9.4.1 Cathode Rays

Increased understandings of cathode rays led to the development of television

Pre-requisite Knowledge

- **Cathode Ray**: Moving **electrons** (across a vacuum) not known during experimentation
- **Cathode Ray Tube**: Evacuated (almost all gas removed) **glass tube** with **two electrodes, cathode (-) and anode (+)**.
  - Electron travels from **negative cathode to positive**
  - Must be **low pressure** (requires minimal collisions between air and electrons/cathode rays)
  - Must have **high voltage** (to pull electrons off the cathode and through to the anode
    - **CRTs only work on DC**, so transformers (AC) **do not work** – induction coil used instead

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

- Cathode rays had **multiple behaviours**
- **German scientists** supported cathode rays having a **wave nature**
- **English scientists** supported cathode rays having a **particle nature**

Wave Properties	Particle Properties
• **Oscillations in space that transferred energy**, not matter (caused fluorescence) • **No mass**, not affected by gravity • **Diffracted** (bent around corners) • **Reflected** (changed direction when bounced off) • **Refracted** (bent in changing medium) • **Interference/shadows** (superimposed creating a resultant wave)	• Localised in space, has/**carries momentum** • **Could charge objects negatively** • **Deflected** by magnetic and electric fields

1.2 Explain that cathode ray tubes **allowed the manipulation of a stream of charged particles**

- Cathode ray tubes are **glass tubes** (see prerequisite)
- Objects can be **placed inside** the tube to manipulate the stream of charged particles
- An **electric field** can be formed by placing two new electrodes parallel to the tube
- A **magnetic field** can be formed by magnets from outside the tube

1.3 Identify that **moving charged particles in a magnetic field experience a force**

- Recall that a **charge in a magnetic field experiences a force**

$$F = qE$$

F = force on charge (N), E = electric field strength (V/m, N/C), q = size of charge (C)

- A charge that **moves at constant velocity** also experiences a force inside a magnetic field

1.4 Identify that **charged plates produce an electric field**

- **Electric field** is a region in which **charged particles experience a force**
- Is a vector quantity, so has **strength** (force acting on charge) and **direction** (+ to -)

1.5 Describe quantitatively the **force acting on a charge moving through a magnetic field $F = qvB\sin\theta$**

$$F = qvB\sin\theta$$

Where F = force on charge (N), q = size of charge (C), v = velocity (ms^{-1}), B = magnetic field strength (T), θ = angle the **charge** enters the magnetic field (degrees). **When parallel to field strength lines, = 0**

- Magnitude of force measured using **formula above**
  - Magnetic field goes from **North to South**
- Direction of force: use the right hand palm rule where:
  - **Thumb** points to the direction proton is moving (point the opposite way of arrow if an **electron**)
  - **Fingers** point in the direction of the magnetic field
  - **Palm** indicates direction of force

1.6 Discuss qualitatively the **electric field strength due to a point charge**, positive and negative **charges** and oppositely charged parallel **plates**

- Field lines go **from** a **positive charge** (lines go out of charge) **to** a **negative charge** (into charge)
- Oppositely charged **parallel plates** similarly go from **positive plate to negative plate**
  - Form a **uniform electric field** between the plates

IMAGES

- **Line density** of the field lines represents the **strength** of the electric field

1.7 Describe quantitatively the **electric field due to oppositely charged parallel plates**

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

Where E = strength of electric field (V/m, N/C), V = supplied voltage (V), d = distance (m)

- Strength of the field is proportional to **voltage supplied** and inversely proportional to **distance between the plates**

1.8 Outline **Thomson's experiment** to measure the **charge/mass ratio of an electron**

- **Charge/mass ratio** of an electron: **q/m**. Our aim is to find q/m

EXPRESSION FOR VELOCITY OF CATHODE RAY

1. A **beam of cathode ray** emitted, accelerated towards **multi-anode collimators**
   - Multi-anode collimators make sure rays are fine and well defined
   - The beam simply goes to the end of the screen and ends up at **position 1** (strikes fluorescent screen)
2. The **electric field** voltage is turned on
   - The beam **deflects** by going **towards the positive plate** – ends up at **position 2**
3. The **magnetic field** is turned on by supplying current (voltage)
   - Magnetic field goes **into the page**, thumb to the left, so force is downwards – ends up **position 3**
4. Adjustments to strength of **electric field and magnetic field** can make it return to **position 2**
   - This means that at that moment, $\mathbf{F_E = F_B}$

THE CALCULATIONS (**FORCE CALCULATIONS)**

$F_E = F_B$ (shown above)

$F_E = qE$ (above, 1.3)

$F_B = qvB \sin 90 = qvB$ (above, 1.5, and particle passes perpendicular to lines

$qE = qvB$

$\boldsymbol{v = \frac{E}{B}}$ (this is the **expression for velocity of cathode ray**)

FIND Q/M

5. Only have **magnetic field on** (turn off electric field) – ray deflects down to **position 3**
   - This path of the ray forms the **arc of a big circle.** This is because force is perpendicular to direction of cathode ray, therefore follows the **centripetal force formula** (radius measured using equipment)

THE CALCULATIONS (**CENTRIPETAL CALCULATIONS)**

$F_C = F_B$ (shown above)

$F_C = \frac{mv^2}{r}$ (where r is radius of arc of cathode ray, recall Space)

$F_B = qvB \sin 90 = qvB$ (above, 1.5, and particle passes perpendicular to lines

$\frac{mv^{\not 2}}{r} = q\not vB$

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

$\frac{q}{m} = \frac{v}{rB} \rightarrow sub\ in\ v: \boldsymbol{\frac{q}{m} = \frac{E}{rB^2}}$ (which is what we are trying to find)

CONCLUSION

- Proved cathode rays were negatively charged **particles** as **they had a mass** (waves do not have mass)
  - Ended the debate over nature of cathode rays
- Particles had a **large negative charge** with very little mass
- Contributed to discovery of **electrons** – same q/m ratio measured in different materials of cathode

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

CATHODE RAY OSCILLOSCOPE (CRO)

- CRO used to display **pattern and strength of electric signals**

IMAGE OF CRO WITH X AND Y PLATES

- **<u>Electric gun</u>**: similar to Thomson's experiment – beam accelerated towards **anodes**
  - Separate small voltage supplied to cathode to **generate current and heat it**
    - **'Thermionic emission/devices'** – heat to ensure high electron density
  - **Grid** between anode and cathode to control **number of electrons striking per unit of time**
- **<u>Deflection system</u>:** to display information on screen – 2 **electric plates**
  - Y plates: **horizontal** and operate **vertical deflections**
    - Amplified copy of **external signal input** (type and strength of signal)
  - X plates: **vertical** and operate **horizontal deflections**
    - Time-based voltage, independent of external signal input
- **<u>Display screen</u>**: pixels from **fluorescent materials** – **phosphors**
  - Pixel fluoresces when ray strikes a pixel, then fades

TELEVISION

- Similar to CRO
- **<u>Electron gun</u>**: **three** electron guns in a colour TV (RGB)
  - Grid in each electron gun controls brightness of display, controlled by signals from antenna
- **<u>Deflection system</u>**: **uses magnetic fields** by current coils – more efficient, larger deflections
- **<u>Display screen</u>**: pixels, but with three sub-pixels – red, green and blue phosphors
  - **Shadow mask** in colour TV to ensure it hits corresponding spot in pixel
- Electron guns scan out a series of horizontal lines across the screen 50 times a second
  - Scans from left to right with voltage as a **saw-tooth fashion**

1.P1 Perform an investigation and gather first-hand information to o**bserve the occurrence of different striation patterns** for **different pressures in discharge tubes**

- **Julius Plücker** observed that when pressure of a gas decreased, **changes progressively** took place
- Appearance of dark and light bands became known as **stration patterns**

Aim: To observe different striation patterns for different pressures in discharge tubes

Risk Assessment:

- High voltage potential difference applied across cathode tube ray – handled by a teacher
- High voltage **induction coil** – high energy electrons can be released in the form of X rays
    - Stay 1 m away

Equipment: power pack, leads, set of discharge tubes with varying pressures, induction coil

Method:

1. Set up experiment as shown right
2. Connect negative terminal of induction coil to cathode, + to anode terminal
3. Turn on power pack to 6V
4. Observe discharge tube, repeat for each cathode

Results:

ROW OF STRIATION PATTERNS

Explanation:

- Cathode rays accelerate from cathode to anode.
- As discharge tube has small amount of gas, when cathode ray hits an electron:
    - Either **absorb into gas** particle and ionise it
    - Or move the orbiting electron into a h**igher energy state**, where it drops back and **releases energy in the form of light**
- In medium or low, there are **dark spaces** – electrons having insufficient energy to excite gas molecules
    - Spaces are named: **Aston's dark space**, cathode glow, **Crooke's dark space**, negative glow, **Faraday's dark space**, positive column, anode glow, anode dark space

1.P2 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** and containing a **glass wheel** and analyse the information gathered to **determine the charge on the cathode rays**

Type of Discharge Tube	Diagram	Observation	Conclusion
Maltese Cross: placed in path of cathode ray		Outline/shadow seen at the end of CRT	Showed cathode rays travelled in straight lines Showed diffraction, rays seemed to bend around cross **Wave**
Electric plates: by applying potential difference to two plates		Deflected cathode rays (towards + plate)	Showed cathode rays were **negative** and charged
Fluorescent display screen: works as cathode rays caused a 'glow' when hitting surface		The screen glowed in a line	Cathode rays carried energy **Wave**
Glass wheel aluminium coated, on a set of rails		Wheel spins and moves when cathode ray hits	Cathode rays had momentum **Particle**

- Showed that:
  - Cathode rays travelled in **straight lines** and showed **diffraction**
  - **Caused fluorescence** and carried energy
  - Deflected by magnetic and electric fields and therefore **had (negative) charge**
  - **Had both energy and momentum**
- Showed cathode rays had both wave and particle properties – J. J. Thomson hypothesised they were electrons

1.P3 Solve problems and analyse information using $F = qvB\sin\theta$, $F = qE$ and $E = \frac{V}{d}$

See Physics in Focus Page 172 to 178