Answer
A cloud of electrons is produced by thermionic emission (from a
¿ODPHQW XQGHUJRLQJ HOHFWULFDO KHDWLQJ DQG DFFHOHUDWHG E\ D SRWH
GLuHUHQFH 7KH JDLQ LQ NLQHWLF HQHUJ\ LV JLYHQ E\ H9 FKDUJH RQ HOHFWUR
[SRWHQWLDO GLuHUHQFH EXW WKH LQLWLDO NLQHWLF HQHUJ\ RI HOHFWURQ
vary. This will result in small variation in velocities of electrons in the beam.

0DJQHWLF ¿HOGV DUH XVHG WR IRFXV WKH EHDP 7 WKH FH H[HUWHG RQ
HOHFWURQ LQ D PDJQHWLF ¿HOG RI ÀX[GHQVLW\ % GHSHQGV RQ LWV YHORFL
(F = Bev).

Therefore, if there are a range of velocities, the force focusing the beam will also vary between electrons and cause them to be focused through
GLuHUHQW DQJOHV 7KLV ZRXOG PHDQ WKDW WKH LPDJH LV QRW IRFXVHG WR
GH¿QLWH SRLQW DQG ZRXOG DSSHDU EOXUUHG UHGXFLQJ WKH ORZHU OLPLW
resolution further.

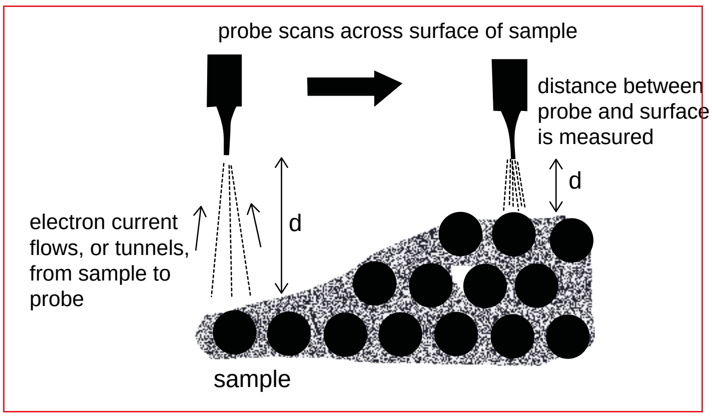
It is also possible that, having different velocities and therefore momenta, there will also be a variation in De Broglie wavelength in the beam.

7KLV FRXOG PHDQ WKDW WKH SDUWLFOH
transmitting through the sample, which could reduce the resolution. A greater problem, however, would be that the transmission of the
HOHFWURQV WKURXJK WKH VDPSOH ZRXOG EH DuHFWHG E\ WKH YDULDWLRQV
their wavelength and not just by the thickness of the sample. This would give false readings on the thickness or density of the sample and reduce the clarity or detail (and therefore the resolution power).

Scanning Tunneling Electron Microscope (STEM)

The sample is charged so that it contains excess electrons. If it does not conduct electricity, then it can be coated with a thin layer of metal.
$ YHU\ VPDOO SRWHQWLDO GLuHUHQFH LV DSSOLHG EHWZHHQ WKH VDPSOH D
WKH SUREH 7KH SUREH VFDQV DFURVV WKH VXUIDFH DQG PHDVXUHV WKH ÀRZ
of electrons from the surface, which indicates the height of the sample and allows the microscope to create a 3D map of the surface's shape.

Fig. 5 Scanning Tunneling Electron Microscope (STEM)

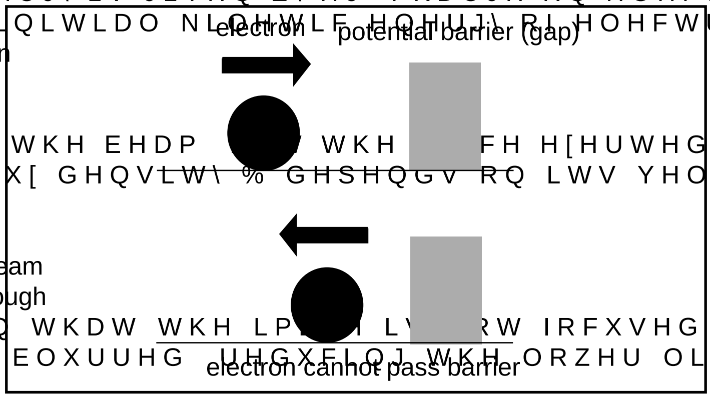


Tunneling

The probe maps the height of the surface by measuring how many electrons 'do the impossible' and jump the gap.

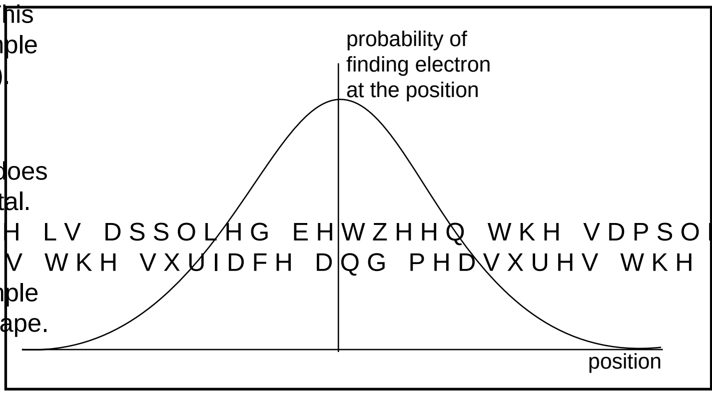
7KH HOHFWURQV VKRXOG QRW EH DEOH WR ÀRZ DFURVV WKH JDS IURP WKH VDPS
to the probe. The gap is a potential barrier, which means the electrons
GR QRW KDYH WKH UHTXLUHG HQHUJ\ WR ÀRZ IURP RQH WR WKH RWKHU

Fig. 6 Viewing the electron as a particle, it does not contain
HQRXJK HQHUJ\ WR MXPS WKH JDS 7
electrons to the probe



The electron can instead be viewed as a wave with a wave function –
DQ HTXDWLRQ WKDW GHVFULEHV WKH SU
SRVLWLRQ 7KLV FDQ EH VLPSOL¿HG DV D

)LJ D 7KH SUREDELOLW\ RI ¿QGLQJ
along the x-axis is given by the height of the curve. The most
SUREDEOH SODFH WR ¿QG WKH HOHF
7KH SUREDELOLW\ RI ¿QGLQJ LW JHW
from the centre



:KHQ YLHZHG OLNH WKLV WKH HOHFWUR
barrier.

Fig. 7b When the electron is placed next to the potential barrier there is a small probability that it has already crossed over it. If this seems strange, consider that nuclear fusion in stars would not work without protons doing much the same thing. We only exist because this happens in the Sun

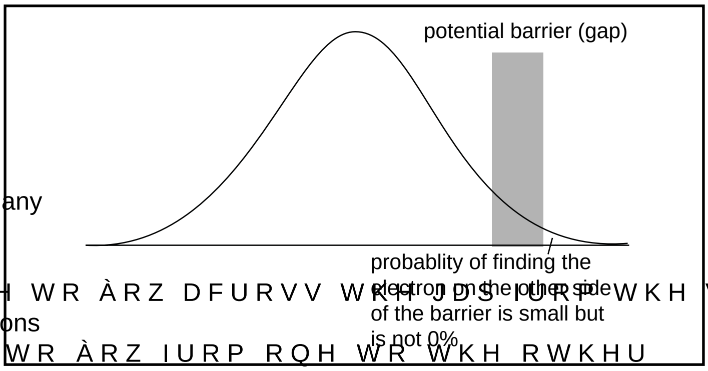
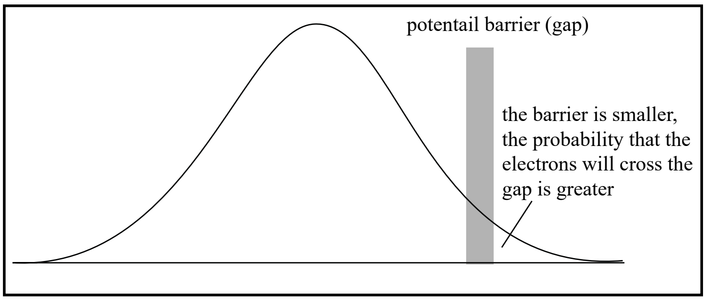


Fig. 7c When the gap is smaller the probability that the electron has crossed the barrier is greater



Variations on the Microscopes

There are a number of varieties of electron microscope, we have concentrated on the main two types.

- Electrons can be passed through a thin sample like in a TEM, but detected using the probe to scan how many electrons are passing through. This combination of the two techniques produces a microscope with the capabilities somewhere between the two. It enables smaller details to be mapped than the TEM is capable of while also being able to look at thicker samples. As the density and depth of the structures in the sample changes, the number of electrons being transmitted changes.
- Like an optical microscope, the TEM can also focus beams of electrons that are scattered off the surface of a sample rather than be transmitted through. Again, in some variations this can be done in finer detail using a probe.
- Secondary images can be produced by measuring the interactions of electrons with samples. For instance, high energy electrons that are absorbed will produce X-rays that can also be detected.
- The diffraction patterns produced by using beams of electrons with De Broglie wavelength, similar to the atomic spacings, can be used to investigate the lattice structure in crystals. In these cases, an image of the structure is not produced, but rather the diffraction pattern itself is studied to reveal details about the crystal's atomic makeup.

Question 4

The probe in the STEM is only around 1nm from the sample. Explain why only a very small voltage is applied across the gap to create the current of tunnelling electrons. [2 marks]

Answer

If the potential difference is large enough, there would be a spark as the electrons jumped across the gap. ✓ This would create spikes in the current flow and give false readings about the height of the sample. ✓

Question 5

Use the idea of quantum tunnelling and the diagrams in **Figure 7** to explain how the scanning tunnelling electron microscope creates a 3D map of the surface of a sample. [3 marks]

Answer

If we say the probability of finding the electron across the barrier in *figure 7b* is 1%, then for every one hundred electrons 'stuck' on one side of the barrier, one of them will be able to cross it. ✓

When the height of the sample gets higher and the gap decreases, like in *figure 7c*, the probability will increase. Let's say it is now 5%. For every one hundred electrons on the sample, now five will tunnel across – the current will increase. ✓

The STEM maps the surface by measuring the flow of current, the higher the current, the smaller the gap and the higher the sample. ✓ (You don't need to give the numbers; they were just to explain how it works a little more clearly.)

Question 6

Compare the advantages and disadvantages of the two types of electron microscope in terms of their uses.

Answer

TEM (transmission electron microscope) uses the wave properties of beams of electrons to create an image, so the resolution of the image is limited by the wavelength of the electrons. It is also affected by the variations in the electrons velocity, the fluctuations in the magnetic field strength used to focus the beam, and the shape of the focusing magnetic fields (all of which reduce the minimum resolution).

The STEM (scanning tunnelling electron microscope) relies instead on the quantum nature of the particles and is not affected by their apparent wavelength. It can operate in a much smaller scale, right down to locating individual atoms on the surface of a structure. It maps the shape of the surface in fine detail, but will not look at any structure beneath the surface.

The advantage of the TEM is that, like optical microscopes, it uses absorption based on the density and thickness of the sample to create more of an image of the sample. It requires very carefully prepared thin samples in order to work, whereas a STEM sample's thickness is less important, making it easier to prepare.

If the object is not electrically conductive it needs to be coated in a thin layer of metal to be seen by a STEM, which could lead to false details on the surface where the metal coating was not uniform (scientists thought they had found bacteria on a sample of Martian rock scanned using a STEM, but it was discovered later to be a defect in the metal coating). Provided the sample can be cut thin enough, the TEM can look at any type of material, conductive or not.

Question 7

Why is it important that the key processes inside both transmission and scanning tunnelling electron microscopes are conducted in a vacuum? [4 marks]

Answer

For TEMs, the beam of electrons would be scattered by collision with the gas particles in air and would cause a distortion or reduction in resolution. ✓

Likewise, in a STEM the presence of air would cause variations in the energy barrier, changing the probability that electrons would tunnel the gap and therefore make the current a less reliable indicator of the size of the gap (and shape of the sample). ✓

The presence of oxygen might also cause oxidation of the surfaces. This would change the appearance, and, in the case of the STEM, the conductivity of the sample in places. ✓ In the case of the TEM it would change the proportion of electrons being transmitted, both of which would cause variations in the image being created or mapped. ✓

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