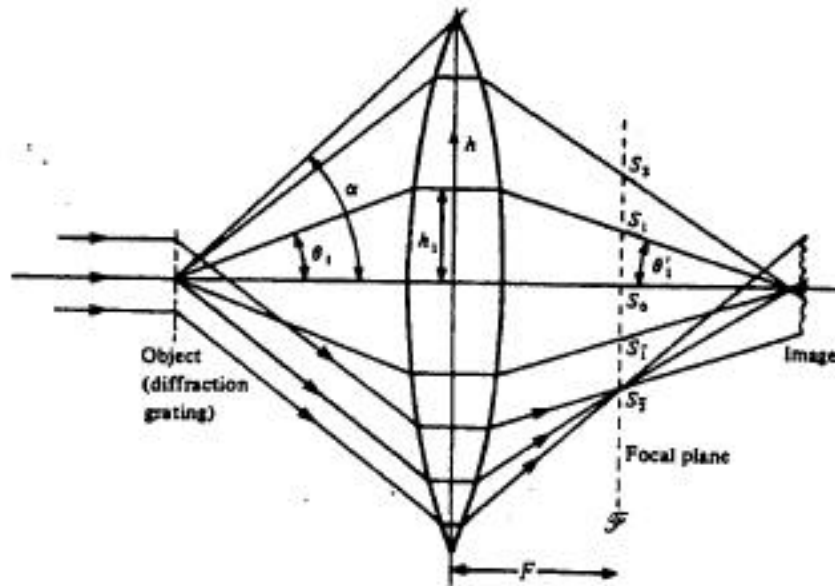


Figure 3. A diffraction grating is used as an object in the microscope. The resolution is determined by the largest order of diffraction received by the objective with acceptance angle

The smallest spacing of diffraction grating for which this diffracted beam is accepted by the objective is given by

$$d_{min} = \lambda / \sin \alpha$$

Where $\sin \alpha$ is known as the numerical aperture with α the acceptance angle of the objective. Since the electron wave has a wavelength of 10^{-12} metres, while the light wave has a value of 5×10^{-7} metres, at first sight it would seem that the resolving power of the electron microscope should be nearly a million times greater. However, this advantage is not as great as this, because electron lenses are not as free of defects (aberrations) as are well-designed glass lenses. In practice, the electron microscope can resolve features as small as an atom (10^{-10} m). Advances in optical microscopy, especially the confocal optical microscope, have enabled the optical microscope to achieve a resolution close to the theoretical limit.

Contrast formation

The most important difference is that contrast is formed in different ways. In the light microscope, we usually view differences in the absorption of the specimen. If white light illumination is used, we can get coloured images by using the different absorptions at different wavelengths. In the electron microscope, absorption is not important, and we use an aperture in the back focal plane to create the contrast. The back focal plane contains a diffraction pattern and by selecting a limited number of diffracted beams with the aperture, strong contrast is produced in the image. Bright parts of the image correspond to regions where the diffraction is strong, and dark parts to where it is weak.

Specimen requirements

There are strict requirements on a specimen in order to get an image of it in the electron microscope. Because electrons interact very strongly with matter, the specimen has to be very thin, less than 10^{-7} metres (0.1 micrometres) thick. This means that specimen preparation is very important. Additionally, the specimen is placed in a vacuum, and in an intense magnetic field, which means that living specimens cannot be viewed in the conventional transmission electron microscope.

Illustrating the wave nature of the electron with the electron microscope

The diffraction pattern of a metal film is shown in Figure 4. This pattern was obtained by evaporating metal in a vacuum onto a salt crystal and dissolving away the salt, leaving a thin unsupported film. The film was used as a specimen in the electron microscope and the microscope operated in such a way that the back focal plane is imaged onto a photographic film. The rings indicate that the electrons are behaving in exactly the same way as x-rays which produce an almost identical diffraction pattern. Each ring corresponds to constructive interference of the waves reflected from layers of atoms called crystal planes in the metal film.

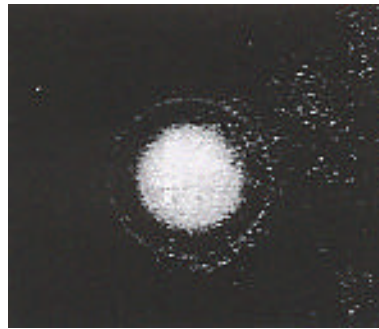


Figure 4: The diffraction pattern of a metal film showing the rings corresponding to diffraction from the crystal planes.

Even in the image of the electron microscope, evidence is clearly visible of the wave nature of the electrons, in the form of Fresnel fringes. Fresnel fringes are visible in images of sharp edges, in optical microscopy, and are related to the more familiar diffraction fringes formed when light is shone through a slit. Constructive and destructive interference occur as the waves diffract around the edge. Figure 5 shows Fresnel fringes formed in the electron microscope.

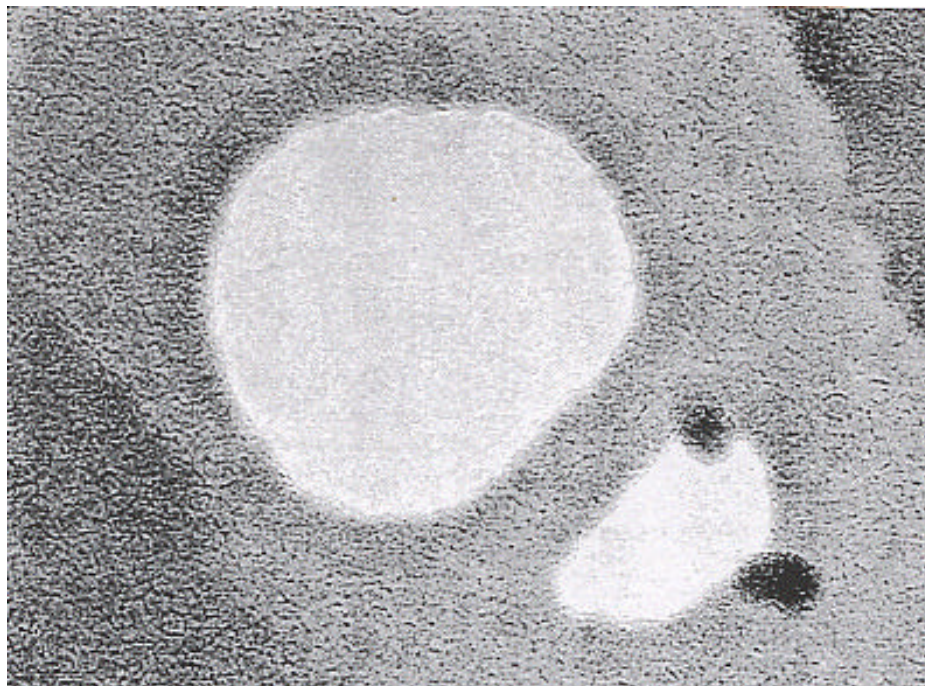


Figure 5: Electron microscope image of a hole in a carbon film showing a bright diffraction fringe (Fresnel fringe).