OCR
Oxford Cambridge and RSA

Thursday 18 June 2015 – Morning

A2 GCE PHYSICS B (ADVANCING PHYSICS)

G495/01 Field and Particle Pictures

ADVANCE NOTICE

Duration: 2 hours

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INSTRUCTIONS TO CANDIDATES

- Take the article away and read through it carefully. Spend some time looking up any technical terms or phrases you do not understand. You are **not** required to research further the particular topic described in the article.
- For the examination on Thursday 18 June 2015 you will be given a fresh copy of this article, together with a question paper. You will not be able to take your original copy into the examination with you.
- The values of standard physical constants will be given in the Advancing Physics Data, Formulae and Relationships booklet. Any additional data required are given in the appropriate question.

INFORMATION FOR CANDIDATES

- Questions in Section C of paper G495/01 Field and Particle Pictures will refer to this Advance Notice material and may give additional data related to it.
- Section C will be worth about 40 marks.
- Sections A and B of paper G495/01 will be worth about 60 marks.
- There will be 2 marks for quality of written communication (QWC) assessed in Sections B and C.
- This document consists of **8** pages. Any blank pages are indicated.

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Seeing with electrons

Given the role it has played in scientific and technological revelation and development over the centuries, it is fair to describe the microscope as one of the most important inventions in history. Although it is not known for certain who actually invented it, the optical microscope was in use from the end of the 16th century and led to rapid developments in our knowledge of what became known as the microscopic world. For hundreds of years it remained based upon a standard design. That same design provided the template for the invention that would eventually supersede it as the main tool to be used for the study of some of the smallest objects in the natural world: the electron microscope.

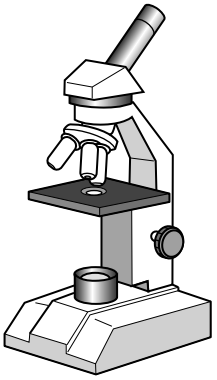


Fig. 1: a compound optical microscope

The compound optical microscope

Although it is possible to use a single convex lens as a simple magnifying glass, substantial magnifications (more than 30×) only become possible by using combinations of lenses to produce what is called a compound microscope; a simple version is drawn in Fig. 2 with rays included.

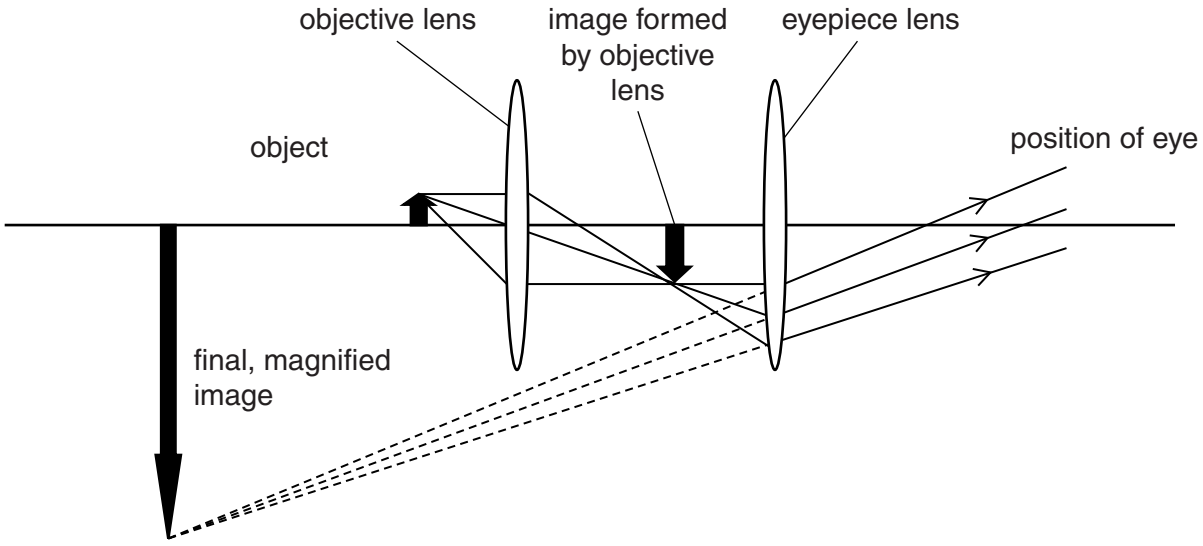


Fig. 2: compound microscope, schematic

The lens closest to the object is called the *objective lens*; it forms an inverted and magnified image of the object. This image is viewed through the *eyepiece lens*, which acts as a magnifying glass to produce a final highly-magnified image of the object.

As with all imaging systems, the performance of a microscope can be described in terms of *magnification* and *resolution*. Typically, laboratory microscopes have a maximum magnification of about 2000×. The resolution of an image is defined in terms of the size of the smallest distinct object visible on the image. When considering modern digitised images this is usually quantified as the actual distance represented by each pixel. However, the production of the image is itself limited by the diffraction caused when the incident light interacts with the tiny structures of the specimen. This leads to a diffraction limit dependent upon the wavelength of the light being used. Laboratory microscopes using visible light are limited to a resolution which makes it impossible to identify objects that are smaller than approximately half the wavelength of the light being used i.e. about 250 nm for visible light.

Improving the view

Developments in lens design and production, along with the use of a variety of lens combinations and arrangements, led to significant improvements on the early instruments over a period of about 300 years. It was not until the end of the 19th century that the limits of the performance of an optical (light) microscope were fully understood. Progression now only became possible with a radical change of approach which was prompted by a series of important discoveries: the suggestion by Hertz that cathode rays were wavelike (1891), Thomson's discovery of the electron (1897), de Broglie's formula for calculating the wavelength of an electron from its momentum (1924) and Busch's success with the focusing of electron beams using magnetic fields (1926). Using all of these ideas, Ernst Ruska suggested the construction of a microscope that used high-speed electrons instead of light waves, and he built such a device in 1933. This revolutionary instrument, the first electron microscope, was a type known as a transmission electron microscope (TEM). For producing it Ruska was awarded the Nobel Prize for Physics over half a century later, in 1986. Fig. 3 shows a modern version of the instrument.

Fig. 3: a modern electron microscope

Fig. 4 is a schematic diagram comparing the structure of a TEM with that of an optical microscope.

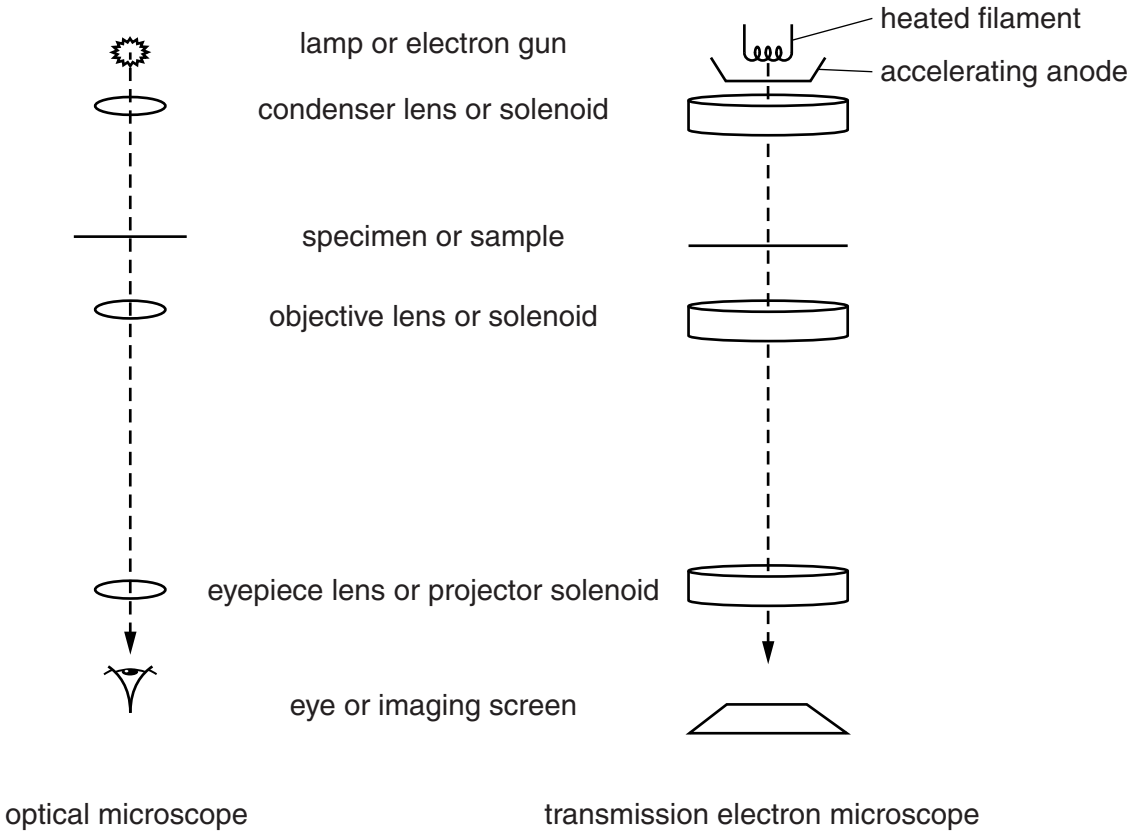


Fig. 4: comparison of the structure of an optical and an electron microscope

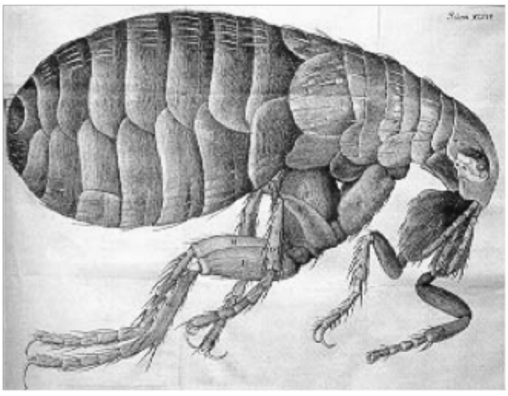
In the electron microscope, the source of the electrons is an electron gun. When a current is passed through the filament coil, it heats up and electrons boil off the surface. Individual electrons require about 4 eV of energy to escape the surface and the number of electrons emitted depends on the temperature of the filament. The electrons are emitted into a gap, across which there is a large potential difference creating an electric field. This causes them to accelerate through the accelerating anode and at high speed they pass through the first of a series of short circular solenoids and are focused onto the sample being imaged. The magnetic field strength inside a solenoid depends upon the number of turns for the coil and the current it carries. Complicated combinations of solenoids are used and these are equivalent to the illumination system in an optical microscope which produces and focuses the light onto the sample.

The flow of electrons from filament to sample produces a beam current along the tube of the microscope and into the sample chamber. The tube and chamber need to be evacuated and so efficient pumps are an integral part of electron microscope assemblies. The vacuum environment, while essential for the operation of the instrument, does limit the usefulness of the instrument and often samples need to be carefully prepared before being imaged.

When the high-speed electrons meet the sample, a number of different interactions can occur resulting in heating and sometimes including the production of x-rays. If the sample is thin, however, and the electrons are of very high energy then most will pass through the sample, being scattered and diffracted as they do so. The amount of interaction will depend upon the types of atoms in the sample, the sample density and other similar factors so that a transmission image can be obtained. It is because the wavelength of the electrons is much smaller than that of visible light that superior performance is possible. For example, electrons accelerated from rest through a potential difference of 50 kV will gain sufficient momentum to give them a de Broglie wavelength of about 5 picometres which, theoretically, would produce a much better resolution than an optical microscope.

A later development of the instrument was the scanning electron microscope (SEM). For thicker samples and lower energy electrons, many *secondary electrons* will be emitted. These are produced when an incident electron excites an electron below the surface of the sample. The excited electron moves towards the surface and can escape if it has not lost too much energy in the process. The secondary electrons emitted at each beam position are detected, giving a signal that varies as the beam moves across the sample. Electric fields are sometimes used to deflect the electrons, scanning the beam across the sample in a raster pattern. This allows an image of the surface to be built up on a display screen. Modern instruments use photomultiplier tubes and CCDs to produce high-quality images.

Fig. 5a shows an image of a flea drawn by Robert Hooke in 1665. Fig. 5b is a view of a fly's eye obtained by a 21st century SEM. At this magnification (about 1000×) it can be seen that the eye consists of an array of small lenses.



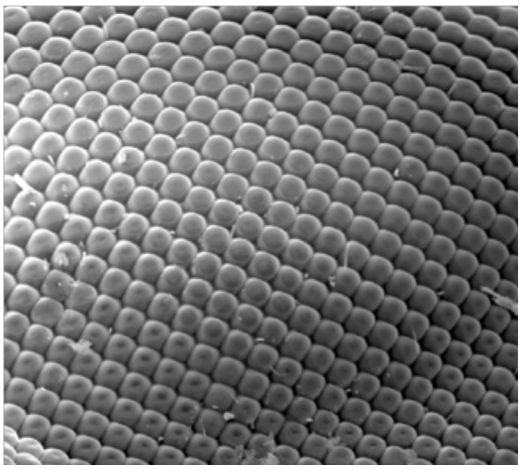


Fig. 5a (left) and 5b (right): images of a flea from Robert Hooke's *Micrographia* (1665) and a fly's eye from a modern SEM, respectively.

Scrutinising the future

Magnification and resolution continue to be improved as technology develops. Electron microscopes have progressed significantly, though they remain based on Ruska's original ideas. Additional challenges being met include real-time imaging and the ability to image living organisms. Meanwhile, microscopes based on other ideas and principles have emerged, including scanning tunnelling microscopes and atomic force microscopes, but we shall be forever indebted to those early pioneers of electron microscopy for paving the way to a smaller world.

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