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SENIOR SIX TERM 3

TOPIC 1/3: ATOMIC PARTICLES

Competency: The learner appreciates the structure of the atom and how the components of the atom are applied in different devices.

Dalton's Atomic Theory(1803–1808)

John Dalton proposed his atomic theory in the early 19th century, laying the foundation for modern chemistry and physics. Though some points have been modified with later discoveries of subatomic particles and isotopes, his core ideas remain fundamental to our understanding of matter.

Key Postulates:

- **All matter is composed of atoms:** Matter, whether an element, compound, or mixture, is made up of extremely small, discrete particles called atoms.
- **Atoms are indivisible and indestructible:** Dalton proposed that atoms cannot be subdivided, created, or destroyed.
- **Atoms of the same element are identical:** All atoms of a specific element are the same in terms of mass, size, and properties. Atoms of different elements have different masses and properties.
- **Atoms combine in simple whole-number ratios:** Compounds are formed when atoms of different elements join together in fixed, simple, whole-number ratios (e.g., H_2O , not $\text{H}_2.5\text{O}$).
- **Atoms are rearranged in chemical reactions:** Chemical reactions involve the separation, combination, or rearrangement of atoms; the atoms themselves are not changed into atoms of another element during the process.

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Subatomic Particles and Their Properties

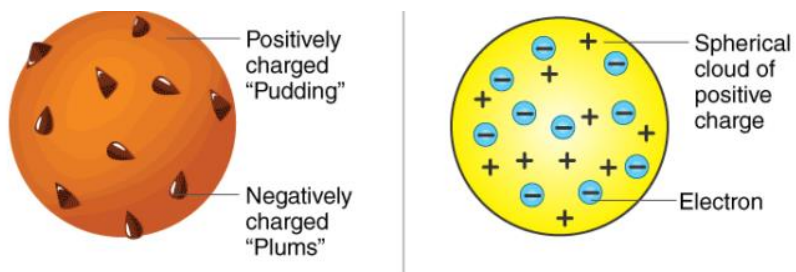
Contrary to Dalton's original idea, atoms are divisible and are composed of even smaller subatomic particles: **protons**, **neutrons**, and **electrons** and isotopes show atoms of the same element can differ in mass

Particle	Location	Charge	Relative Mass (approx.)
Proton	Nucleus (center)	Positive (+1)	1 atomic mass unit (amu)
Neutron	Nucleus (center)	Neutral (0)	1 atomic mass unit (amu)
Electron	Electron cloud (orbiting the nucleus)	Negative (-1)	~0 (about 1/2000 of a proton/neutron)

Key Properties:

- **Nucleus:** Protons and neutrons are packed tightly in the dense, central nucleus, which contains almost all of the atom's mass.
- **Electrons:** Electrons orbit the nucleus in an "electron cloud" or specific energy levels/shells. They are held in orbit by the electromagnetic force of attraction to the positive nucleus.
- **Charge Neutrality:** A typical, neutral atom has an equal number of protons and electrons, which balances the positive and negative charges to an overall charge of zero.
- **Atomic Identity:** The number of protons determines the element's atomic number and identity (e.g., all carbon atoms have 6 protons).
- **Empty Space:** Most of the atom's volume is empty space; the nucleus is extremely small compared to the overall size of the atom.
- Atoms of the same element with the same number of protons but different number of neutrons are called **isotopes**.

Thomson's plum pudding atomic structure model



Thomson's Plum Pudding Model (1904) proposed the atom as a sphere of uniform positive charge (the "pudding") with negatively charged electrons (the "plums") embedded within it, like raisins in a cake, to explain the atom's neutrality after discovering the electron. It suggested electrons were scattered in a diffuse positive cloud, but this model was later disproven by Rutherford's gold foil experiment, which revealed a dense, positive nucleus.

Key features of the model:

- **Positive Sphere:** The atom was a solid, positive sphere or "soup".
- **Embedded Electrons:** Tiny, negative electrons were scattered throughout this positive mass.
- **Neutral Atom:** The total negative charge of the electrons balanced the positive charge, making the atom neutral.

Significance:

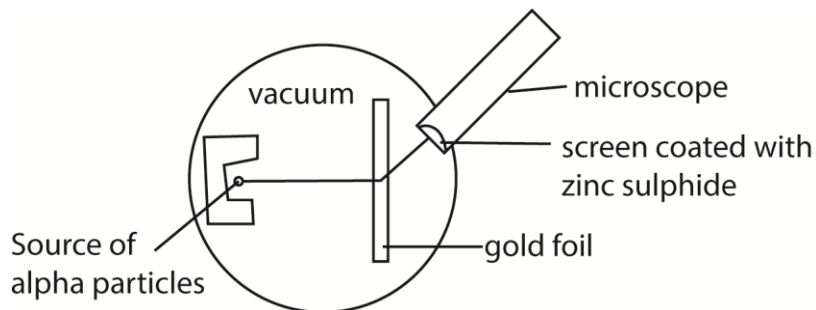
- It was an important early attempt to incorporate the newly discovered electron into an atomic structure.
- It paved the way for future models, eventually being replaced by Rutherford's nuclear model, which introduced the nucleus.

Rutherford's Scattering Experiment & Observations

Procedure

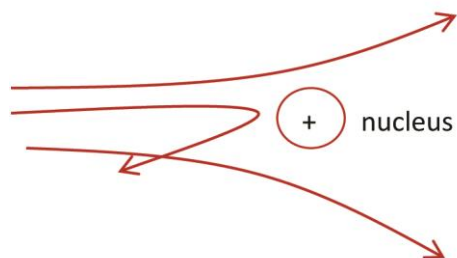
- **Alpha particle source:** A radioactive material (like radium) emitted α -particles.
- **Gold foil target:** A very thin sheet of gold (about 100 nm thick) was used.
- **Detection screen:** A fluorescent screen coated with zinc sulfide surrounded the foil to detect scattered α -particles.

Method



- α -particles were directed at the gold foil.
- Their scattering patterns were observed as flashes of light on the screen.
- It was carried out in a darkened room so that the scintillations can be seen clearly and the apparatus is evacuated to ensure that the particles are able to reach the screen without losing energy.

Observations



- **Most α -particles passed straight through** the foil without deflection.
- **Some α -particles were deflected at small angles**, showing repulsion.
- **A very few were deflected at large angles**, even bouncing back.
- These results were unexpected under the earlier “plum pudding” model of the atom.

Conclusions from Rutherford's Experiment (Atomic Structure)

- **Atoms are mostly empty space:** Explains why most α -particles passed through.
- **Existence of a dense, positively charged nucleus:** Large-angle deflections showed a concentrated positive mass at the center.
- **Electrons orbit the nucleus:** To balance the positive charge, electrons must surround the nucleus.
- **Mass of atom concentrated in nucleus:** Protons and neutrons reside there, giving atoms their weight.
- **Rutherford's atomic model** replaced Thomson's plum pudding model and laid the foundation for Bohr's refinements.

The Bohr Model of the Atom

The Bohr Model of the Atom is a planetary-style model where electrons orbit the nucleus in fixed energy levels. It was proposed by Niels Bohr in 1913 and explained the hydrogen atom's spectral lines.

Key Features of the Bohr Model

- **Electrons orbit the nucleus in fixed paths:** Similar to planets around the Sun, but restricted to certain energy levels.
- **Energy levels are quantized:** Electrons can only occupy specific orbits, not in-between.
- **Electron transitions produce radiation:** When electrons jump between orbits, they absorb or emit energy as light.
- **Explains hydrogen's emission spectrum:** Each spectral line corresponds to an electron transition.
- **Nucleus is small and positively charged:** Contains protons (and later understood to include neutrons).

Strengths of the Bohr Model

- Explained atomic spectra: Especially hydrogen's discrete spectral lines.
- Introduced quantization: A major step toward quantum mechanics.
- Improved Rutherford's model: Solved the problem of electrons spiraling into the nucleus.

Limitations of the Bohr Model

- Only works well for hydrogen-like atoms: Fails for multi-electron atoms.
- Does not explain fine details: Such as spectral line splitting or intensities.
- Replaced by quantum mechanical models: Modern theory uses electron clouds and probability distributions.

Modern atomic theory

The modern atomic model is the *quantum mechanical model of the atom*, which describes electrons as existing in regions of probability called orbitals rather than fixed paths

Key Features of the Modern Atomic Model

- **Quantum mechanical foundation:** Based on Schrödinger's wave equation, treating electrons as both particles and waves.
- **Electron cloud:** Electrons are not in fixed orbits (like Bohr suggested) but in diffuse regions around the nucleus.
- **Orbitals:** Specific shapes (s, p, d, f) describe where electrons are most likely to be found.

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- **Energy levels and sublevels:** Electrons occupy quantized shells and subshells, explaining chemical behavior.
- **Uncertainty principle:** Heisenberg showed we cannot know both the exact position and momentum of an electron simultaneously.
- **Electron configurations:** Arrangement of electrons determines chemical properties and periodic trends.

Strengths of the Modern Model

- **Explains spectra of multi-electron atoms** (unlike Bohr's model).
- **Accounts for chemical bonding** through orbital overlap and hybridization.
- **Predicts periodic trends** such as atomic size, ionization energy, and electronegativity.
- **Supports modern chemistry and physics** including semiconductors, lasers, and quantum computing.

Limitations

- **Highly mathematical:** Requires advanced quantum mechanics to fully understand.
- **Probabilistic nature:** Cannot give exact electron positions, only likelihood distributions.

Cathode Rays and cathode ray oscilloscope

Cathode rays

These are streams of fast moving electrons that travel from the cathode to the anode.

Properties of cathode rays

- (i) They travel in straight lines.
- (ii) They are negatively charged.
- (iii) They are deflected by both electric and magnetic fields.
- (iv) They cause fluorescence in some metals e.g. Zinc metal.
- (v) They ionize gaseous atoms.
- (vi) They affect photographic plates.
- (vii) They produce X – rays when stopped by a metal target.
- (viii) They possess momentum therefore they have mass.

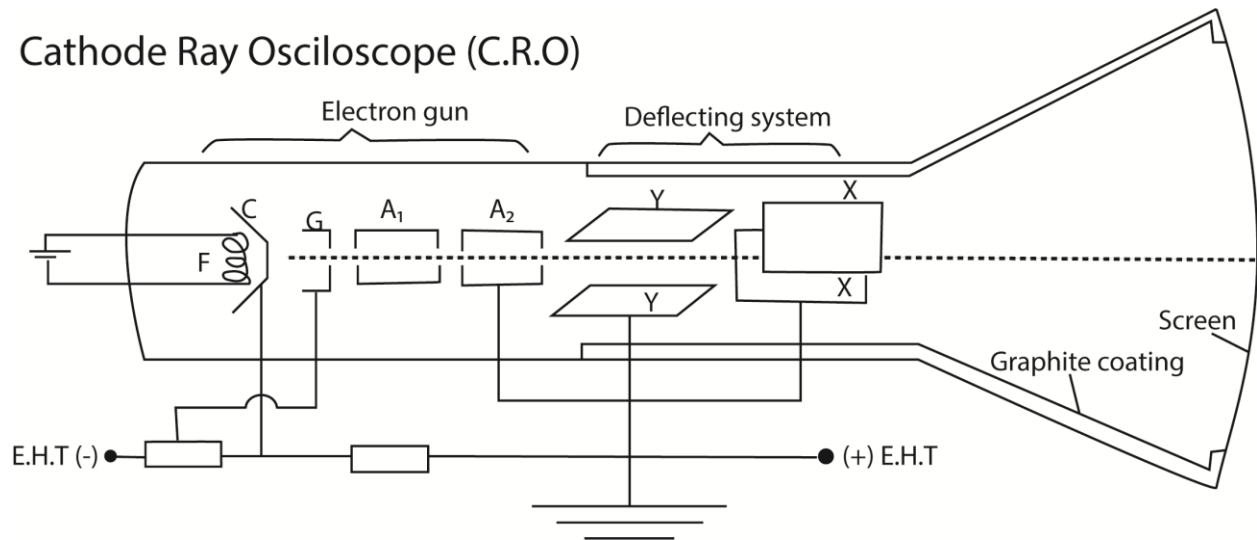
Cathode ray oscilloscope (CRO)

The cathode ray oscilloscope is an electronic instrument that uses cathode rays/electron to analyze different aspects of electrical signals such as amplitude, frequency and power

Structure

Parts of CRO are shown below

Cathode Ray Oscilloscope (C.R.O)



Structure The C.R.O consists of three principal components or features, namely

- (i) **The electron gun** made of the following;
 - **The Filament F:** When a current flows through the filament, it glows and heat from the filament heats the cathode.
 - **The Cathode C:** Emits electrons when heated by the filament.
 - **The Grid G:** the grid is made at a negative potential with respect to the cathode. It controls the number of electrons entering the Anode, thus the Grid controls the brightness on the screen.
 - **Accelerating and focusing Anode A1 and A2:** the anode is at a positive potential. It accelerates the electron beam to a high speed along the tube.
- (ii) **The deflecting system** consists of the X -Plates and Y – plates;
 - X – Plates are placed vertically and form a horizontal electric field. Therefore it deflects the electron beam horizontally.
 - Y – Plates are placed horizontally and form a vertical electric field. Therefore it deflects the electron beam vertically.
- (iii) **The fluorescent screen** coated with a fluorescent material such as Zinc sulphide or Phosphor. The fluorescent screen emits light (glows) when struck by fast moving electrons.

Graphite coating:

This is used:

- (i) to prevent the electron beam from the influence of electric field
- (ii) It collects secondary electrons emitted by the screen to the earth.

Mode of action of a C.R.O

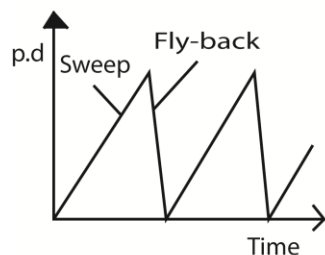
- The cathode is heated using a low voltage supply and produces electrons by the process of thermionic emission.
- The electrons are accelerated and focused into a fine beam by the anode to fall on the screen producing a bright spot.
- The brightness of the spot on the screen is controlled by the control grid

How the grid controls the brightness of the spot of a C.R.O

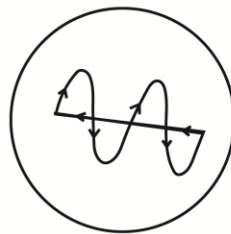
- The grid is connected to a negative potential.
- If the potential of the grid is more negative, only few electrons with high K.E (or speed) will pass through it. Thus the screen will be less bright.
- If the potential of the grid is less negative, many electrons will pass through it. Thus the screen will be brighter.

Deflection; Time-base

Action of a C. R. O



(i) p.d applied to X-plates



(ii) Trace of spot on screen

If a battery were connected between the Y-plates, so as to make the upper one positive, the electrons in the beam would be attracted towards that plate, and the beam would be deflected upwards. In the same way, the beam can be deflected horizontally by a potential difference applied between the X-plates.

When the oscillograph is in use, the alternating potential difference to be examined is applied between the Y-plates. If that were all, then the spot would be simply drawn out into a vertical line.

To trace the wave-form of the alternating potential difference, the X-plates are used to provide a time-axis.

A special valve circuit generates a potential difference which rises steadily to a certain value, as shown in (i), and then falls rapidly to zero; it can be made to go through these changes tens, hundreds, or thousands of times per second.

This potential difference is applied between the X-plates, so that the spot is swept steadily to the right, and then flies swiftly back and starts out again.

This horizontal motion provides what is called the time-base of the oscillograph.

On it is superimposed the vertical motion produced by the Y-plates; thus, as shown in Fig. ii) above, the wave-form of the potential difference to be examined is displayed on the screen.

Uses of a C.R.O

- (i) Measures both a.c and d.c voltages
- (ii) Measures frequencies or compare frequencies
- (iii) Measures phase difference
- (iv) Measure small time intervals (used as a clock)
- (v) Displays wave forms
- (vi) diagnosis heartbeat and brain in hospitals.

Comparison of CRO with a moving coil Voltmeter

- (i) The C.R.O has very high impedance. It gives accurate voltages than a moving coil voltmeter.
- (ii) A CRO can measure both d.c and a.c voltage. A moving coil voltmeter measures only D.C voltages unless a rectifier is used.
- (iii) A CRO has negligible inertia as compared to a moving coil voltmeter. The C.R.O respond almost instantaneously.
- (iv) CRO doesn't give direct voltage readings.

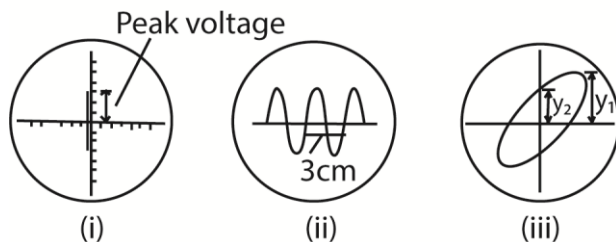
Uses of Oscillograph

In addition to displaying waveforms, the oscillograph can be used for measurement of voltage, frequency and phase.

- (i) A.C. voltage

An unknown a.c. voltage, whose peak value is required, is connected to the Y-plates. With the time-base switched off, the vertical line on the screen is centered and its length then measured as shown in figure (i) below. This is proportional to twice the amplitude or peak voltage, V_0 . By measuring the length corresponding to a known a.c. voltage V , then V_0 can be found by proportion.

Uses of oscillograph



Alternatively, using the same gain, the waveforms of the unknown and known voltages, V and V_0 , can be displayed on the screen. The ratio V/V_0 is then obtained from measurement of the respective peak-to-peak heights.

- (ii) Comparison of frequency

If a calibrated time-base is available, frequency measurements can be made. In Fig. (ii) above, for example, the trace shown is that of an alternating waveform with the time-base switched to the '5 millisecc/cm' scale. This means that the time taken for the spot to move 1 cm horizontally across the screen is 5 milliseconds. The horizontal distance on the screen for one cycle is 3 cm. This corresponds to a time of 5×3 ms or $15 \cdot 0$ ms = 15×10^{-3} seconds, which is the period T.

$$\therefore \text{frequency} = \frac{1}{T} = \frac{1}{15 \times 10^{-3}} = 66.7 \text{ Hz}$$

If a comparison of frequencies, f_1, f_2 is required, then the corresponding horizontal distances on the screen are measured. Suppose these are d_1, d_2 respectively.

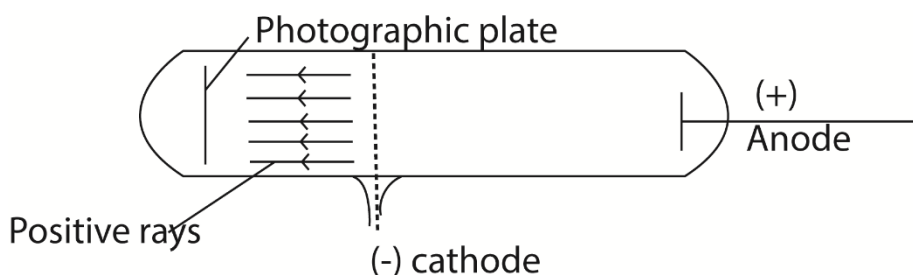
$$\text{Since } f \propto \frac{1}{T}, \text{ then } \frac{f_1}{f_2} = \frac{T_2}{T_1} = \frac{d_2}{d_1}$$

(iii) Measurement of phase

Positive rays

- Positive rays are streams of positively charged particles.

Production of positive rays in a discharge tube

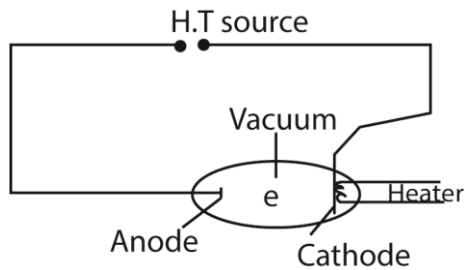


- Positive rays are produced when a stream of electrons is passed through a vapor (gas) in discharge tube.
- The electrons dislodge electrons from the atoms producing positively charged ions.
- The positive ions are accelerated towards perforated cathode.
- The ions pass through the slits and are further accelerated.
- These ions constitute a stream of positive rays.

Properties of positive rays

- They travel in straight lines
- They are positively charged
- They are more massive compared to cathode rays
- They are reflected by strong magnetic fields
- They have smaller specific charge (q/m) compared to the cathode rays (this is because they are more massive than the cathode rays)
- They are deflected by strong electric fields in opposite direction to that of the cathode rays in the same field

Electron dynamics



Consider an electron moving from cathode to anode.

- Let the p.d between the cathode and anode be V . The electron will be accelerated by the electric field and hence it gains K.E.
- If the electron starts from the cathode with zero velocity and reaches the anode with velocity $u \text{ m s}^{-1}$, then the K.E gained by

$$\frac{1}{2} m u^2 = eV, \text{ where } e = \text{electron charge, } 1.6 \times 10^{-19} \text{ C}$$

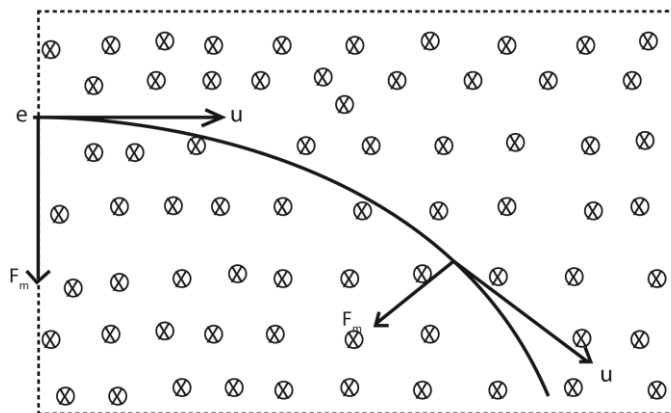
Or

$$u = \sqrt{\frac{2eV}{m}} = \sqrt{2 \left(\frac{e}{m}\right) V}$$

The quantity $\left(\frac{e}{m}\right)$ is called the specific charge of the electron

Deflection of an electron in a magnetic field

Consider an electron entering a uniform magnetic field of flux B , at right angles to its direction of motion with velocity u .



When the electron enters the field, the magnitude of its speed u does not change because the magnetic force is perpendicular to the direction of the electron, But instead its direction changes and the electron moves in a circular arc.

Let r be the radius of the circular arc (path)

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The centripetal force on the electron, $F = \frac{mu^2}{r}$ (i)

The force due to the magnetic field, $F = Beu$ (ii)

From (i) and (ii)

$$\frac{mu^2}{r} = Beu$$

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

$$\text{and } u = \frac{Bre}{m}$$

Since the speed of the electron is constant, its K.E is also constant hence,

$$\text{Kinetic energy} = \frac{1}{2}mu^2 = \frac{e^2B^2r^2}{2m}$$

Example 1

An electron moves in a circular path at $3.0 \times 10^6 \text{m/s}$ in a uniform magnetic field of flux $2.0 \times 10^{-4} \text{T}$. Find the radius of the path.

[mass of an electron $m_e = 9.11 \times 10^{-31} \text{kg}$, $e = 1.6 \times 10^{-19} \text{C}$]

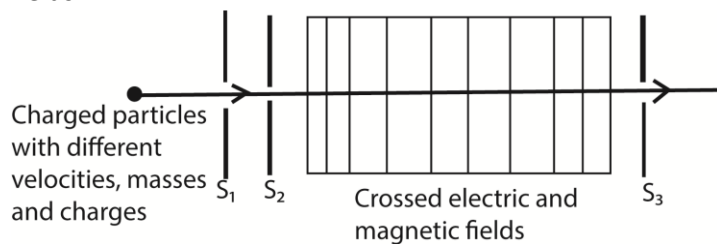
$$r = \frac{mu}{Be}$$

$$= \frac{9.11 \times 10^{-31} \times 3.0 \times 10^6}{2.0 \times 10^{-4} \times 1.6 \times 10^{-19}}$$

$$= 8.5 \text{cm}$$

Crossed fields

Crossed fields are fields in which a uniform magnetic field and a uniform electric field are perpendicular to each other producing deflections opposite to each other. If the magnetic force and electric force in the crossed fields are of the same magnitude, there is no deflection on charged particles that enter such fields.



The slits S_1 and S_2 confine the particles into a narrow beam as they enter the crossed fields. The only particles that emerge at slit S_3 are those which are undeflected, and therefore they emerge with the same velocity u .

The electric force F_E due to the electric field = eE

The magnetic force F_m due to the magnetic field = Beu

For crossed fields $F_E = F_m$

$$eE = Beu$$

$$\therefore u = \frac{E}{B} \text{ this is the velocity of particles emerging at } S_3$$

Therefore all particles that emerge at S_3 will have the same velocity $u = \frac{E}{B}$ regardless of their mass and charge.

The crossed fields can be used as a velocity selector of particles of a single velocity from a beam of particles of different velocities.

Example 2

An electron accelerated by a p.d of 1.5KV passes through an electric field crossed with a uniform magnetic field of flux density 0.45T. Calculate the value of the electric field needed for the electron to emerge undeflected.

Solution

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

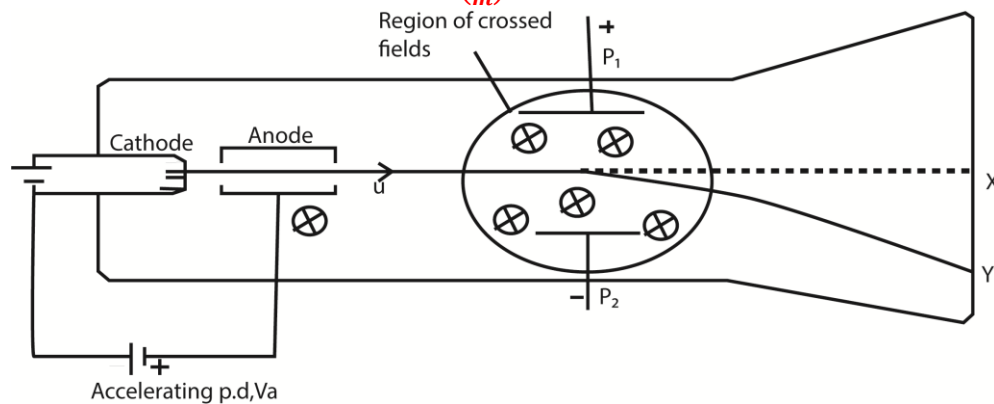
$$\text{Also } \frac{1}{2}mu^2 = eV$$

$$u = \sqrt{\frac{2eV}{m}}$$

$$\therefore \frac{E}{B} = \sqrt{\frac{2eV}{m}}$$

$$E = B\sqrt{\frac{2eV}{m}} = 0.45\sqrt{\frac{2 \times 1.6 \times 10^{-19} \times 1.5 \times 10^3}{9.11 \times 10^{-31}}} = 1.033 \times 10^7 \text{NC}^{-1}$$

Determination of Specific Charge ($\frac{e}{m}$) of an electron: (J.J Thomson’s Method)



- The electrons are produced thermionically by a hot filament cathode and are accelerated towards a cylindrical anode and pass through it.
- The small hole on the anode confines the electrons to a narrow beam.
- When both the electric field and the magnetic field are off, the electrons reach the screen at X and cause fluorescence.
- If the velocity of the electrons on emerging from the anode is u then

$$eV_a = \frac{1}{2}mu^2$$

$$\Rightarrow \frac{e}{m} = \frac{u^2}{2V_a} \dots\dots\dots (i)$$
 Where V_a is the accelerating voltage between the cathode and anode.
- The magnetic field is switched on and the beam is deflected to position Y.

- In order to bring the beam back to the original position X, the electric field is switched on and adjusted until the beam is at X again.
- This implies that The magnetic force = the electric force

$$Beu = eE$$

$$\therefore u = \frac{E}{B} \dots\dots\dots (ii)$$

Substituting eqn. (ii) in (i)

$$\frac{e}{m} = \frac{E^2}{2B^2Va} \quad \text{but } E = \frac{V}{d}$$

$$\therefore \frac{e}{m} = \frac{V^2}{2B^2d^2Va} \quad \text{where, V is the p.d between the plates at separation of d apart}$$

Example 3

A beam of electrons is accelerated through a p.d of 500V and enters a uniform electric field of strength $3.0 \times 10^3 \text{V/m}$ created by two parallel plates of length 2.0cm. Calculate:

- (a). the speed of the electrons as they enter the field.

$$\text{From } \frac{1}{2}mu^2 = eV$$

$$u = \sqrt{\frac{2eV}{m}} = \sqrt{\frac{2 \times 1.6 \times 10^{-19} \times 500}{9.11 \times 10^{-31}}} = 1.325 \times 10^7 \text{ms}^{-1}$$

- (b). the time that each electron spends in the field.

$$t = \frac{x}{u} = \frac{2.0 \times 10^{-2}}{1.325 \times 10^7} = 1.51 \times 10^{-9} \text{s}$$

- (c). the angle from which the electrons have been deflected by the time they emerge from the field.

$$u_x = u = 1.325 \times 10^7 \text{ms}^{-1}$$

$$u_y = a_y t \text{ but } a_y = \frac{eE}{m}$$

$$\therefore u_y = \frac{eEt}{m} = \frac{1.6 \times 10^{-19} \times 3 \times 10^3 \times 1.51 \times 10^{-9}}{9.11 \times 10^{-31}} = 7.956 \times 10^5 \text{ms}^{-1}$$

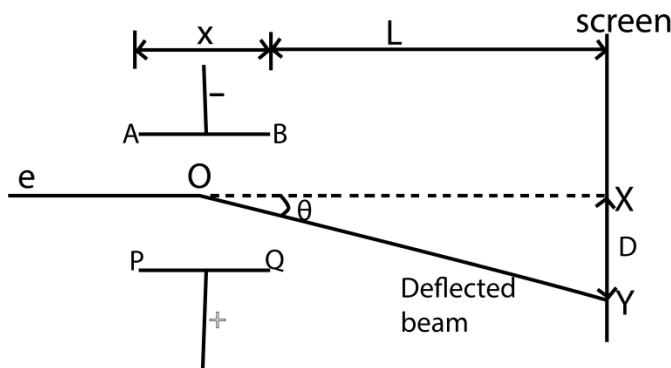
Let the angle be θ

$$\tan \theta = \frac{u_y}{u_x} = \frac{7.956 \times 10^5}{1.3225 \times 10^7}$$

$$\theta = 3.8^\circ$$

Motion of an electron in an electric field

Consider two parallel plates AB and PQ such that AB is vertically above PQ and at a distance d apart. Let x be the length of the plates and V the p.d between the plates.



This electric force is directed towards the positive plate causing the deflection of the beam as shown above.

But for parallel plates $E = \frac{V}{d}$

Thus $F_E = \frac{eV}{d}$

Since the electric field intensity is vertical, there is no horizontal force acting on the electron. Hence the horizontal component of the velocity of the electron does not change.

Let u be the horizontal component of the velocity of the electron entering the electric field.

Motion in the X-direction

$s = ut + \frac{1}{2} at^2$, but $s = x$ and $a = 0$

$\Rightarrow t = \frac{x}{u}$ (i)

Motion in y-direction

$s = ut + \frac{1}{2} at^2$, but $u_y = 0$, $s = y$ and $a = \frac{eE}{m}$ from $ma = eE$

$y = \frac{1}{2} \left(\frac{eE}{m}\right) \left(\frac{x}{u}\right)^2$

$= \left(\frac{eE}{2mu^2}\right) x^2$

$\Rightarrow y \propto x^2$ or $y = kx^2$ which is an equation for parabola

Thus the motion of an electron in electric field is parabolic

Note

1. The time, t , taken for the electron to pass through the electric field (leave the plates)

$t = \frac{x}{u}$

2. The velocity, V_0 with which electrons leave the plates

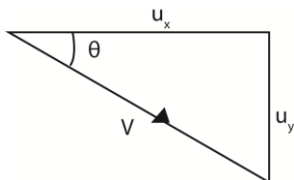
$V_0 = \sqrt{v_x^2 + v_y^2}$

$u_x = u$ and

from $v_y = u_y + a_y t$, but $u_y = 0$ and $a_y = \frac{eE}{m}$ also $t = \frac{x}{u}$ where x is the length of the plates

Thus $v_y = \left(\frac{eE}{m}\right) \frac{x}{u}$ where $E = \frac{V}{d}$

3. Direction (angle) the electron emerges from the region between the plates at angle θ given by



$$\tan \theta = \frac{v_y}{v_x}$$

4. The deflection D of the electron on the screen placed at a distance L from the edge of the plates is obtained from

$$\tan \theta = \frac{D}{L + \frac{1}{2}x} = \frac{eEx}{mu^2}$$

$$\text{hence } D = \frac{eEx}{mu^2} \left(L + \frac{1}{2}x \right) \text{ where } E = \frac{V}{d}$$

Example 4

A beam of electrons is accelerated through a p.d of 2000V and is directed mid-way between two horizontal parallel plates of length 5.0cm and separation of 2.0cm. The p.d across the plates is 80V.

- (a) Calculate the speed of the electrons as they enter the region of between the plates

$$\text{From } \frac{1}{2}mu^2 = eV$$

$$u_x = \sqrt{\frac{2eV}{m}} = \sqrt{\frac{2 \times 1.6 \times 10^{-19} \times 2000}{9.11 \times 10^{-31}}} = 2.65 \times 10^7 \text{ ms}^{-1}$$

- (b) Find the speed of the electrons as they emerge from the region between the plates.

$$u_y = a_y t \text{ but } a_y = \frac{eE}{m},$$

$$E = \frac{V}{d} \text{ and } t = \frac{x}{u_x}$$

$$v_y = \left(\frac{eV}{md} \right) \left(\frac{x}{u_x} \right)$$

$$= \frac{1.6 \times 10^{-19} \times 80 \times 5 \times 10^{-2}}{9.11 \times 10^{-31} \times 2 \times 10^{-2} \times 2.65 \times 10^7}$$

$$= 1.325 \times 10^6 \text{ ms}^{-1}$$

$$V = \sqrt{u_x^2 + u_y^2}$$

$$= \sqrt{(2.65 \times 10^7)^2 + (1.325 \times 10^6)^2}$$

$$= 2.653 \times 10^7 \text{ ms}^{-1}$$

- (c) Explain the motion of the electrons between the plates.

It is parabolic

Example 5

An electron gun operated at $3 \times 10^3 \text{ V}$ is used to project electrons into the space between two oppositely charged parallel plates of length 10cm and separation 5cm. Calculate the deflection of the electrons as they emerge from the region between the charged plates when the p.d is $1.0 \times 10^3 \text{ V}$.

$$\text{From } \frac{1}{2}mu^2 = eV$$

$$u = \sqrt{\frac{2eV}{m}} = \sqrt{\frac{2 \times 1.6 \times 10^{-19} \times 3000}{9.11 \times 10^{-31}}} = 3.246 \times 10^7 \text{ ms}^{-1}$$

$$\text{Also } y = u_y t + \frac{1}{2}a_y t^2 \text{ but } u_y = 0, a_y = \frac{eE}{m}; t = \frac{x}{u}$$

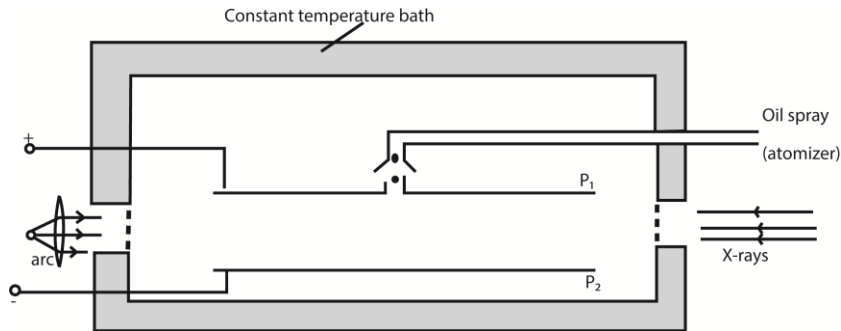
$$\Rightarrow y = \frac{1}{2} \frac{eEx^2}{mu_x^2} \text{ and } E = \frac{V}{d}$$

$$\Rightarrow y = \frac{1}{2} \frac{eVx^2}{mdu_x^2} = \frac{1.6 \times 10^{-19} \times 1000 \times (10 \times 10^{-2})^2}{2 \times 9.11 \times 10^{-31} \times 5 \times 10^{-2} \times (3.246 \times 10^7)^2} = 1.667 \times 10^{-2} \text{m}$$

Therefore, the deflection = $1.667 \times 10^{-2} \text{m}$

Millikan's Oil drop experiment

This is used to determine electronic charge e

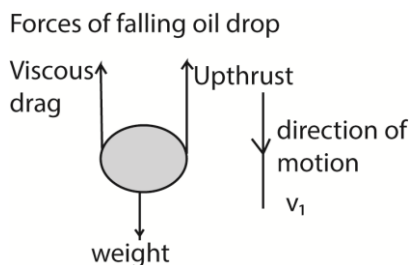


Procedure

- Set up of the apparatus is as shown above
- Oil drops are introduced between the plates P_1 and P_2 by spraying using the atomizer.
- These oil drops are charged in the process of spraying by friction but the charge may be increased by ionization using X-rays.
- The oil drops are strongly illuminated by an intense light from the arc lamp so that they appear as bright spots when observed through a low power microscope.
- With no electric field between the plates, record the time t_1 taken for drop to fall from P_1 to P_2 .
- The electric field between the plates is turned on and adjusted so that the drop becomes stationary.

Case 1

With no electric field, the oil drop falls with a uniform velocity v_1 called terminal velocity



Weight = Upthrust + viscous drag (i)

= volume of the oil drop x density x gravity

= $\frac{4}{3} \pi r^3 \rho g$ (ρ = density of oil, r = radius of oil drop)

Upthrust = weight of air displaced by oil drop

= volume of the air displaced by oil drop x density x gravity

$$= \frac{4}{3}\pi r^3 \sigma g \quad (\sigma = \text{density of air})$$

Viscous drag = $6\pi\eta v_1$ (From Stokes' law)

From 1

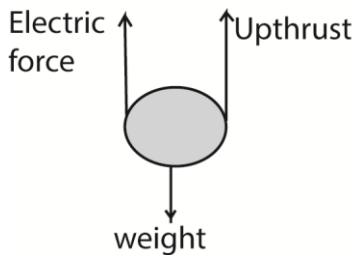
$$\frac{4}{3}\pi r^3 \rho g = \frac{4}{3}\pi r^3 \sigma g + 6\pi\eta v_1 \dots\dots\dots (ii)$$

$$r = \left[\frac{9\eta v_1}{2g(\rho - \sigma)} \right]^{\frac{1}{2}}$$

Case 2

When the electric field is applied so that the drop is stationary, the drop has no velocity and no acceleration.

Forces of stationary oil drop



Weight = Upthrust + electric force

$$\frac{4}{3}\pi r^3 \rho g = \frac{4}{3}\pi r^3 \sigma g + qE \dots\dots\dots (iii)$$

From (ii) and (iii)

$$q = \frac{6\pi\eta v_1}{E} \text{ but } E = \frac{V}{d}$$

Substituting for r

$$q = \frac{6\pi\eta d v_1}{V} \left[\frac{9\eta v_1}{2g(\rho - \sigma)} \right]^{\frac{1}{2}}$$

Note: the density of air at room temperature is very small compared to that of oil and thus may be assumed negligible (when it's not given) in calculations. This implies that the up thrust due to the displaced air is Zero.

$$q = \frac{6\pi\eta d v_1}{V} \left[\frac{9\eta v_1}{2g\rho} \right]^{\frac{1}{2}}$$

Precautions

To improve on the accuracy of the experiment, the following precautions need to be taken into account

- (i) A non-volatile oil or low vapor pressure oil should be used to reduce evaporation since evaporation would alter the mass of the drop
- (ii) The experiment is enclosed in a constant temperature enclosure. This is to eliminate convection currents and changes in the viscosity of air as a result of temperature changes.
- (iii) An X-ray tube is used to increase the charge of the oil drop.

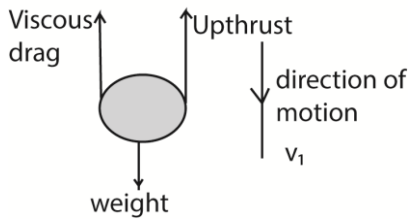
Example 6

Oil droplets are introduced into the space between two flat horizontal plates, set 5.0mm apart. The plate voltage is then adjusted to exactly 780V so that one of the droplets is held stationary. Then the

plate voltage is switched off and the selected droplet is observed to fall a measured distance of 1.5mm in 11.2s. Given that the density of the oil used is 900kgm^{-3} and the viscosity of air is $1.8 \times 10^{-5}\text{Nsm}^{-2}$, find;

i) The radius of the oil drop

Forces of falling oil drop



Weight = Upthrust + viscous drag

$$\frac{4}{3}\pi r^3 \rho g = \frac{4}{3}\pi r^3 \sigma g + 6\pi r \eta v_1$$

Density of air is negligible, $\sigma = 0$

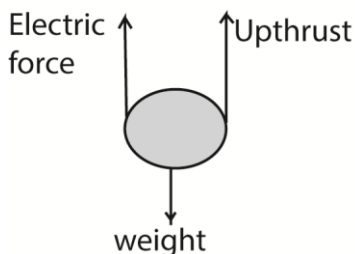
$$r = \left[\frac{9\eta v_1}{2g\rho} \right]^{\frac{1}{2}}$$

$$\text{Velocity, } v_1 = \frac{\text{distance travelled by oil drop}}{\text{time}} = \frac{1.5 \times 10^{-3}}{11.2} = 1.339 \times 10^{-4} \text{ms}^{-1}$$

$$\therefore r = \left[\frac{9 \times 1.8 \times 10^{-5} \times 1.339 \times 10^{-4}}{2 \times 9.81 \times 900} \right]^{\frac{1}{2}} = 1.1 \times 10^{-6} \text{m}$$

ii) The charge of the droplets

Forces of stationary oil drop



Weight = Upthrust + electric force

$$\frac{4}{3}\pi r^3 \rho g = \frac{4}{3}\pi r^3 \sigma g + qE$$

But $\sigma = 0$ (can be neglected, $E = \frac{V}{d}$)

$$q = \frac{4\pi r^3 \rho g d}{3V} = \frac{4\pi (1.1 \times 10^{-6})^3 \times 900 \times 9.81 \times 5 \times 10^{-3}}{3 \times 780} = 3.2 \times 10^{-19} \text{C}$$

iii) The number of electrons on the drop

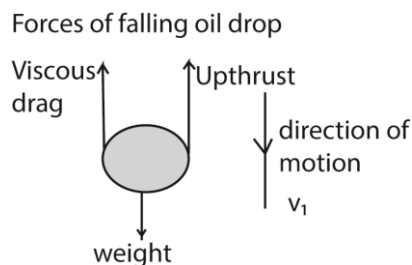
$$n = \frac{q}{e} = \frac{3.2 \times 10^{-19}}{1.6 \times 10^{-19}} = 2$$

thus the drop has acquired 2 electrons

Example 7

a) Calculate the radius of a drop of oil of density 900kgm^{-3} which falls with a terminal velocity of $2.9 \times 10^{-4}\text{m/s}$ through air of viscosity $1.8 \times 10^{-5}\text{Nsm}^{-2}$.

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Weight = Upthrust + viscous drag

$$\frac{4}{3}\pi r^3 \rho g = \frac{4}{3}\pi r^3 \sigma g + 6\pi \eta v_1$$

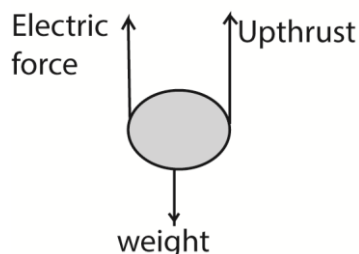
Density of air is negligible, $\sigma = 0$

$$r = \left[\frac{9\eta v_1}{2g\rho} \right]^{\frac{1}{2}}$$

$$r = \left[\frac{9 \times 1.8 \times 10^{-5} \times 2.9 \times 10^{-4}}{2 \times 9.81 \times 900} \right]^{\frac{1}{2}} = 1.63 \times 10^{-6} \text{ m}$$

b) If the charge on the drop is $-3e$, what p.d must be applied between the plates 5.0mm apart in order to keep the drop stationary?

F Forces of stationary oil drop



$$\frac{4}{3}\pi r^3 \rho g = \frac{4}{3}\pi r^3 \sigma g + qE$$

But $\sigma = 0$ (can be neglected, $E = \frac{V}{d}$)

$$V = \frac{4\pi r^3 \rho g d}{3 \times 3e} = \frac{4\pi (1.63 \times 10^{-6})^3 \times 900 \times 9.81 \times 5 \times 10^{-3}}{3 \times 3 \times 1.6 \times 10^{-19}} = 1,668 \text{ V}$$

The Bainbridge Mass Spectrometer

Consists of three main parts, namely

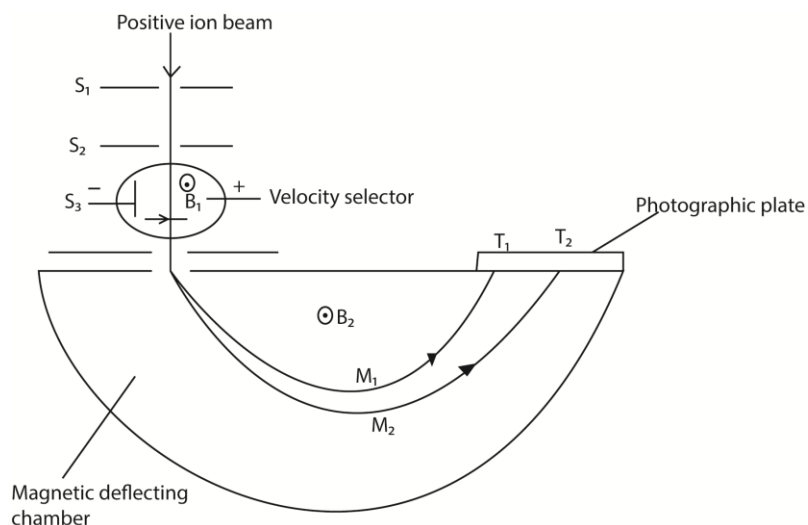
- Accelerating electric field
- Velocity selector
- Deflecting chamber

Uses of a Bainbridge mass spectrometer

1. To measure the specific charge of positive rays or ions
2. To separate isotopes of an element
3. To determine the atomic masses of the positive rays or ions

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Determination of specific charge of positive ions using a Bainbridge spectrograph



T_1 and T_2 are tracers on photographic plate, S_1 , S_2 and S_3 are slits

Mode of Action

- Positive ions are produced in a discharge tube and admitted as a beam through slits S_1 and S_2 .
- The beam then passes between insulated plates P, Q, connected to a battery, which create an electric field of intensity E .
- A uniform magnetic field B_1 , perpendicular to E is applied over the region of the plates and all ions, charge e with the same velocity, v given by $B_1 e v = E e$ will then pass undeflected through the plates and through a slit S_3 .
- The selected ions are deflected in a circular path of radius r by a uniform perpendicular magnetic field B_2 and an image is produced on a photographic plate as shown.

In this case

$$\frac{mv^2}{r} = B_2 e v$$

$$\therefore \frac{m}{e} = \frac{r B_2}{v}$$

But for the ions selected $v = \frac{E}{B_1}$ from above

$$\therefore \frac{m}{e} = \frac{r B_2 B_1}{E}$$

Or specific mass-charge ratio or specific charge, $\frac{e}{m} = \frac{E}{r B_2 B_1}$,

$$\therefore \frac{m}{e} \propto r, \text{ for given magnetic and electric fields.}$$

Since the ions strike the photographic plate at a distance $2r$ from the middle of the slit S_3 , it follows that the separation of ions carrying the same charge is directly proportional to their mass. Thus a 'linear' mass scale is achieved.

Ionic separation is obtained by

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$$m_1 = \frac{r_1 B_2 B_1 q}{E} \text{ and } m_2 = \frac{r_2 B_2 B_1 q}{E}$$

$$m_1 - m_2 = \frac{B_2 B_1 q}{E} (r_1 - r_2)$$

$$r_1 - r_2 = \frac{E}{B_2 B_1 q} (m_1 - m_2)$$

Where $r_1 - r_2 =$ ionic separation

Example 8

The magnetic flux density in both fields is 0.4T and the electric field in the velocity selector is $2 \times 10^4 \text{Vm}$.

(i) What is the velocity of an ion which goes un deviated through the slit system

$$B_1 = B_2 = B = 0.4\text{T and } E = 2 \times 10^4 \text{Vm}$$

For crossed fields in the velocity selector

$$B_1 q u = E q$$

$$\therefore u = \frac{E}{B_1} = \frac{2 \times 10^4}{0.4} = 5 \times 10^4 \text{ms}^{-1}$$

(ii) The source is set to produce singly charged ions of magnesium isotopes as Mg – 24 and Mg – 26. Find the distance between the images formed by the isotopes on the photographic plate, assuming the atomic masses of the isotopes are equal to their mass numbers numerically.

In the deflection chamber, $F_m = F_e$

$$B_2 q u = \frac{m u^2}{r}, r = \frac{m u}{B_2 q}, d = \frac{2 m u}{B_2 q} \text{ since } r = \frac{d}{2}$$

Also $m_1 = 24\text{U}$ and $m_2 = 26\text{U}$

$$d_1 = \frac{2 m_1 u}{B_2 q} \text{ and } d_2 = \frac{2 m_2 u}{B_2 q}$$

$$d_2 - d_1 = \frac{2u}{B_2 q} (m_2 - m_1) = \frac{2 \times 5 \times 10^4}{0.4 \times 1.6 \times 10^{-19}} (26 - 24) \times 1.67 \times 10^{-27} = 5.22 \times 10^{-3} \text{m}$$

(iii) Calculate the ratio of the times the two isotopes take to complete a semi-circle. {Assume $1\text{U} = 1.67 \times 10^{-27} \text{kg}$ and $e = 1.60 \times 10^{-19} \text{C}$ }

$$\text{Radius, } r = \frac{m u}{B q} \text{ and circumference of semicircle} = \pi r = \frac{\pi m u}{B q}$$

$$\text{Time taken to complete semi-circle} = \frac{\pi r}{u} = \frac{\pi m}{B q}$$

$$\text{Ration of time form Mg-24 and Mg-26} = \frac{24}{26}$$

Thank you
Dr. Bbosa Science