# *Cambridge*

# *A2 Level*

# *Physics*

## *CODE: (9702)*

## *Chapter 27*

# Chapter 27: Charged particles

## Observing the force

You can use your knowledge of how charged particles and electric currents are affected by fields to interpret diagrams of moving particles. You must bear in mind that, by convention, the direction of conventional electric current is the direction of flow of positive charge. When electrons are moving, the conventional current is regarded as flowing in the opposite direction.

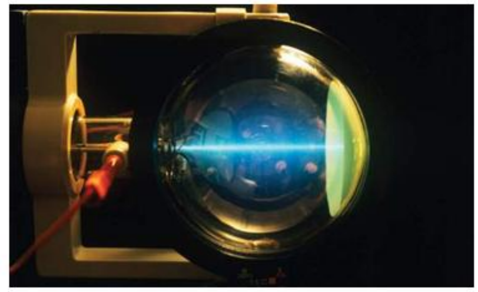

**Figure 27.2** An electron beam tube.

In Figure 27.3, a beam of electrons is moving from right to left, into a region where a magnetic field is directed into the plane of the paper.

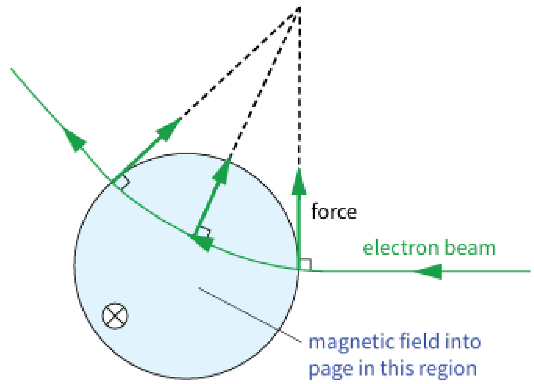


**Figure 27.3** A beam of electrons is deflected as it crosses a magnetic field. The magnetic field into the plane of the paper is represented by the cross in the circle.

## The magnetic force on a moving charge

We can make an intelligent guess about the factors that determine the size of the force on a moving charge in a uniform magnetic field (Figure 27.6). It will depend on:

- ■ the magnetic flux density B (strength of the magnetic field)
- ■ the charge Q on the particle
- ■ the speed v of the particle.

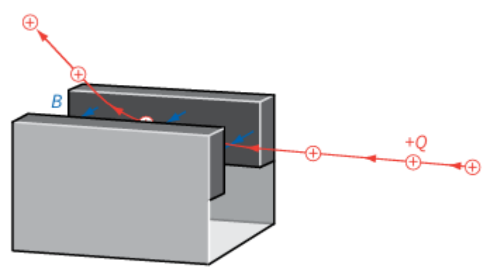


**Figure 27.6** The path of a charged particle is curved in a magnetic field.

If the charged particle is moving at an angle $\theta$ to the magnetic field, the component of its velocity at right angles to B is $v\sin\theta$. Hence the equation becomes:

$$F = BQv\sin\theta$$

We can show that the two equations $F = BIL$ and $F = BQv$ are consistent with one another, as follows.

Since current $I$ is the rate of flow of charge, we can write:

$$I = \frac{Q}{t}$$

Substituting in $F = BIL$ gives:

$$F = \frac{BQL}{t}$$

Now, $\frac{L}{t}$ is the speed $v$ of the moving particle, so we can write:

$$F = BQv$$

For an electron, with a charge of $-e$, the magnitude of the force on it is:

$$F = Bev \quad (e = 1.60 \times 10^{-19}\,\mathrm{C})$$

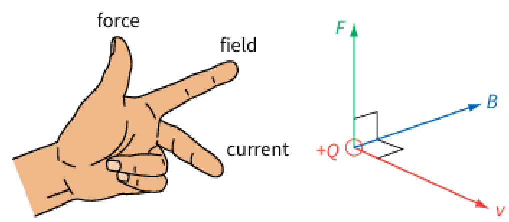


**Figure 27.7** Fleming's left-hand rule, applied to a moving positive charge.

## Orbiting charges

Consider a charged particle moving at right angles to a uniform magnetic field. It will describe a circular path because the magnetic force F is always perpendicular to its velocity. We can describe F as a centripetal force, because it is always directed towards the centre of the circle

The centripetal force on the charged particle is given by:

$$\text{centripetal force} = \frac{mv^2}{r}$$

The centripetal force is provided by the magnetic force $Bev$. Therefore:

$$Bev = \frac{mv^2}{r}$$

Cancelling and rearranging to find $r$ gives:

$$r = \frac{mv}{Be}$$

You can also write this equation in terms of the momentum $p$ of the particle, that is:

$$p = Ber$$

The equation $r = \frac{mv}{Be}$ shows that:

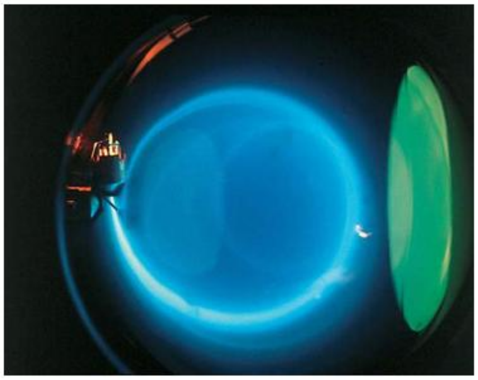

Figure 27.8 In this fine-beam tube, a beam of electrons is bent around into a circular orbit by an external magnetic field. The beam is shown up by the presence of a small amount of gas in the tube. (The electrons travel in an anticlockwise direction.)

### The charge-to-mass ratio of an electron

Experiments to find the mass of an electron first involve finding the charge-to-mass ratio $\frac{e}{m_e}$. This is known as the specific charge on the electron – the word 'specific' here means 'per unit mass'.

Using the equation for an electron travelling in a circle in a magnetic field, we have $\frac{e}{m_e} = \frac{v}{Br}$. Clearly, measurements of $v$, $B$ and $r$ are needed to measure $\frac{e}{m_e}$.

## Electric and magnetic fields

Now we will consider what happens when an electron beam passes through an electric field and a magnetic field at the same time

## Velocity selection

Balancing the effects of electric and magnetic fields is also used in a device called a **velocity selector**. This is used in devices such as mass spectrometers where it is desired to produce a beam of charged particles all moving with the same velocity. The construction of a velocity selector is shown in Figure 27.11.

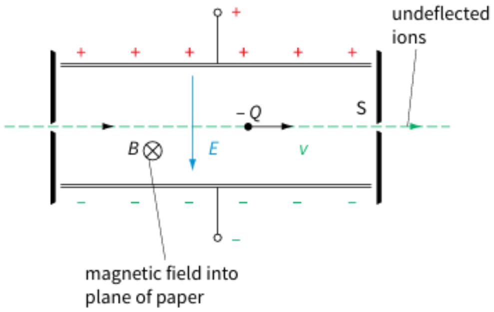


Figure 27.11 A velocity selector – only particles with the correct combination of charge, mass and velocity will emerge through the slit S.

## The Hall effect

In Chapter 26, you saw how to use a Hall probe to measure magnetic flux density. The **Hall effect** is another mechanism in which the magnetic and electric forces on a moving charged particle are balanced. A Hall probe works as follows. The probe itself is made of semiconductor (Figure 27.12). This material is used because the electrons move much faster in a semiconductor than in a metal for a given current, and so the effect is much greater.

The charge is detected as a small voltage across the probe, known as the **Hall voltage.**

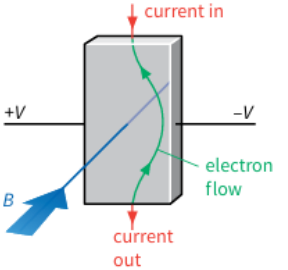


Figure 27.12 Electrons are deflected as they move through the Hall probe.

## An equation for the Hall voltage

As we have seen, this voltage arises because electrons accumulate on one side of the Hall probe. There is a corresponding lack of electrons on the opposite side, i.e. a positive charge. As a result, there is an electric field between the two sides. The electric field strength E is related to the Hall voltage $V_H$ by:

$$E = \frac{V_H}{d}$$

In some materials, the charges moving are not electrons – for example, they may be positively-charged 'holes'. Consequently we can write a more general equation for the Hall voltage replacing e with q, where q is the charge of an individual charge carrier. This gives

$$V_H = \frac{BI}{ntq}$$

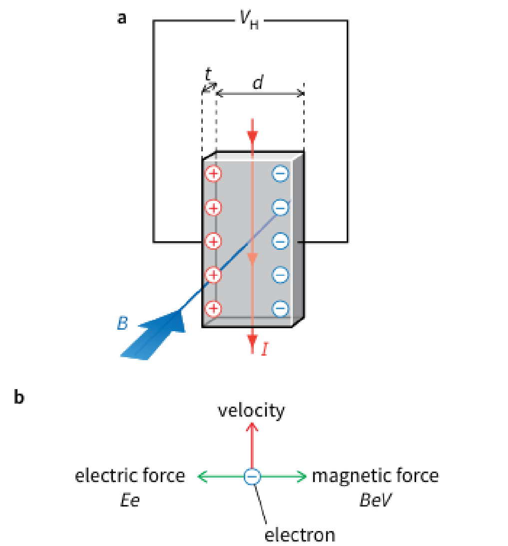


**Figure 27.13** **a** The Hall voltage is measured across the slice of semiconductor. **b** The forces on an electron when the electric and magnetic forces on it are balanced.

## Discovering the electron

One of the leaders in this field was the English physicist J.J. Thomson (Figure 27.14). In the photograph he is shown with the deflection tube which he used in his discovery of the electron. His tube was similar in construction to the deflection tube shown in Figure 27.9.

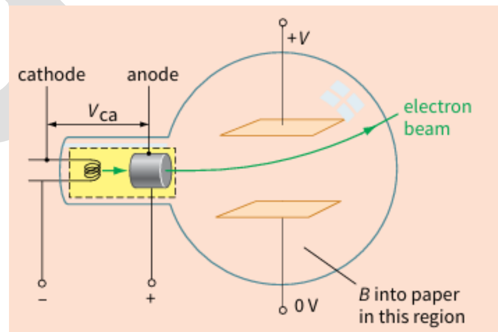


**Figure 27.9** The path of an electron beam in a deflection tube.

Here is a summary of his observations and what he concluded from them:

■ ■ The beam in his tube was deflected towards a positive plate and away from a negative plate, so the particles involved must have negative charge. This was confirmed by the deflection of the beam by a magnetic field.

■ ■ When the beam was deflected, it remained as a tight, single beam rather than spreading out into a broad beam. This showed that, if the beam consisted of particles, they must all have the same mass, charge and speed.

- By applying both electric and magnetic fields, Thomson was able to balance the electric and magnetic forces so that the beam in the tube remained straight. He could then calculate the charge-to-mass ratio $\frac{e}{m_e}$ for the particles he had discovered. Although he did not know the value of either $e$ or $m_e$ individually, he was able to show that the particles concerned must be much lighter than atoms. They were the particles which we now know as electrons. In fact, for a while, Thomson thought that atoms were made up of thousands of electrons, although his ideas could not explain how so many negatively charged particles could combine to produce a neutral atom.