Electron Microscopes

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What is the size of the smallest object one can see with the naked eye? Equal to the thickness of the hair? One-tenth of that? Well, that's the approximate limiting size of our vision – about 20 µm[1].

When we wish to clearly see objects smaller than that we use a microscope, which is an arrangement of lenses that creates an image bigger in size than the object. The best optical microscopes can magnify objects about a 100 times, which means we should be able to see objects of the size of 200 nm. At this scale we are still far away from the size of the atoms.So, if we wish to see clearly the structure of matter at the level of an atom, we need to do better. The limitation of scale arises due to the wavelength of light itself, which is around 500 nm. To understand why the wavelength limits the scale of objects that can be clearly seen, we may draw an analogy. Consider waves spreading out in a lake or a pond. If we stand a pole or a stick in the path of the spreading waves, the wave patterns get disturbed. But, this happens only if the thickness of the pole is comparable or larger than the wavelength of the waves. We cannot notice changes in the patterns formed by the waves if the obstacle is tiny. The situation with light waves is similar. Roughly speaking, and ignoring all other limitations, light of a wavelength ë can resolve, or show as distinct, objects whose size is larger than ë/2. To beat the limit imposed by visible light we could of course consider using radiation of shorter wavelengths, such as x-rays, and reach a smaller scale. An x-ray microscope will, at least in

[1] **Small lengths:** 1 µm = 10^{-6} m (micrometer). 1 nm = 10^{-9} m (nanometer). 1 pm = 10^{-12} m are SI units for very small length scale.
An earlier, and still commonly used unit is Ångström (Å), which is equal to 10^{-10} m.

principle, enable use to see objects in the region of 0.1 nm. The problem with x-rays is that it is impossible to find materials that will behave like lenses or mirrors for x-rays like we have for optical microscopes, so an x-ray microscope is an impractical device. What is the way out?

The solution lies in using electron beams instead of light beams! This is feasible because of a peculiar property of matter at tiny scales. At the scale of the order of atomic size, particles exhibit dual nature, i.e. they behave like particles as well as waves. So, a beam of particles such as electrons, protons or neutrons will behave like a light wave in some situations. The wave associated with these particles, which have a mass, are called matter waves. Victor Loius de Broglie recognized this dual aspect of matter in 1924, paving the way for the modern theory of quantum mechanics, which could answer many questions that had plagued classical mechanics and electrodynamics. De Broglie proposed that for a particle of momentum p, the associated matter wave has a wavelength ë = h/p, where h is the Planck's constant. In other words, the wavelength associated with these massive particles is inversely proportional to their momenta. For a moderately energetic and easily handled beam of electrons the wavelength would be less than a nanometer. These matter waves can essentially do the same job as light waves passing through or reflected from a medium. A beam of electrons falling on a surface, or passing through a thin film gets affected due to the presence of the particles in its way. So, the intensity of the beam of electrons falling on a screen will show variations due to the structures in the sample through which the beam has passed. This fluctuation in its trajectory, or what is called scattering, can be related to the nature of the surface. More importanly, electrons are charged particles and it is relatively easy to manipulate their motion by the use of electric and magnetic fields, not very different from using mirrors or lenses to manipulate the path of a light beam. These similarities between visible light and electron beams gave birth to the idea of an electron microscope. Of course, one cannot see electrons, or the waves associated with them, but not unlike our eyes, there are devices which can register the incidence of electrons and give us a photograph-like image of the patterns formed by the electron beams. The big advantage over optical microscopes? The ability to 'see' *at very tiny* scales – about 0.1 nm. So, in short, an electron microscope is a device that exploits the matter waves associated with a beam of high energy electrons passing through a thin medium or getting reflected from its surface to create an image of the tiny structures in the medium on a detector. The effective magnification may be as high as 50 million. The electron microscope was invented by Ernst Ruska in Gemany in 1931.

Let us see what is there inside an electron microscope. The overall scheme is in principle similar to an optical microscope, except that no light is used for imaging, and details finer than those accessible by using light can be observed. An important difference is that *the entire arrangement is in vacuum.* The electron microscope is also much larger than an optical microscope – its size is about half a metre in each dimension. It is not portable, and is cumbersome to operate.

The main building blocks of an electron microscope are – the vacuum system, the electron gun, the beam manipulators, the sample holder and the detector. The vacuum shell (made of stainless steel or aluminium) confines all parts, with provision to control and manipulate the electron beam and the sample of interest from the outside. The pressure inside the shell is about a billion times lower than the air outside! Such low pressure is achieved and maintained by special vacuum pumps that run continuously. Thus, the major component of an electron microscope is just the vacuum system. The next major component is the electron gun and its associated electrical units, which produce a fine beam of high energy electrons and enable its focusing and steering. To produce the electron beam there is a cathode, made of a tiny a refractory metal filament coated with a special compund such as LaB_6, which gives off electrons in copious quantities when heated to about 1000 °C. The electrons are then accelerated by applying a large voltage (20–50 kV) between the cathode and the another electrode, called the anode. For comparison, the voltage across the terminals of an ordinary dry cell is only 1.5 V. Another set of of electrodes in the form of rings and apertures of different sizes and carrying different voltages are used for steering and focusing the beam of electrons. More complex guns also have current carrying coils to generate magnetic fields for the same purpose, thereby achieving greater precision and more intense beams. Broadly stated, more intense beams means sharper and more contrasty images, while higher energy means a better resolution[2] and penetration of the beam into the sample.

The wavelengths corresponding to 20–50 keV electrons are in the range 0.09–0.06 nm. For comparison the approximate size of the hydrogen atom is 0.06 nm, so these electron beams can – at least in principle – resolve features comparable to atomic dimensions. The electron beam can be imaged either in the reflection mode or in the transmission mode. In the former mode the features on the surface of the solid can be observed. In the latter mode sub-surface features can be observed, provided the sample is very thin. The transmission mode gives higher resolution, but the reflection mode is often more useful as it can scan surface features and structures of larger and thicker samples. The detector can be a glass plate coated with a metalized fluorescent material (like in old television screens), so that the

[2] **Resolution** of an instrument is defined as the smallest difference between the value of the property being measured, that can be measured as being distinct by the instrument. In the context of the microscope, this is the smallest length separation between two features on a single object, or the separation between two objectes) that can be differentiated in the image.

light emitted by the striking electrons gives a visible image. In recent times, however, it is more usual to have an electronic (CCD) sensor chip to collect the electrons, giving an image like in a digital camera.

Samples are introduced into the path of the elctron beam by breaking the vacuum in a small compartment and after the samples are correctly placed the compartment is sealed-off and evacuated. It is common to have multiple samples in one large sample holder, which can be moved in-vacuum to allow uninterrupted observation of many samples in one go. The sample needs to be a (partial) conductor of electricity. In case of a non-conducting sample an additional step of making a thin conducting edge to the sample is needed before inserting the sample in the compartment. Furthermore, the sample must not contain any volatile components, such as water. One must note, that since the electron microscope works in vacuum, no living cell will survive a trip to the electron microscope. So the images of living organisms obtained from electron microscopes are those of *dead* cells!

The electron microscope has proved to be an extremely valuable tool. Electron microscopes have revealed the structure of matter at the tiniest length scale – almost down to the atomic size; they have enabled us to discover the structure of cells, viruses, proteins in great detail. They are used in all branches of scientific research and industry – from molecular biology research, to examining meteorites and detecting structural defects in engineering materials.