

HSC Physics

SAMPLE LECTURE SLIDES

HSC Exam Preparation Programs
4 October 2015



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Overview

1. Gravity
2. Projectile Motion
3. Space Launch & Return
4. Special Relativity
5. The Motor Effect
6. Electromagnetic Induction
7. Transformers
8. Electric Motors
9. Cathode Rays
10. Quantum Theory
11. Solid State Physics
12. Superconductivity

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9. Cathode Rays

9.1 Gas-Discharge Tubes

By the 1850's vacuum pumps had become efficient enough to reduce the pressure inside a thick-walled glass tube to 0.01% of normal air pressure.

By passing a current through a vacuum tube, Faraday was the first to notice a strange light arc with its beginning at the cathode (negative electrode) & its end near the anode (positive electrode).

The explanation of this fluorescence is that at low pressures, the distance between gas particles is large enough that charged atoms (ions) naturally present in air can accelerate to high speeds. Collisions between ions & neutral atoms can be strong enough to excite valence electrons to higher energies, which is then released as light.

As air pressure is further lowered, dark spaces form in the tube, resulting in striation patterns. At ~ 0.1 kPa, the dark spaces spread down the tube, due to fewer gas collisions, until the tube is totally dark. For a short time the glass near the anode glows (usually green). This was called a cathode ray.

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9.1 Gas-Discharge Tubes

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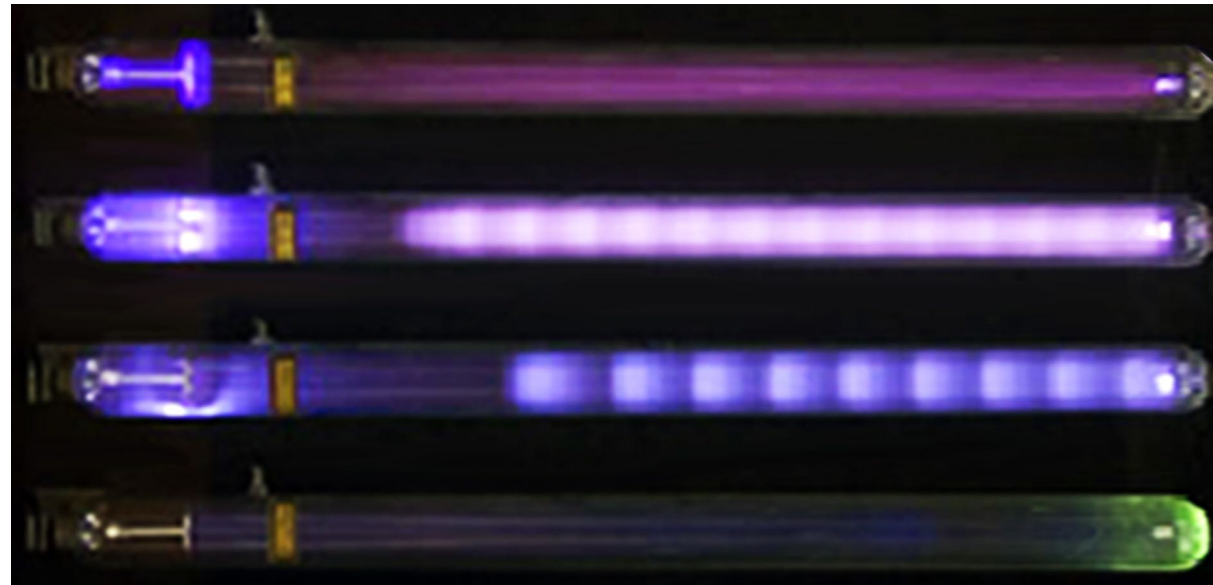


Figure 1: Striation patterns in gas-discharge tubes. Tubes are at pressures of 0.4, 0.3, 0.2, & 0.1 kPa from top to bottom. Nothing is observed at pressures above 0.5 kPa. Cathodes & anodes are at the left & right ends of the tubes, respectively.

9.2 Wave or Particle?

In 1880, Edison popularised a method of making cathodes out of wire filaments that could be heated to red-hot. Electrons in the metal could gain enough thermal energy to be 'boiled off', a process termed thermionic emission.

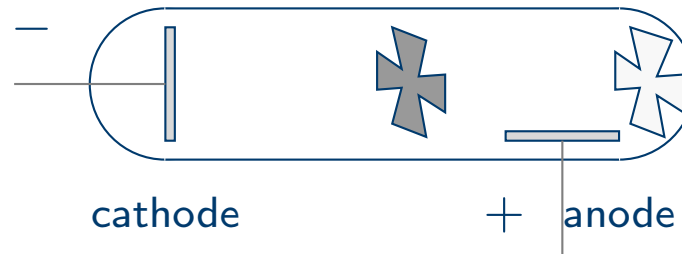
This is different to gas-discharge tubes, where cathode rays were caused by electrons ejected from gas atoms. Edison's tube pressures could be lowered to 10^{-4} Pa, since they did not need gas in them to work. These were the first functional cathode ray tubes.

Cathode rays were originally thought to be waves, but a hot debate ensued as to whether they could be particles. The properties of cathode rays were determined by the following experiments.

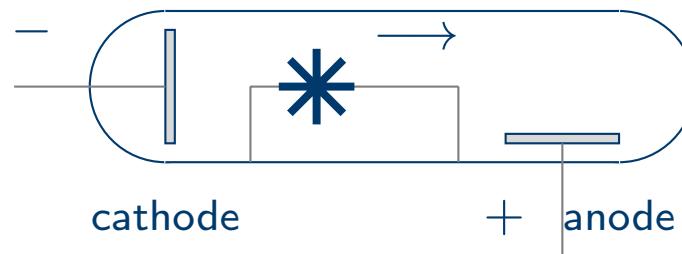
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9.2 Wave or Particle?

- **Maltese cross experiment:** A well-defined shadow is observed when a Maltese cross (or any shape) is fixed inside a cathode ray tube. This demonstrates that cathode rays *travel in straight lines*.



- **Paddle wheel experiment:** A well-oiled paddle wheel turns when placed on a track inside a cathode ray tube. This demonstrates that cathode rays can *exchange momentum*.



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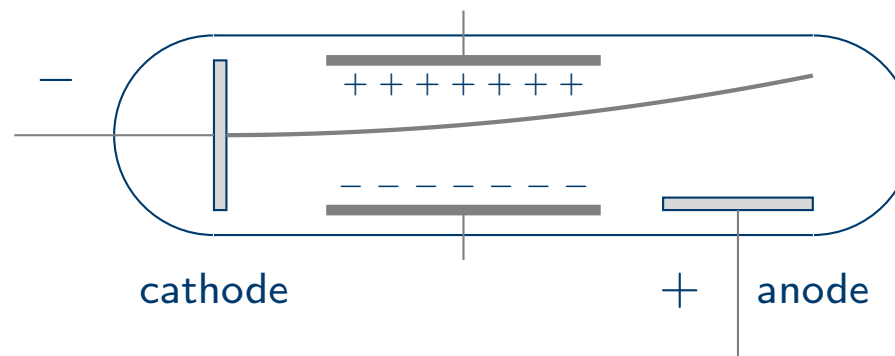
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9.2 Wave or Particle?

- **Electric plates experiment:** A uniform electric field was able to deflect cathode rays towards the positive plate. This demonstrates that cathode rays *are negatively charged*.



This last experiment was conducted by J.J. Thomson in 1897 (Cambridge, UK) & resolved the debate that cathode rays were particles. Scientists knew it was impossible to deflect electromagnetic waves with an electric field. Thomson's experiment marked the discovery of the electron, subsequently recognised as the first fundamental particle of physics (Nobel Prize, 1906).

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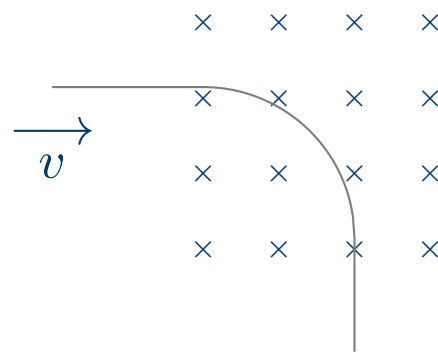
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9.3 Magnetic Fields

Recall that in magnetic fields, electrons travel in circular paths. This is because magnetic fields exert a force at right-angles to the particle's velocity, effecting a centripetal acceleration.



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

$$v = \frac{qrB}{m}$$

Direction of deflection is given by the Right-Hand Rule from Chapter 5.

In the case of negatively-charged particles, e.g. electrons, we orient our thumb in the opposite direction to the velocity, i.e. in the direction of conventional current.

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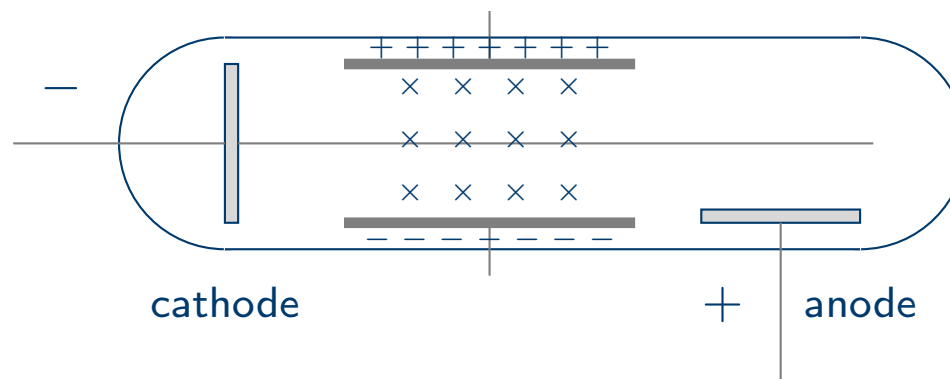
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9.4 Thomson's Experiment

Thomson's experimental set-up consisted of the following steps:

- Initially used only a magnetic field to deflect cathode rays & measured the radius of deflection (r) at that magnetic field strength (B).
- Switched on charged parallel plates, so as to create a uniform electric field (E) to deflect the cathode rays in the opposite direction.
- Adjusted the electric field strength until there was no net deflection of the cathode rays, i.e. the forces exerted by the electric & magnetic fields were balanced.



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9.4 Thomson's Experiment

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- Equating the magnetic force with the electric force, Thomson calculated the velocity of the cathode rays using

$$qvB = qE$$
$$\therefore v = \frac{E}{B}$$

- Finally, the measured velocity, radius of curvature, and magnetic field strength could be substituted into

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

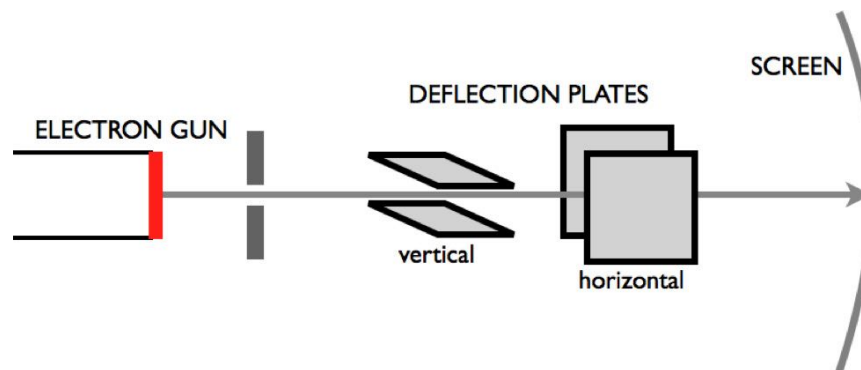
to determine the charge-to-mass ratio, q/m , of the cathode rays.

Hence, cathode rays were particles with charge & mass, with q/m measured as 1.76×10^{11} C/kg. To put this number in perspective, q/m for a H^+ ion is 1800x smaller.

9.5 Applications of CRTs

Cathode ray tubes are used in a wide range of devices including cathode ray oscilloscopes (CRO's), electron microscopes & televisions/monitors.

- **Step 1:** Hot cathode produces a beam of electrons.
- **Step 2:** Electrons accelerate towards anode (direction of the screen).
- **Step 3:** Electric plates/magnets allow horizontal & vertical deflection, making it possible to direct the electron beam to any point on the screen.
- **Step 4:** Screen is chemically coated to fluoresce when hit with electrons.



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Question 1 (11 Marks)

Alice and Bob separately investigate the effect of a magnetic field on a charged particle moving at constant speed in a vacuum. The observed paths are shown to scale to each other below.



(a) Why are the paths circular? (2 Marks)

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(b) Despite travelling at a constant speed, these particles are accelerating. How much work is done by the magnetic field? (1 Mark)

(c) Which path contains the greater magnetic flux? (1 Mark)

(d) Which path contains the greater magnetic flux density? (1 Mark)

(e) Given the radius that Bob observes is half that which Alice observes, and the two particles have the same mass and constant speed, what can be deduced about the charges of the particles? (2 Mark)

(f) One of the experimenters is observing a positron (a positively charged electron). Is it Alice or Bob? (1 Mark)

(g) Given Alice measures a radius of 10 cm with a field strength of 0.02 T, calculate the speed of the positron. (3 Marks)

9.6 HSC-Adapted Questions

Solution

- (a) The paths are circular because the force acting on the particles is constant & at right-angles to their velocities.
- (b) Since the force is perpendicular to the particles' displacements at all times, the magnetic field does no work.
- (c) The path Alice observes contains the greater magnetic flux, since there are more field lines through the area.
- (d) The path Bob observes contains the greater magnetic flux density, since the field lines are more closely spaced.
- (e) From the figure, Bob is using twice the magnetic field strength, since there are twice as many field lines per unit area in his experiment. Hence, the product of the radius & field strength (rB) is the same for Alice & Bob. Since charge obeys $q = mv/rB$, the particles have equal but opposite charges.

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(f) Using the right-hand rule, Alice & Bob are observing negatively & positively charged particles, respectively. Hence, Bob observes the positron.

(g) Taking Alice's measurements of $r = 0.1$ m & $B = 0.5$ T, the product rB is 0.05 m T. Using Part (e), this product is the same for Bob, who is observing the positron.

Equating the force from the magnetic field with the centripetal force, we have

$$qvB = \frac{mv^2}{r}$$
$$\therefore v = \frac{qrB}{m}$$

The mass & charge of a positron is 9.1×10^{-31} kg & 1.6×10^{-19} C, respectively. Substituting these values into the equation, we arrive at

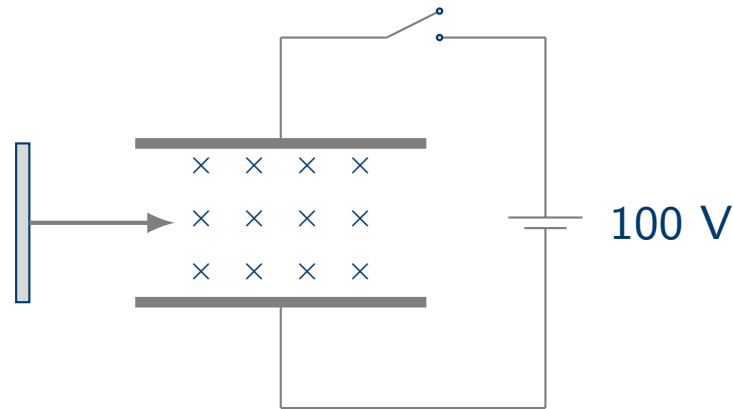
$$v = \frac{1.6 \times 10^{-19} \text{ C} \times 0.05 \text{ m T}}{9.1 \times 10^{-31} \text{ kg}} = 8.8 \times 10^9 \text{ m s}^{-1}.$$

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Question 2 (14 Marks)

Two parallel metal plates are connected in an open circuit & enclose a magnetic field as shown. A cathode ray enters the field between the plates.



- (a) Explain how a cathode ray can be produced. (3 Marks)
- (b) In which direction will the cathode ray be deflected? (1 Mark)

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(c) Cathode rays are beams of electrons. Given the electron velocities are 1×10^5 m/s & the strength of the magnetic field is 0.02 T, calculate the force acting on the electrons. (2 Marks)

(d) The switch is closed & surface charges build up on the metal plates. Use a diagram to clearly show the sign of the charges on each plate. (1 Mark)

(e) The resulting electric field exactly cancels the deflection of the magnetic field. Deduce the magnitude of the electric field. (2 Marks)

(f) Hence, determine the distance between the parallel plates. (2 Marks)

(g) Explain how this experimental set-up was used by Thomson to measure the charge-to-mass ratio of an electron. You should include at least one equation in your answer. (3 Marks)

9.6 HSC-Adapted Questions

Solution

(a) Two electrodes can be connected to a voltage supply. If the voltage is sufficiently large & the electrodes are in a vacuum, the negative electrode (cathode) can get hot enough to emit, or 'boil off', electrons. The electric field between the electrodes will accelerate the electrons towards the positive electrode (anode). The cathode ray can then be focussed using a collimator.

(b) Using the right-hand rule, the magnetic field deflects the beam downward.

(c) The magnitude of the force exerted by the magnetic is calculated using,

$$\begin{aligned} F &= qvB \\ &= 1.602 \times 10^{-19} \text{ C} \times 1 \times 10^5 \text{ m s}^{-1} \times 0.02 \text{ T} \\ &= 3.20 \times 10^{-16} \text{ N.} \end{aligned}$$

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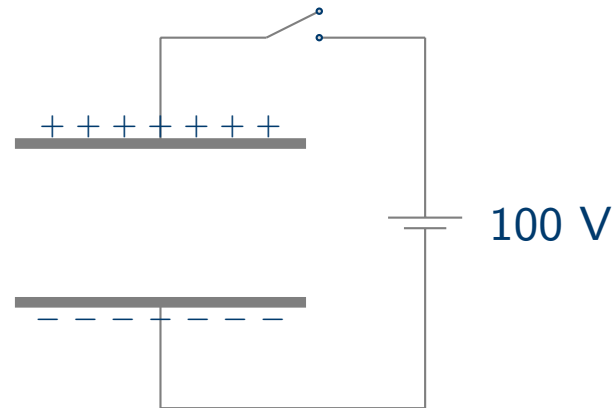
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(d)



(e) The force, F , exerted by the electric field must equal 3.20×10^{-16} N. Hence, the magnitude of the electric field, E , is

$$\begin{aligned} E &= \frac{F}{q} \\ &= \frac{3.20 \times 10^{-16} \text{ N}}{1.602 \times 10^{-19} \text{ C}} \\ &= 2000 \text{ N C}^{-1}. \end{aligned}$$

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(f) For parallel plates separated by a distance d , the electric field is given by,

$$\begin{aligned} E &= \frac{V}{d} \\ \therefore d &= \frac{V}{E} \\ &= \frac{100 \text{ V}}{2000 \text{ N C}^{-1}} \\ &= 0.05 \text{ m.} \end{aligned}$$

(g) Thomson adjusted the strengths of the electric & magnetic fields to create an undeflected electron beam. This allowed him to calculate the velocity of the electrons, since equal electric & magnetic forces implies $qE = qvB$, or $v = E/B$. Together with the radius of the deflected path, measured when the electric field was off, he calculated the charge-to-mass ratio using

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