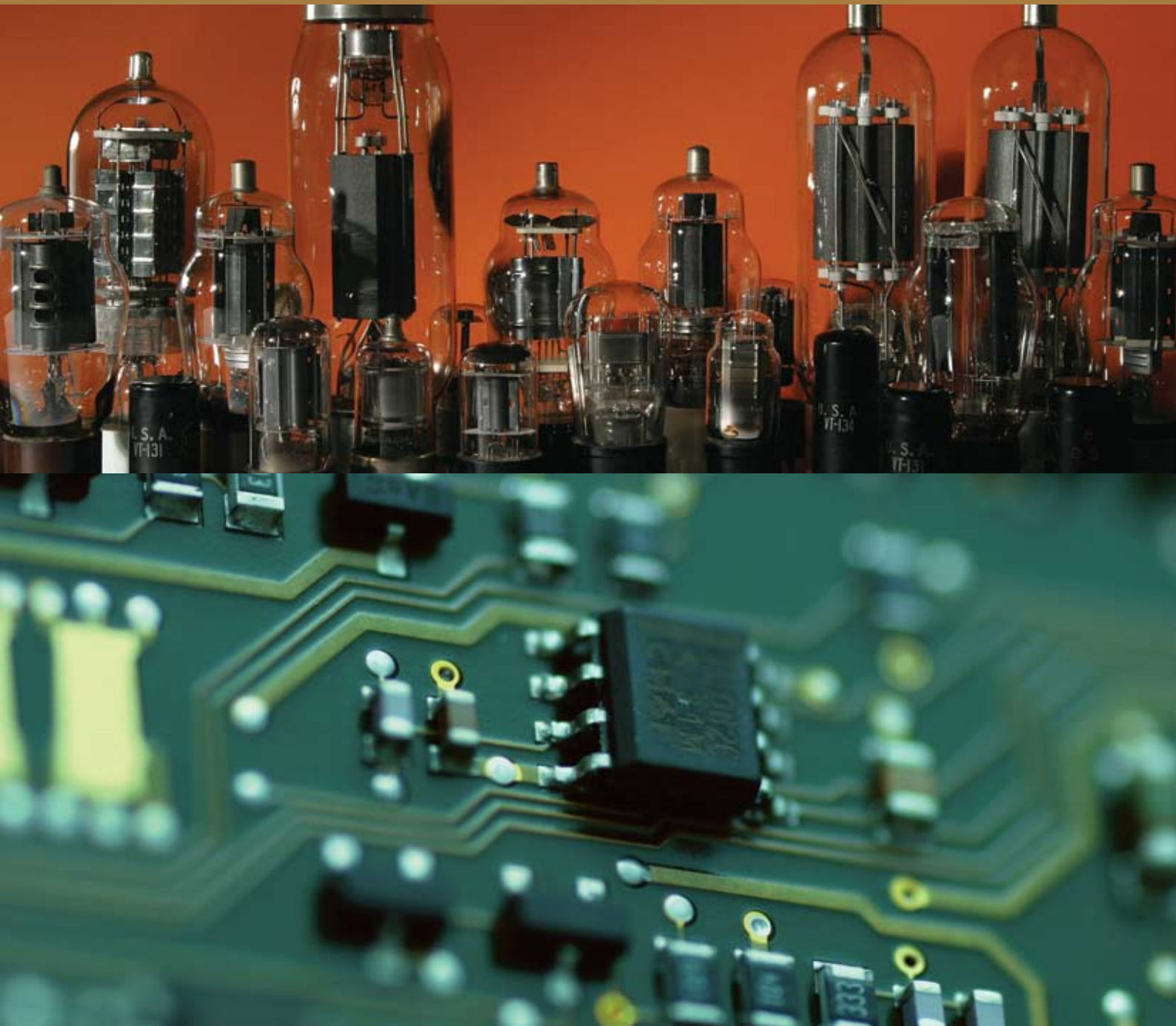




Mind map

FROM IDEAS TO IMPLEMENTATION



From CRTs to CROs and TVs

*Increased understandings of cathode rays led to the development of television***Introduction**

The first observations and experiments with cathode rays needed a number of other technical advances to be made first. These included:

1. a way of producing DC electricity
2. Faraday's work on electromagnetic induction and the induction coil
3. an improved vacuum pump
4. glass-blowing skills, to make the vacuum tubes of sufficient quality

The original investigations came about from a desire to see what would happen if a spark was made in a vacuum. Crooke's discharge tubes, a development of the original Geissler tubes, allowed the first observations of cathode rays.

The study of cathode rays helped lead scientists to the realisation that the atom was indeed made up of smaller parts. This in turn opened the door to further refined models of the atom, which were used to explain newly found observations such as the Balmer series of emission lines of hydrogen, and to enable the progress of technology to develop cathode ray tubes into useful tools in televisions and oscilloscopes. These cathode ray tube devices have only just been superseded by liquid crystal display and plasma screen technologies.

10.1

A cathode ray tube: the idea

What is a cathode ray tube and what are cathode rays?

A cathode ray tube (CRT) consists of an evacuated glass tube (almost all gas removed) and two metal electrodes, one embedded at each end of this glass tube. The two electrodes are connected to a power source, usually via an induction coil.

The electrode connected to the negative terminal of the power source is named the **cathode**, while the electrode connected to the positive terminal is named the **anode**. When the power is on, the **cathode rays**, which we know today are in fact moving electrons (this was not understood historically; see later sections), flow from the negative cathode to the positive anode inside the tube just like in an electric circuit.

Figure 10.1 is a schematic drawing of a fundamental CRT. This structure is modified to form the basis of many useful electronic appliances, as discussed later.



NOTE: A CRT is sometimes also known as a discharge tube.

A cathode ray tube



Essential requirements for a functional CRT

- **Low pressure:** A functional CRT must have its glass tube evacuated to a very low gas pressure, preferably close to vacuum. This is because the cathode and anode are separated by quite a large distance inside the tube. The low pressure inside the tube ensures minimal collisions between the air molecules inside the tube and the electrons (cathode rays) as they make their way from the cathode to the anode. (The effect of various pressures on the nature of the discharge inside a cathode tube is briefly discussed in the first-hand investigation section.)
- **High voltage:** Low pressure alone is not enough to ensure the electricity can ‘jump’ across such a big gap. Extremely high voltage is required to pull the electrons off the cathode and have enough kinetic energy to make their way from the cathode to the anode. It is important to note that CRTs only work on DC; hence, transformers cannot be used to step up the voltage to the required value (Why?). Instead, an induction coil is used to step up the voltage.

Before we can continue our study of CRTs, we must first learn about **electric fields** and how charged particles behave in electric and **magnetic fields**.

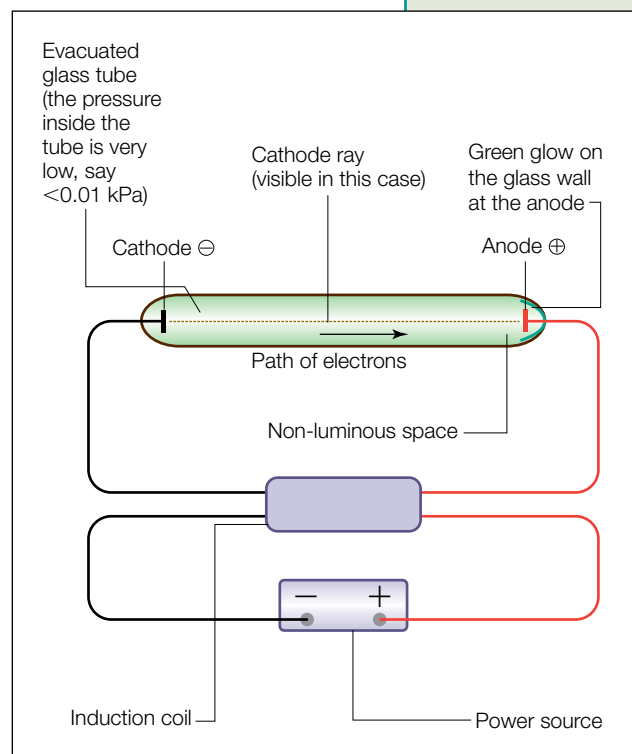


Figure 10.1
Induction coil and power source

Electric fields

- **Identify that charged plates produce an electric field**
- **Discuss qualitatively the electric field strength due to a point charge, positive and negative charges and oppositely charged parallel plates**
- **Describe quantitatively the electric field due to oppositely charged parallel plates**

Definition

An **electric field** is a region in which charged particles experience a force.

An electric field is a vector quantity, which means it must have both magnitude and direction:

Definition

The **strength of an electric field** at any point is defined as the size of the force acting per unit of charge.

The **direction of the electric field** at any point is defined as the direction of the force a positive charge would experience placed at this point.

10.2

Electric fields associated with various charged objects

Electric field around a point charge

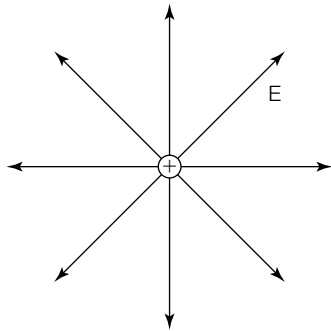


Figure 10.2 Electric field around a positive charge

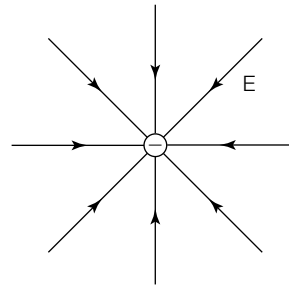


Figure 10.3 Electric field around a negative charge



NOTE: The density of the field lines represents the strength of the electric field, and the arrows point in the direction of the electric field.

Electric field between charges

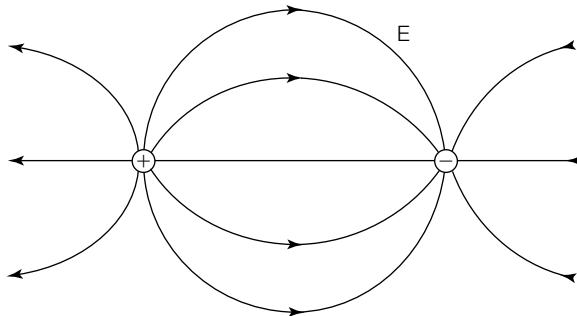


Figure 10.4 Electric field between a positive and negative charge

Electric field between a pair of parallel electric plates

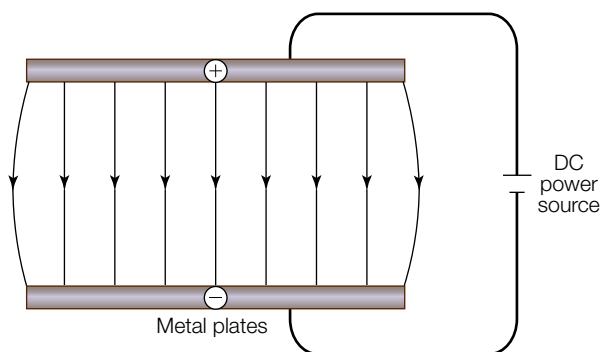


Figure 10.5 Electric field between a pair of parallel electric plates



NOTE: The parallel field lines represent uniform electric field.

Parallel plates

The **strength of the electric field** between a pair of parallel electric plates is proportional to the size of the applied voltage and inversely proportional to the distance separating the plates. It is governed by the equation:



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

Where:

E = the strength of the electric field, measured in V per metre (E can also be measured in N C^{-1})

V = the supplied voltage, measured in V

d = the distance of separation between the electric plates, measured in m

■ *Solve problems and analyse information using: $E = \frac{V}{d}$*

Example

A capacitor is built using a pair of parallel electric plates. If the voltage applied to the plates is 1400 V, and the distance separating the two plates is 0.70 cm, determine the strength of the electric field produced.

Solution

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

$$V = 1400 \text{ V}$$

$$d = 0.70 \text{ cm} = 0.0070 \text{ m}$$

$$\begin{aligned} E &= \frac{1400}{0.0070} \\ &= 2.0 \times 10^5 \text{ V m}^{-1} \end{aligned}$$

See Section 10.3 for examples of $E = \frac{V}{d}$ using $F = qvB \sin \theta$ and $F = qE$.



Worked examples
17, 18

10.3

Forces acting on charged particles in electric and magnetic fields



Worked examples
17, 18

- *Identify that moving charged particles in a magnetic field experience a force*
- *Describe quantitatively the force acting on a charge moving through a magnetic field $F = qvB\sin\theta$*
- *Solve problems and analyse information using: $F = qvB\sin\theta$ and $F = qE$*

Recall that a charge experiences a force inside an electric field, and a charge that moves at a **constant velocity** also experiences a force inside a magnetic field.

Force on a charge in an electric field

Magnitude

The magnitude of the force acting on a charge when it is in an electric field will be equal to the product of the strength of the field and the size of the charge; it is governed by the equation:

$$F = qE$$

Where:

F = the size of the force acting on the charge, measured in N

E = the strength of the electric field, measured in V m^{-1} (or N C^{-1})

q = the size of the charge, measured in C

Direction

For positive charges, the forces act in the direction of the electric field.
For negative charges, the forces act in the opposite direction to the electric field.



NOTE: One can also deduce the direction of the forces by using the fact that charges are attracted to the opposite polarity and repelled by the same polarity; for instance, in the case of a pair of electric plates, a positive charge will be repelled by the plate that is positive and attracted to the negative plate

Example 1

A small object carrying a positive charge of 5.0 mC is placed inside an electric field with strength of $2.4 \times 10^3 \text{ V m}^{-1}$ directed towards the right. Determine the strength and direction of the force acting on this object.

Solution:

$$F = qE$$

$$q = 5.0 \times 10^{-3} \text{ C}$$

$$E = 2.4 \times 10^3 \text{ V m}^{-1}$$

$$\begin{aligned} F &= 5.0 \times 10^{-3} \times 2.4 \times 10^3 \\ &= 12 \text{ N} \end{aligned}$$

To the right, because for positive charges, the forces act in the direction of the electric field.

Example 2

Suppose an oil drop carrying a negative charge of 6.40×10^{-19} C is placed carefully inside a uniform electric field created by a horizontal pair of parallel electric plates. The parallel plates have a voltage supply of 1550 V with the top plate positive, and the separation distance is 1.20 cm.

- Determine the strength and direction of the electric field produced by the electric plates.
- If the oil drop is to be suspended mid-way between the two plates, find the mass of the oil drop.
- If the polarity of the parallel plates is suddenly reversed, calculate the acceleration of the oil drop.

Solution

$$(a) \ E = \frac{V}{d}$$

$$V = 1550$$

$$d = 0.012 \text{ m}$$

$$E = \frac{1550}{0.012}$$

$$\approx 1.29 \times 10^5 \text{ V m}^{-1}$$

Direction: down, that is, the electric field runs from the top positive plate to the bottom negative plate.

- The oil drop can only be suspended if its weight force is exactly balanced by the upward force it experiences due to the electric field. That is:

Weight force = force due to the electric field

$$\text{i.e. } \mathbf{F}_g = \mathbf{F}_E$$

$$\mathbf{F}_E = q\mathbf{E}$$

$$\mathbf{F}_E = (6.4 \times 10^{-19}) \times (1.3 \times 10^5)$$

$$\approx 8.27 \times 10^{-14} \text{ N}$$

Thus:

$$\mathbf{F}_g = 8.27 \times 10^{-14} \text{ N}$$

$$\text{Also } \mathbf{F}_g = mg$$

$$m = \text{mass of the oil drop}$$

$$g = 9.8 \text{ m s}^{-2}$$

$$m = \frac{\mathbf{F}_g}{g}$$

$$= \frac{8.27 \times 10^{-14}}{9.8}$$

$$\approx 8.44 \times 10^{-15} \text{ kg}$$

- When the polarity is reversed, the net force acting on the oil drop will no longer be zero. The oil drop will experience a downward force which is the sum of its weight and the electric force, thus an acceleration results.

$$\mathbf{F} = ma$$

$$\mathbf{F} = 8.27 \times 10^{-14} \times 2 \text{ N}$$

$$m = 8.44 \times 10^{-15} \text{ kg}$$

$$a = \frac{F}{m}$$

$$= \frac{8.27 \times 10^{-14} \times 2}{8.44 \times 10^{-15}}$$

$$\approx 19.6 \text{ m s}^{-2}, \text{ down (since the force is acting downwards)}$$

Example 3

The top plate of a horizontal pair of parallel electric plates is positive. The plates produce a uniform electric field of 9500 N C^{-1} between them. An electron is projected into the electric field horizontally to the left.

- Determine the force experienced by the electron due to the electric field as it passes through the field.
- Describe the motion of the electron as it moves through the electric field.
- Does gravity affect the motion of the electron? Discuss.

Solutions

$$\begin{aligned}\text{(a) } \mathbf{F} &= q\mathbf{E} \\ &= 1.6 \times 10^{-19} \times 9500 \\ &= 1.52 \times 10^{-15} \text{ N, up}\end{aligned}$$



NOTE: Here, the unit for the electric field is N C^{-1} , and is equivalent to V m^{-1} .

- The horizontal component of the electron's motion—to the right—will be subject to no net force (assuming no friction), and thus remains constant throughout. The vertical component will be subject to an upward force, hence acceleration. Therefore, the electron will move towards the right while at the same time curving upwards, like an upside-down projectile.
- The weight force of the electron acts downwards, which therefore in theory should counteract the upward force due to the electric field. However, the weight force on the electron is as little as $9.11 \times 10^{-31} \times 9.8 = 8.9 \times 10^{-30} \text{ N}$, which is almost 15 orders of magnitude smaller than the force due to the electric field; thus in reality the weight force will have virtually no effect on the motion of the electron.

Force on a charge inside a magnetic field**Magnitude**

The magnitude of the force acting on a charged particle as it moves through a magnetic field is governed by the equation:

$$\mathbf{F} = q\mathbf{vB}\sin \theta$$

Where:

\mathbf{F} = the size of the force acting on the charge, measured in N

q = the size of the charge, measured in C

\mathbf{v} = the velocity of the charge relative to the magnetic field, measured in m s^{-1}

\mathbf{B} = the strength of the magnetic field, measured in T

θ = the angle at which the charge enters the magnetic field, measured in degrees ($^{\circ}$)



NOTE: Students may want to remember ' qvB ' as 'Queen Victoria Building.'

Direction

The direction of the force acting on a charge as it moves through a magnetic field can be determined by applying the **right-hand palm rule**.

Definition

The **right-hand palm rule** states: when the thumb of the right hand points to the direction in which the positive charge is moving (or to the opposite direction to which the negative charge is moving), and the fingers point to the direction of the external magnetic field, then the palm pushes in the direction of the force (see Fig. 10.6).

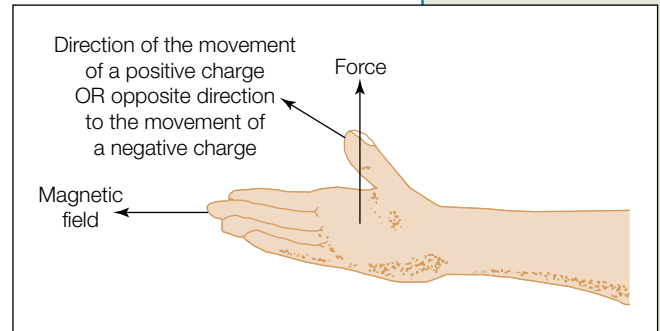


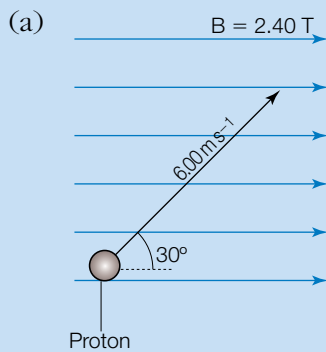
Figure 10.6
Applying the right-hand palm rule to moving charges



NOTE: Recall a negative charge moving in one direction is equivalent to a positive charge moving in the opposite direction

Example 1

Determine the size and direction of the forces acting on the following charges:



Force on a charge inside a magnetic field

Solution

$$F = qvB \sin \theta$$

q = charge of a proton

$$= 1.602 \times 10^{-19} \text{ C}$$

$$v = 6.00 \text{ m s}^{-1}$$

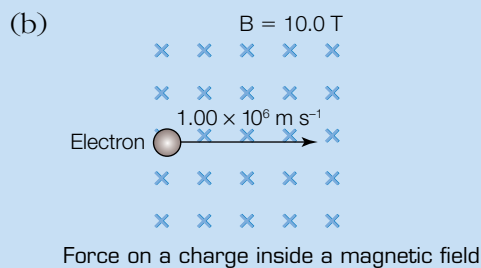
$$B = 2.40 \text{ T}$$

$$\theta = 30^\circ$$

$$\therefore F = (1.602 \times 10^{-19}) \times 6.00 \times 2.40 \times \sin 30^\circ$$

$$F \approx 1.15 \times 10^{-18} \text{ N}$$

Direction: Into the page, that is, thumb points in direction of v , fingers to the right, palm pushes into the page.

**Solution**

$$F = qvB \sin \theta$$

$$q = \text{charge of an electron} \\ = -1.602 \times 10^{-19} \text{ (negative)}$$

$$v = 1.0 \times 10^6 \text{ m s}^{-1}$$

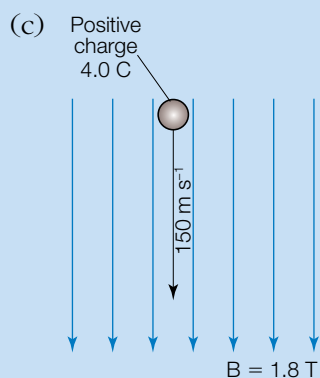
$$B = 10 \text{ T}$$

$$\theta = 90^\circ \text{ since the pathway of the } e^- \text{ is } \perp \text{ to the field lines}$$

$$\therefore F = (1.602 \times 10^{-19}) \times 1.0 \times 10^6 \times 10 \times \sin 90^\circ$$

$$F = 1.6 \times 10^{-12} \text{ N}$$

Direction: Down the page.

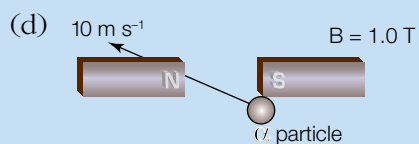
**Solution**

$$F = qvB \sin \theta$$

$$\theta = 0^\circ, \text{ since the pathway of the charge is parallel to the magnetic field lines}$$

$$\therefore F = 4.0 \times 150 \times 1.8 \times \sin 0^\circ$$

$$F = 0 \text{ N}$$



Solution

$$F = qvB \sin \theta$$

$$q = 2 \times \text{charge of a proton}$$

$$= 2 \times 1.602 \times 10^{-19}$$

$$\theta = 90^\circ$$

$$\therefore F = (2 \times 1.602 \times 10^{-19}) \times (10) \times (1.0) \times \sin 90^\circ$$

$$F = 3.2 \times 10^{-18} \text{ N}$$

Direction: Down, because magnetic field runs from 'N' to 'S', so fingers point to the right. Thumb into the page.



Simulation:
magnetic forces

Example 2

A helium nucleus is moving to the right at a constant velocity. As it passes through a magnetic field with a strength of 2.0 T perpendicularly, it experiences an upward force of 1.28×10^{-17} N.

- Determine the direction of this magnetic field.
- Calculate the velocity at which the helium nucleus is moving.

Solution

- Into the page, that is, thumb to the right, palm pushes up, thus fingers are into the page.

$$(b) F = qvB \sin \theta$$

$$F = 1.28 \times 10^{-17} \text{ N}$$

$$q = 2 \times 1.6 \times 10^{-19} \text{ C (since the helium nucleus has a double positive charge)}$$

$$v = ?$$

$$B = 2.0 \text{ T}$$

$$\theta = 90^\circ$$

$$v = \frac{F}{qB \sin \theta}$$

$$v = \frac{1.28 \times 10^{-17}}{(2 \times 1.6 \times 10^{-19}) \times 2.0 \times \sin 90^\circ}$$

$$v = 20 \text{ m s}^{-1}, \text{ to the right.}$$

Example 3

Suppose a very strong magnetic field is directed into the page. An electron that is moving at a constant velocity enters this magnetic field from the right, as shown in Figure 10.7. Describe the subsequent motion of this electron.

Solution

The electron will describe a circle inside this magnetic field, as shown in Figure 10.7. The magnetic force ($F = qvB \sin \theta$) acting on the electron provides the centripetal force for this circular motion.

Explanation: As the electron enters the magnetic field, the right-hand palm rule shows that it will experience an upward force that causes it

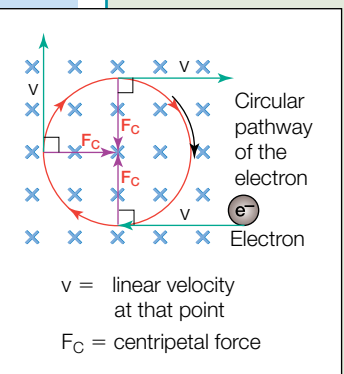


Figure 10.7 Force on an electron inside a magnetic field

to curve up. If we then follow the charge and continue applying the right-hand palm rule on the charge as it curves inside the magnetic field, we will find that the magnetic force is always perpendicular to the direction in which the charge is travelling. By definition, a motion in which the forces always act perpendicularly to the linear velocity is a circular motion. Hence, it follows that the magnetic force provides the centripetal force for the circular motion described by this electron.



NOTE: If the magnetic field is weak, then the electron will not describe a full circle within it; instead, it will curve up as an arc of a circle.

10.4

Debates over the nature of cathode rays: waves or particles?

- *Explain why the apparent inconsistent behaviour of cathode rays caused debate as to whether they were charged particles or electromagnetic waves*

Today, we know that the cathode rays produced by a CRT are beams of electrons. However, a little over 100 years ago, scientists were vigorously debating the nature of these cathode rays, particularly in deciding whether cathode rays were indeed waves (rays) or particles. German scientists including Heinrich Hertz strongly believed cathode rays were waves. Hertz mistakenly 'proved' that cathode rays could not be deflected by electric plates because there was a small amount of gas in his CRT. In addition, the fact that cathode rays could cast shadows and be diffracted as well as cause fluorescence provided evidence for the wave nature of cathode rays.

On the other hand, English scientists strongly supported the particle nature of cathode rays. Experiments that showed cathode rays were able to charge objects negatively through interaction. Other experiments with paddle wheels showed cathode rays carried and were able to transfer momentum. These suggested cathode rays were particles.

Each group was desperately trying to prove the other party wrong, but could not provide strong and convincing evidence to support their own theory. The debate was eventually settled in 1897, when British scientist J. J. Thomson conducted his famous experiment to measure the **charge to mass ratio** for cathode rays, consequently successfully proving the particle nature of cathode rays.

10.5

J. J. Thomson's charge to mass ratio experiment

- *Explain that cathode ray tubes allowed the manipulation of a stream of charged particles*
- *Outline Thomson's experiment to measure the charge to mass ratio of an electron*



NOTE: You should be able to confidently reproduce the content of this experiment and its implications, including sketching the diagrams.

Aim

The aim of the experiment is to measure the charge to mass (q/m) ratio of cathode rays.

Procedure

Before conducting the experiment, Thomson assumed that cathode rays were negatively charged particles and were emitted from the cathode. He set up a CRT similar to the one shown in Figure 10.8 (a) and (b). The experiment involves two parts.

Part I: Finding an expression for the velocity of the cathode ray

- A beam of cathode ray is emitted at the cathode and is made to accelerate towards the multi-anode collimators to enter the main part of the tube, as shown in Figure 10.8 (a). This ensures the cathode ray that enters the main tube is fine and well defined. The beam keeps travelling in a straight line to reach the end of the tube and strikes the mid-point of the fluorescent screen.
- The electric field is turned on by switching on the voltage supply to the electric plates. The beam is deflected in the direction opposite to that of the electric field, say for this case up (see Fig. 10.8a). This idea was illustrated in example 3 on page 174—electric charges experience a force inside an external electric field, which causes a deflection.
- The magnetic field is turned on by supplying a current to the coil. The current is directed so that the magnetic field produced by the coil deflects the cathode ray in the opposite direction to that imposed by the electric field, say for this case down (see Fig. 10.8a).
- The strengths of the electric and magnetic fields are adjusted so that the deflections created by each field exactly balance out. Consequently the beam will travel to the end of the tube undeflected, and will again hit the middle of the fluorescent screen.
- Thus the force acting on the cathode ray from the electric field can be equated to the force acting from the magnetic field; hence:

$$F_E = F_B$$

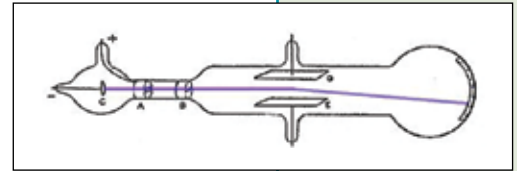
$$F_E = qE \text{ and}$$

$$F_B = qvB \sin \theta = qvB \text{ (since } \theta \text{ is } 90^\circ, \text{ because the cathode ray is always perpendicular to the magnetic field)}$$

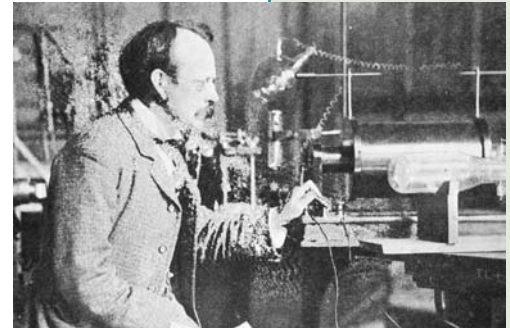
Therefore:

$$qE = qvB$$

$$v = \frac{E}{B}$$



Thomson's apparatus



J. J. Thomson

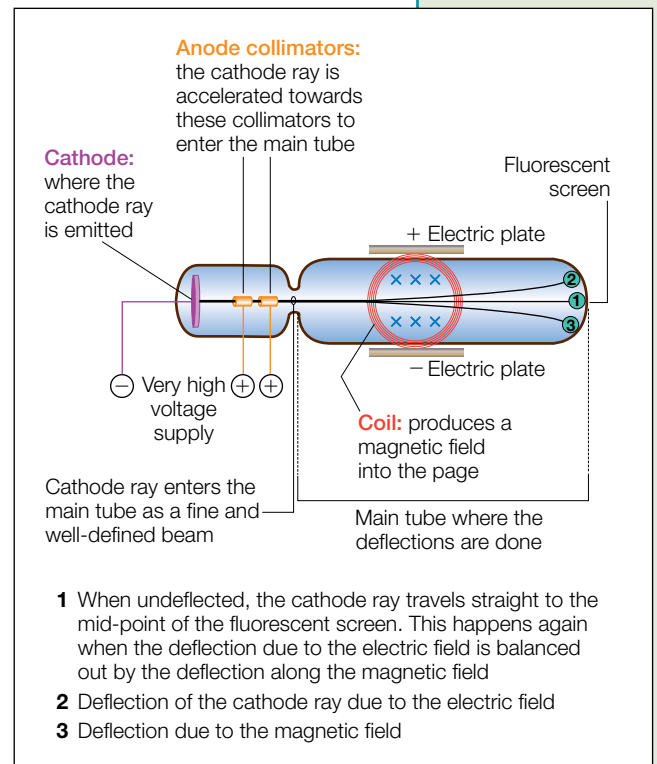


Figure 10.8 (a)
A CRT used by Thomson to measure the ' q/m ' of cathode rays

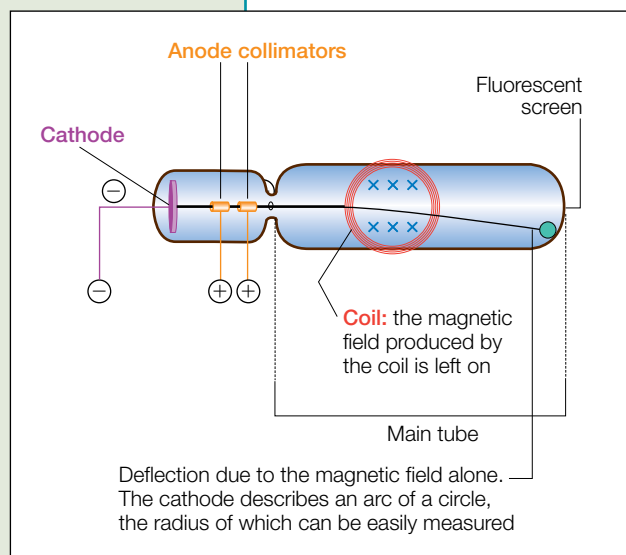


Figure 10.8 (b)
A CRT used by Thomson to measure the ' q/m ' of cathode rays

Part II: Finding the charge to mass ratio of the cathode ray

- The electric field is then turned off and the magnetic field is left on. The cathode ray is deflected by the magnetic field only, and thus curves down in an arc of a circle as shown in Figure 10.8 (b).



NOTE: This principle was outlined in example 3 on page 177.

- Since the magnetic force ($\mathbf{F} = q\mathbf{v}\mathbf{B}$) provides the electron with the centripetal force:

$$\mathbf{F}_c = \mathbf{F}_B$$

$$\mathbf{F}_c = \frac{mv^2}{r} \quad (\text{where } r \text{ is the radius of the arc described by the cathode ray); and}$$

$$\mathbf{F}_B = q\mathbf{v}\mathbf{B}$$

Therefore:

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

$$mv = qrB$$

$$\frac{q}{m} = \frac{v}{rB}$$

Since $v = \frac{E}{B}$, therefore:

$$\frac{q}{m} = \frac{E}{rB^2}$$

- The strength of the electric field (\mathbf{E}) and magnetic field (\mathbf{B}) can be determined (by measuring the size of the applied voltage and current) and the radius r of the arc described by the cathode ray can be measured. Thus the charge to mass ($\frac{q}{m}$) ratio can be calculated.

Conclusions from the experiment and their implications

- The experiment proved cathode rays were indeed (negatively charged) particles:* The fact that the charge to mass ratio of cathode rays was successfully measured indicated that cathode rays had measurable mass, which in turn provided definitive evidence for the particle nature of cathode rays. (Waves do not have mass.) This effectively ended the debate over the nature of cathode rays.
- It showed that the particles had a large (negative) charge with very little mass* (especially compared to alpha particles).
- It contributed to the discovery of electrons and the development of the models of atoms:* The results from the experiment laid the foundation for Thomson's discovery that cathode rays were in fact a new class of particles, later to be called electrons. The fact that *the same charge to mass ratio was measured even when*

different materials were used as the cathode indicated that cathode rays (electrons) are common to all types of atoms. This was one piece of evidence that led Thomson to believe electrons were subatomic particles, and later to propose the 'plum pudding' model of atoms. (See Chapter 14.)

- *It allowed the mass of electrons to be calculated:* Millikan's famous oil drop experiment (not required by the syllabus) accurately determined the charge of electrons. Knowing the charge to mass ratio of electrons, the mass of electrons could be easily calculated. Later, a similar idea was used to measure the charge to mass ratio for protons, from which other useful information was deduced.

USEFUL WEBSITES

Further information on J. J. Thomson's experiments:

<http://dbhs.wvusd.k12.ca.us/webdocs/AtomicStructure/Disc-of-Electron-Intro.html>

Hear J. J. Thomson speak of 'the electron':

<http://www.aip.org/history/electron/jjsound.wav>



Properties of cathode rays

- *Perform an investigation to demonstrate and identify properties of cathode rays using discharge tubes:*
 - *containing a Maltese cross*
 - *containing electric plates*
 - *with a fluorescent display screen*
 - *containing a glass wheel*
 - *analyse the information gathered to determine the sign of the charge on cathode rays*



CRT containing a Maltese cross, electric plates, fluorescent display screen, glass wheel

Even before J. J. Thomson had performed his experiment to measure the charge to mass ratio for cathode rays, scientists like William Crookes had built many high-quality CRTs to investigate the physical properties of cathode rays.

Some of the physical properties of cathode rays are described below. Most of these properties can be easily demonstrated in school laboratories as shown in the photos above. These properties were stated or described long before the nature of cathode rays was identified. Now that we know that cathode rays are fast moving electrons, all these properties make a lot more sense.



NOTE: You should remember how cathode rays would behave physically in each situation and be confident in reproducing the diagrams.

FIRST-HAND INVESTIGATION

PHYSICS SKILLS

H14.1A, B, E, G, H



Risk assessment matrix

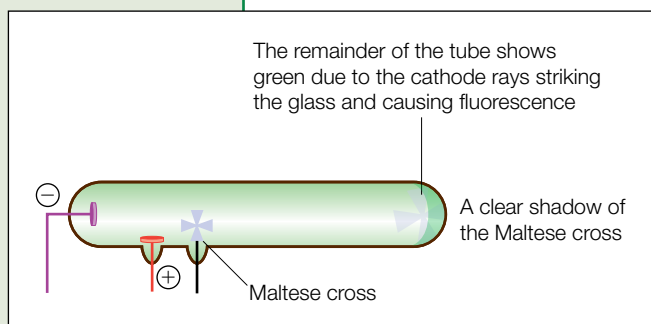


Figure 10.9
CRT containing a
Maltese cross

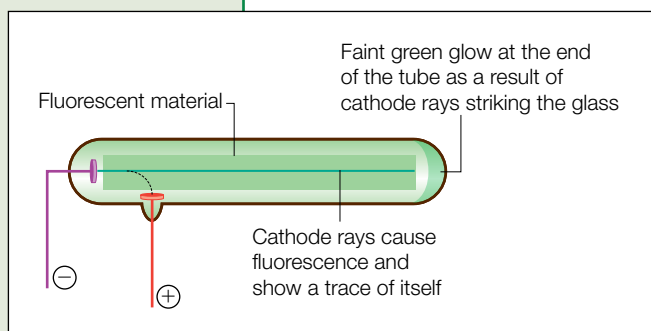


Figure 10.10
CRT with
fluorescent
background
material

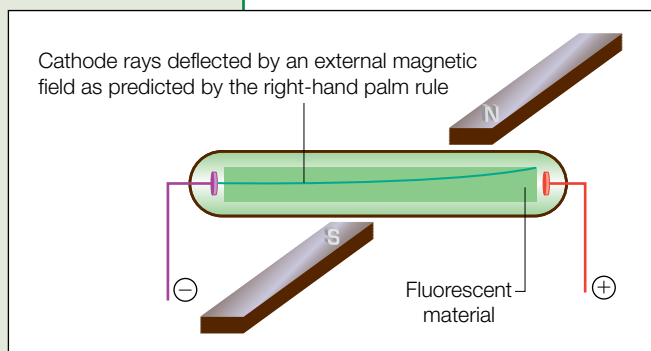


Figure 10.11
Cathode ray
reflected by
magnetic field

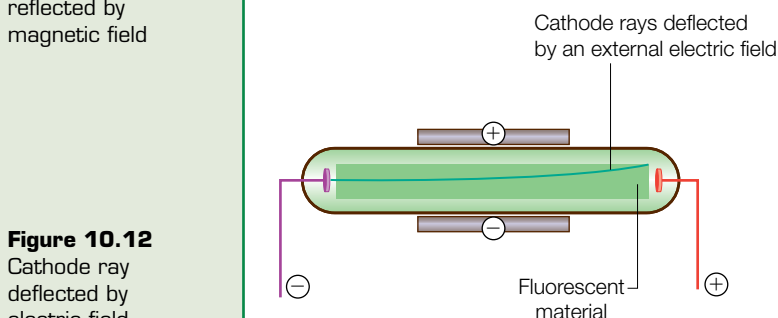


Figure 10.12
Cathode ray
deflected by
electric field

- **Cathode rays are emitted at the cathode and travel in straight lines:** This is shown by using a CRT containing a Maltese cross (see Fig. 10.9). The cathode rays illuminate the Maltese cross and cast a clearly defined shadow of it at the other end of the tube.

ANALOGY: This property is similar to light, which is able to cast a clearly defined shadow because it travels in a straight line.

- **Cathode rays can cause fluorescence:** This is shown by using a CRT containing a background fluorescent material (see Fig. 10.10); as the cathode ray passes from the cathode to the anode, it causes this material to fluoresce and leave a clear trace of itself. Cathode rays are also able to cause the wall of the glass tube to glow, as shown in many of the other scenarios.
- **Cathode rays can be deflected by magnetic fields:** When a pair of bar magnets is placed next to the CRT from the previous example (see Fig. 10.11), the cathode rays are deflected as predicted by the right-hand palm rule.
- **Cathode rays can be deflected by electric fields:** Similarly, when a pair of electric plates is used (see Fig. 10.12), the cathode rays are deflected in the direction opposite to that of the electric field.



NOTE: Hertz was not able to show cathode rays being deflected by an electric field, and this led him to believe cathode rays were waves.

- **Cathode rays carry and are able to transfer momentum:** This is shown by using a CRT containing a paddle wheel (see Fig. 10.13). As the cathode rays strike the paddle wheel, some of their momentum is transferred to the paddle, which makes the paddle wheel roll in the same direction as the cathode rays are travelling.
- **Cathode rays are identical regardless of the type of material used as the cathode:** Cathode rays can also facilitate some chemical reactions and expose photographic films.

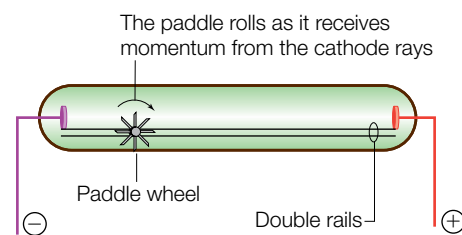


Figure 10.13 A CRT containing a paddle wheel

10.6

Applications of cathode ray tubes (CRTs):
implementation

- **Outline the role of:**
- *electrodes in the electron gun*
 - *the deflection plates or coils*
 - *the fluorescent screen*
- in the cathode ray tube of conventional TV displays and oscilloscopes**

Having learnt a lot about CRTs and cathode rays, we can now turn to the implementations of CRTs, that is, how CRTs are used in common electrical appliances, such as cathode ray oscilloscopes and televisions.

Cathode ray oscilloscope

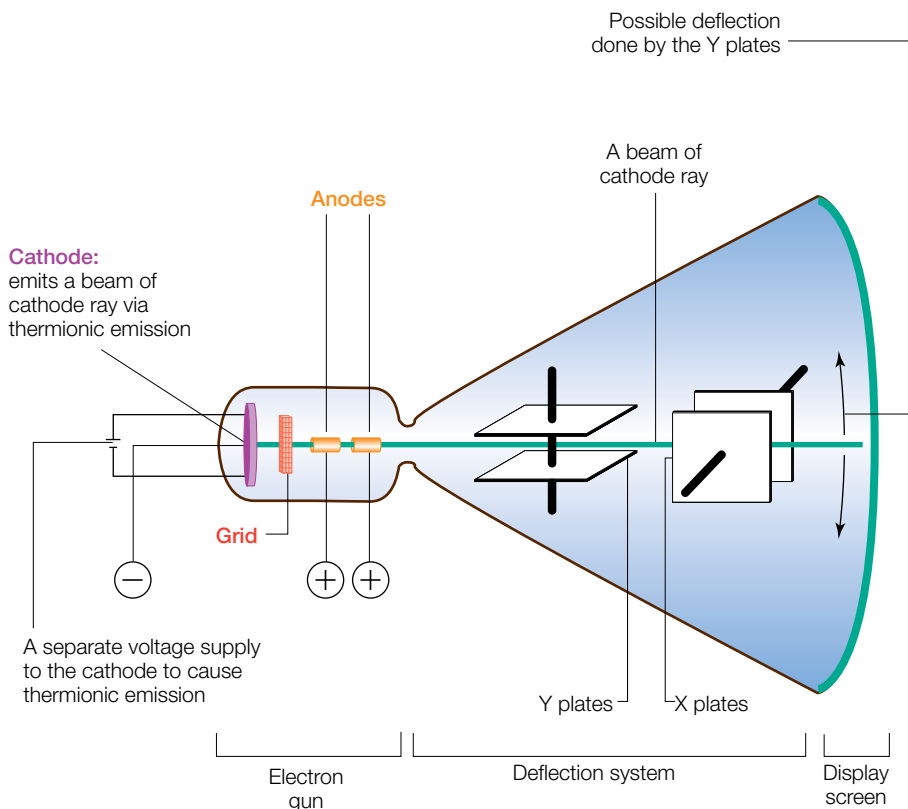
Standard cathode ray oscilloscopes (CROs) are commonly used in science to display the pattern and strength of electric signals in waveforms, from which useful measurements can be obtained. In school laboratories, CROs can be used to measure AC voltages, as mentioned in Chapter 7, or to study sound waves when a microphone is connected to them, as you may have done in the preliminary course.

In more advanced settings, modified CROs were once used in radar systems. CROs are also used in electrocardiogram (ECG) machines, medical devices that display a person's heartbeats as electric signals.

So how are CRTs modified in order to carry out these functions?



A CRO

Figure 10.14 (a)
A CRO

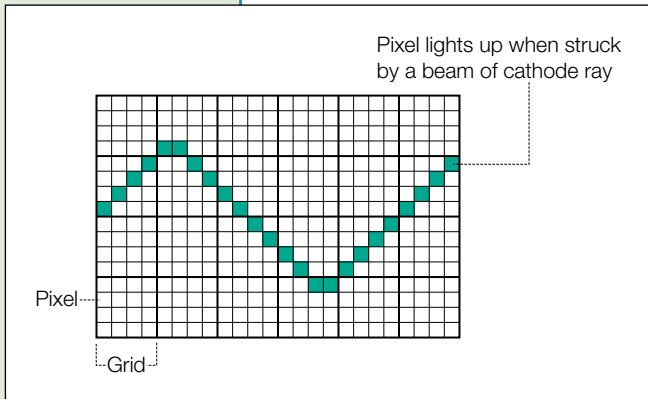


Figure 10.14 (b)
CRO display screen

A standard CRO consists of (see Fig. 10.14a):

- An electron gun, which emits a beam of cathode rays.
- A deflection system, which consists of two sets of parallel electric plates.
- A display screen that has on its inner surface materials that will fluoresce when struck by the cathode rays. The screen usually contains a grid that makes displays easier to read and measure.

Electron gun

As shown in Figure 10.14 (a), the electron gun resembles the one used in Thomson's experiment. A beam of electrons is emitted at the cathode and is accelerated towards the multiple anodes, and then travels into the deflection part of the tube as a fine, well-defined beam.

Two additional features need to be mentioned here. First, in addition to the high voltage supply across the cathode and anodes, a separate small voltage is supplied to the cathode to generate a current in it to heat it. The heated cathode then releases many free electrons. Once freed, these electrons can be accelerated towards the anodes with little effort. This technique is known as the **thermionic emission**, and is utilised here to ensure a high electron density in the cathode ray. For this reason, devices like some CRTs are also named **thermionic devices**. Second, there exists another electrode in between the cathode and anode, which is named the **grid**. Making the grid more positive or negative with respect to the cathode controls the number of electrons reaching the anodes and hence striking the display screen per unit time, which consequently controls the intensity of the cathode ray and thus the brightness of the display.

Deflection system

The deflection system in a CRO helps to manipulate the cathode ray so that useful information can be displayed on the screen. The deflection system of a CRO consists of two sets of parallel electric plates; one pair controls vertical deflections while the other pair controls horizontal deflections.

- *Y plates*: These plates are horizontal and thus are responsible for vertical deflections of the cathode ray. The voltage supply to these plates is an amplified copy of the external signal input, that is, the pattern and the range of deflection is directly related to the type and strength of the input signal.
- *X plates*: These plates are vertical and thus are responsible for horizontal deflections of the cathode ray. Unlike the Y plates, the voltage supply to these plates is normally independent of the external signal input; rather the plates are controlled by inbuilt circuitry that supplies a **time-based voltage**. This signal deflects the cathode ray across the screen from left to right, and then the polarity of the plates quickly reverses so that the cathode ray is deflected swiftly from right to left (quick enough so that this is not seen). By adjusting the pattern of the time-based voltage, one can make the left to right deflection run at different speeds—really slowly across the screen as a dot or so fast so that the dot has an appearance of a line.

By superimposing vertical and horizontal deflections, the cathode ray will move up and down as well as from left to right across the screen, consequently a wave-front display can be obtained.

Display screen

The screen contains many pixels made from fluorescent materials, or **phosphors**. When the fine beam of the cathode ray strikes a pixel, the pixel fluoresces, which allows the information to be displayed (see Fig. 10.14b). Once the beam moves on from a pixel, the fluorescence persists for a short time, then fades.

A CRO displays a signal as a voltage-time graph, and accurate measurements can be obtained with the help of the grid on the screen, a set of 1 cm by 1 cm squares. The vertical voltage can be adjusted, for instance 1 V/cm, 10 V/cm and so on. Horizontally, the grid represents time, which is also freely adjustable, for instance, 1 ms/cm, 10 ms/cm and so on. By knowing these settings, as well as examining the waveform being displayed (i.e. counting the number of grids vertically and horizontally), useful information can be calculated, for instance the amplitude of the wave from the number of vertical grids and the period of the wave from the number of horizontal grids.

If the input signal repeats itself with a suitable period, adjusting the time-based voltage allows the image formed by each new sweep of the beam of the cathode ray to be superimposed onto the previous image, so that a stable image can be viewed. This makes the interpretation of the display easier.



NOTE: Do not confuse 'pixels' and 'grids'.

Television

A television uses a CRT to form images. Its basic principle is similar to that of a CRO, but with a number of marked differences.

Electron gun

Generally, the electron gun used in a TV is similar to that used in a CRO. A black and white TV has only one electron gun, whereas a colour TV has three electron guns, for red, green and blue colours, which are the three primary colours for image formation.

There is also a grid in each electron gun to control the brightness of the display. The grid and the time of turning on or off a particular electron gun are controlled by the amplified electric signals captured by an antenna that receives signals from a TV station.

Deflection system

Unlike a cathode ray oscilloscope, the deflection system of a TV utilises magnetic fields that are created by current coils. Magnetic fields are used in this case to ensure more efficient and larger deflections.

The deflection system is also controlled by the amplified electric signals derived from the antenna.

Display screen

Again, the screen consists of pixels (also known as phosphor dots), which fluoresce when struck by a beam of cathode rays. For a black and white TV, the single phosphor glows white and the intensity ranges from white—when a pixel fully lights up when struck by a beam of cathode rays with a maximal intensity—to dark (black)

when the beam intensity is reduced to zero. The intensity follows a **grey scale**. In a colour TV, each pixel has three sub-pixels of phosphor: one glows red when struck by a cathode ray, one glows green and the other glows blue. A **shadow mask** is employed in a colour TV to ensure the beam from each colour gun only hits the corresponding spot in each pixel, thus the shadow mask is essential for the correct image display in a colour TV. Essentially, the pixels in a colour TV screen only display the three primary colours; by changing the intensities of the sub-pixels, we can obtain the full colour we see everyday.

Also, unlike a CRO, where a beam of cathode rays scans across the screen relatively slowly to trace out a single dot or line, the electron guns of a TV scan a series of horizontal lines across the entire screen 50 times a second. The odd line pixels are scanned first followed by the even lines. The scanning pattern is called a **raster**. After it is struck by a beam of cathode ray, each pixel continues to shine for a short period of time, so the rapid scanning of the entire screen allows an image to be displayed on the entire TV screen without any discernible flickering.



FIRST-HAND INVESTIGATION

PFAs

H1

PHYSICS SKILLS

H13.1 A, B, E

The different striation patterns produced by cathode ray (discharge) tubes with different interior air pressure



Observing different striation patterns



- *Perform an investigation and gather first-hand information to observe the occurrence of different striation patterns for different pressures in discharge tubes*

Procedure

Often a standard kit is provided in the school laboratory. The kit usually consists of five to six discharge tubes that are held vertically and parallel to each other by a stand. Each tube contains a different preset air pressure and is sealed permanently.

The anodes of these discharge tubes are connected together to form one common outlet whereas the cathodes are separated. This means that during the operation of this kit, the positive terminal of the power source can remain attached to the anode, while attaching the negative terminal to each individual cathode selectively operates that particular discharge tube.

As mentioned before, an induction coil is required for the operation of these discharge tubes.

Observations

The following observations can be made from each discharge tube:

'High' pressure tube (say 5 kPa)



NOTE: The usual air pressure at sea level is 1 atmospheric pressure, or 101.3 kPa.

Purple streamers appear between the cathode and anode. With a slightly lower pressure tube, the streamers change to a gentle pink glow that usually fills the entire tube.

'Medium' pressure tube (say 0.1 kPa)

As we move down to an even lower pressure tube, the pink glow starts to break down into alternating bright regions and dark regions. A typical example of this type of discharge is shown in Figure 10.15.

From the cathode to the anode, the glows and dark spaces are named: Aston dark space, cathode glow, Crooke's dark space, negative glow, Faraday's dark space, positive column, anode glow and anode dark space.

The cause of the glows and dark spaces: As a general rule, a glowing region is a result of the electrons (cathode rays) from the cathode carrying different energies. When they collide with the gas molecules in the tube, they cause excitation of these gas molecules, which then release EMR. A dark space not surprisingly is usually a result of electrons having insufficient energy (perhaps due to previous collisions) to excite the gas molecules.

At even lower pressure, the dark spaces elongate, and the glow is usually faint.

'Low' pressure tube (say 0.02 to 0.04 kPa)

When the tube with an extremely low air pressure is used, the glows in the tube completely disappear, that is, the dark spaces take over and fill the entire tube. Here the entire dark space is defined as the Crooke's dark space. The only visible glow in this case is the green fluorescence on the glass wall at the anode region.

The CRTs described in this chapter are typically at this pressure.



NOTE: Although the tube is not producing striations at this pressure, this does not mean the cathode ray does not exist. Its pathway can be easily demonstrated by placing a fluorescent background inside the tube.



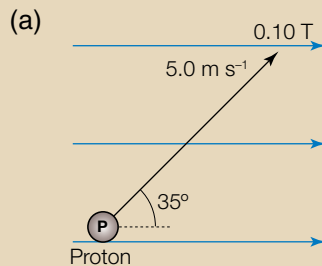
Figure 10.15
A discharge tube with a medium interior air pressure

CHAPTER REVISION QUESTIONS

For all the questions in Chapter 10, take the electrons to have a charge of -1.60×10^{-19} C and a mass of 9.11×10^{-31} kg. Take the proton to have a charge of $+1.60 \times 10^{-19}$ C and a mass of 1.67×10^{-27} kg.

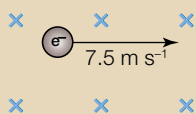


1. **Determine** the size and the direction of the force acting on the following moving charges:

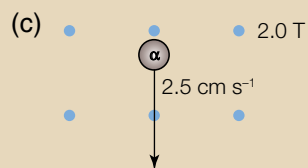


Size and direction of force on charge

(b) \times \times \times 3.0×10^{-2} T



Size and direction of force on charge



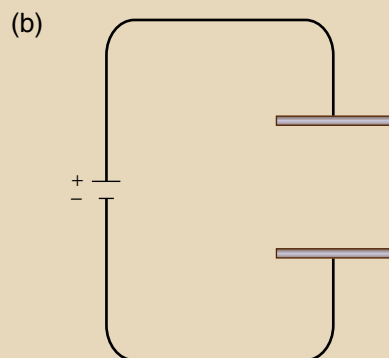
Size and direction of force on charge



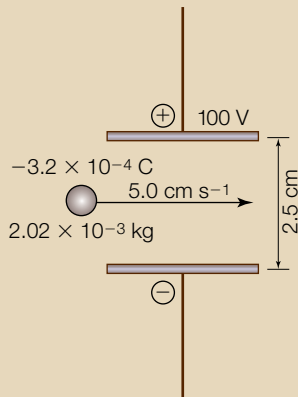
Pb (II) ion
0.20 km s⁻¹

Size and direction of force on charge

2. (a) Why does a cathode ray tube (CRT) require a high voltage to operate?
 (b) How would this high voltage be achieved?
 (c) What are the safety issues involved?
3. Today we know that cathode rays are electrons. Why was it that many decades ago, German scientists believed they were waves?
4. Draw the electric field pattern for the following cases:

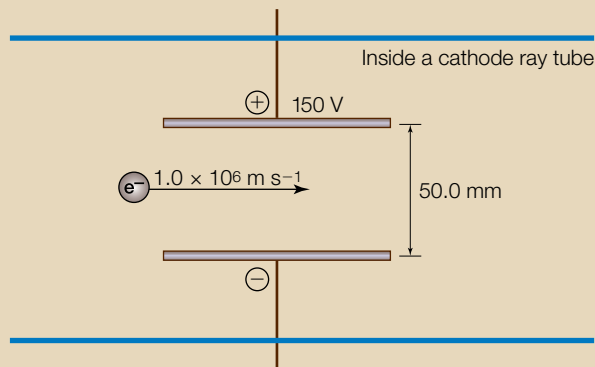


5. A charged particle is moving through a pair of charged parallel electric plates as shown in the diagram:



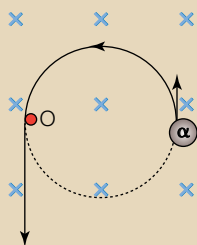
Charged particle through a pair of parallel electric plates

- Determine the strength of the electric field produced by the electric plates.
 - What is the net force acting on this charged particle, including the gravity?
 - Determine the acceleration of this charged particle.
6. The diagram below shows a CRT; a pair of parallel electric plates is placed inside this CRT.



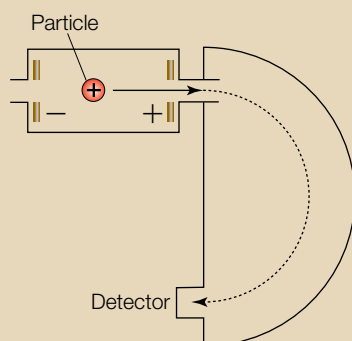
CRT and electric plates

- What will be the required voltage to produce the velocity of the electron?
 - Ignoring gravity, what is the force acting on this electron due to the electric field?
 - What magnetic field, size and direction would you need to balance the force due to the electric field?
7. An alpha particle is describing a circle inside a magnetic field that is directed into the page.
- Suppose this alpha particle is moving at 780 m s^{-1} , and the strength of the magnetic field is 10.0 T . Determine the radius of this alpha particle.
 - If we want the alpha particle to leave the magnetic field at point O in the direction as shown in diagram, how can this be achieved by using a pair of parallel electric plates?



Alpha particle describing a circle

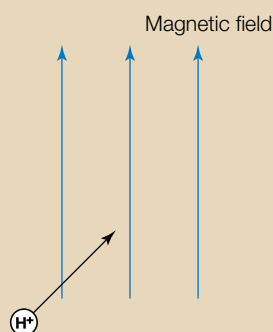
8. A mass spectrometer is used to measure the mass of a charged particle by using the deflection caused by a magnetic field. A schematic drawing is shown.



Mass spectrometer

A particle has a charge of 1.60×10^{-19} C. It is accelerated by the electric collimators to gain a velocity of 200 m s^{-1} . It then enters the semicircular compartment, where a magnetic field deflects it so that it follows an arc of a circle to reach the detector.

- State the direction of the magnetic field that is required to give rise to this deflection.
 - If the magnetic field strength is 2.5 T , and the radius of the circle is 60 cm , what is the mass of the particle?
9. **Describe** the motion of the hydrogen ion as it enters the magnetic field as shown in the diagram.



Motion of hydrogen ion

- Outline** J. J. Thomson's experiment to measure the charge to mass ratio of the cathode ray.
 - Evaluate** the impact of this experiment.
- William Crookes designed many CRTs that enabled him to demonstrate the physical properties of cathode rays. With the aid of a diagram, **describe**:
 - A tube that shows cathode rays travelling in a straight line.
 - A tube that shows cathode rays carrying momentum.
- Describe** how a cathode ray oscilloscope (CRO) is able to display an electrical signal in the form of a wave.
- Describe** two major differences between a CRO and a colour TV.



Answers to
chapter revision
questions