Unit 20 · Electrons

STUDY NOTES

WHAT NEB'S GRADE 12 EXAM ASKS

- **CDC's grid (2078):** Modern Physics (Units 20–25 together): 19 of 75 marks
- **The paper:** 11 MCQs × 1 · 8 short × 5 · 3 long × 8; 3 hours; 1 mark per expected point
- **CDC's model paper:** long (8): what quantization of charge means; a drop of weight 1.5×10^{-14} N held still between plates 10 mm apart by 470 V: the condition $qE = mg$ with a sketch of the forces, the charge $q = mgd/V = 3.2 \times 10^{-19}$ C (2e), and what happens if an alpha particle strikes it
- **MCQ (1 mark)**
  - KE through 100 V: 100 eV
  - Thomson: crossed fields
  - Millikan: charge quantized
  - B doubled → $v = E/B$ halves
  - stronger field, drop still held: less charge
  - E switched off: a circle
  - drop of half the radius: q from V
  - 2 kV → 8 kV: $v \times 2$
  - force between plates: eV/d
- **Short and long (5 or 8 marks, in parts)**
  - circular path in B; period independent of speed
  - prove the path between plates is a parabola; deflection numericals
  - specific charge; Thomson's experiment, e/m
  - Millikan: forces on a drop (free-body diagrams), q falling, rising, still; radius from v_1; why X-rays; why plates horizontal; e from several charges
  - particles in crossed fields: an alpha, an electron at $2v$

Key terms

Electron: charge $-e = -1.6 \times 10^{-19}$ C, mass 9.1×10^{-31} kg (1/1840 of a proton's).

Elementary charge e: size of the charge on one electron, 1.602×10^{-19} C.

Quantization of charge: charge exists only as whole-number multiples of e: $q = \pm ne$.

Specific charge: charge per unit mass, $e/m = 1.76 \times 10^{11}$ C/kg for the electron.

Terminal velocity: steady speed when the drag balances the other forces.

Stokes' law: viscous drag on a small sphere, $6\pi\eta rv$.

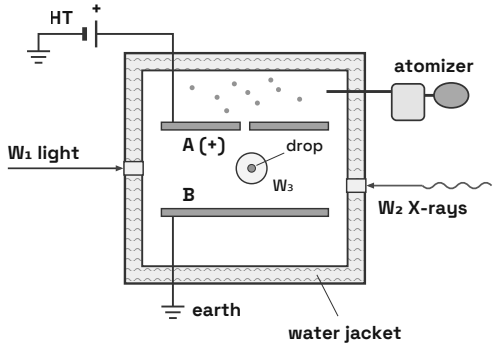
Velocity selector: crossed E and B; only $v = E/B$ passes straight.

Cyclotron frequency: $Be/2\pi m$, revolutions per second in a field.

Formulas

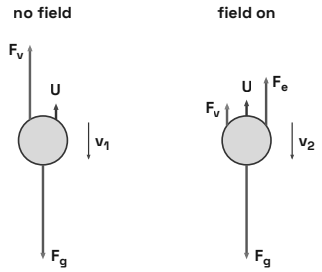
$F_v = 6\pi\eta rv$	η viscosity of air **Use:** Stokes' law
$r = \sqrt{\frac{9\eta v_1}{2(\rho - \sigma)g}}$	ρ oil, σ air **Use:** drop's radius (no field)
$q = \frac{6\pi\eta r(v_1 \mp v_2)}{E}$	− falling, + rising at v_2 **Use:** drop's charge
$qE = mg, E = V/d$	drop held still **Use:** stationary drop
$y = \frac{eE}{2mv^2}x^2$	$E = V/d$ **Use:** parabola between plates
$\tan\theta = \frac{eVx}{mdv^2}$	leaving plates of length x **Use:** direction out
$r = \frac{mv}{Be}, T = \frac{2\pi m}{Be}$	$v \perp B$ **Use:** circle in B
$v = \frac{E}{B} = \frac{V_p}{dB}$	forces balanced **Use:** crossed fields
$\frac{1}{2}mv^2 = eV_a$	V_a accelerating p.d. **Use:** electron gun
$\frac{e}{m} = \frac{E^2}{2V_aB^2} = \frac{V_p^2}{2V_ad^2B^2}$	V_p on the plates **Use:** Thomson

Millikan's oil drop experiment (1909)



Millikan's apparatus: atomizer above plate A (+) with a hole; B earthed; X-rays through one window, light through another, a microscope; a water jacket round the chamber.

- **principle**: a falling drop soon reaches a **terminal velocity** (drag balances weight); its speed with and without a field gives its charge
- plates horizontal, about 1–2 cm apart, A (+), B earthed → uniform $E = V/d$ **down**; plates horizontal and parallel so the field is uniform and **vertical**, along the drop's motion
- **atomizer**: fine drops of clock oil (hardly evaporates)
- **X-rays** ionize the air → drops gain or lose electrons (their charge changes)
- **water jacket**: steady temperature (η depends on it; no air currents)
- negative drop: force **up** towards A



Forces on a drop: falling with no field (weight down; upthrust and drag up); falling in the field (electric force qE up too).

No field (falls at v_1)

1. weight $\frac{4}{3}\pi r^3\rho g$ down; upthrust $\frac{4}{3}\pi r^3\sigma g$, drag $6\pi\eta r v_1$ up
2. $\frac{4}{3}\pi r^3(\rho-\sigma)g = 6\pi\eta r v_1$
3. $r = \sqrt{9\eta v_1/2(\rho-\sigma)g}$

In the field (falls at v_2)

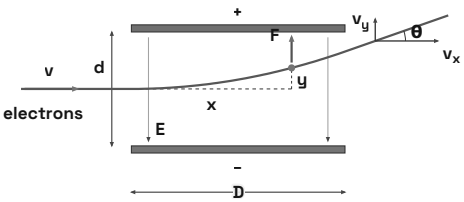
1. $\frac{4}{3}\pi r^3(\rho-\sigma)g = 6\pi\eta r v_2 + qE$
2. left side $= 6\pi\eta r v_1 \rightarrow q = 6\pi\eta r(v_1 - v_2)/E$
3. put in r: $q = \dfrac{6\pi\eta(v_1-v_2)}{E}\sqrt{\dfrac{9\eta v_1}{2(\rho-\sigma)g}}$

- **rising** at v_2: drag down → $q = 6\pi\eta r(v_1+v_2)/E$
- **held still**: no drag; upthrust about 1000 × smaller → $qE = mg$, $q = mgd/V$
- e.g. 1.5×10^{-14} N, 10 mm, 470 V → $q = 3.2\times10^{-19}$ C = **2e**
- **struck by an alpha particle**: charge changes → qE no longer equals mg → the drop moves (less negative charge → falls; more → rises)
- charges found 3.2, 6.4, 3.2×10^{-19} C → all multiples of 1.6×10^{-19} C

Significance

- measured e directly: 1.6×10^{-19} C
- charge is **quantized**: $q = \pm ne$; never 1.5e
- charge, like matter, comes in pieces
- with Thomson's e/m: $m = 1.6\times10^{-19}/1.76\times10^{11} = 9.1\times10^{-31}$ kg

Electron beam in an electric field

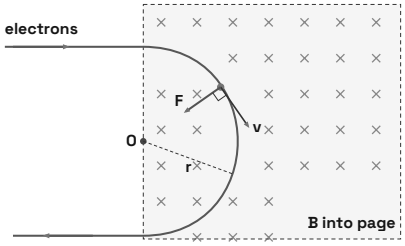


Electron entering midway between plates at speed v: no horizontal force; a constant force eE towards + bends it into a parabola, then straight.

1. horizontal: no force → $x = vt$
2. vertical: $a = eE/m$, from rest → $y = \frac{1}{2}at^2$
3. $y = \dfrac{eE}{2mv^2}x^2 = kx^2$: a **parabola**

- leaving: $v_y = eVx/mdv$; $\tan\theta = eVx/mdv^2$; then a straight line
- force $eE = eV/d$: 8 V across 2 cm → 6.4×10^{-17} N
- entering midway: if $y > d/2$ at the end, it hits a plate

Electron beam in a magnetic field



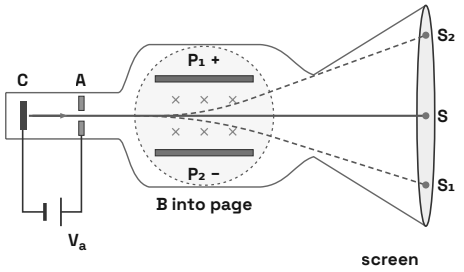
Electron entering a field into the page at right angles: the force evB, always ⊥ v, bends it into a circle.

1. $F = evB \perp v$
2. $Bev = mv^2/r \rightarrow r = mv/Be$

3. $T = 2\pi r/v = 2\pi m/Be$: **independent of speed and radius**; $f = Be/2\pi m$

- no work: direction changes, speed doesn't
- along the field: undeflected; at an angle: a **helix**
- Fleming's left hand for an electron: second finger **against** its motion

Thomson's experiment: e/m (1897)



Thomson's tube: cathode C, anode A, plates P_1 (+) and P_2 (−) with B across them; spot S with no field, S_1 with B alone, S_2 with E alone.

- **principle**: crossed fields; balance them to find v, then use the accelerating p.d.
- tube at very low pressure; **V_a** accelerates; plates with V_p, $E = V_p/d$; coils make $B \perp E$ and the beam; fluorescent screen

1. no fields: spot at S
2. B alone: bent down to S_1, $F_m = evB$
3. E alone: bent up to S_2, $F_e = eE$
4. both, adjusted to S: $evB = eE \rightarrow v = E/B$ (any particle: **velocity selector**)
5. $\frac{1}{2}mv^2 = eV_a \rightarrow e/m = v^2/2V_a$
6. $e/m = E^2/2V_aB^2 = 1.76 \times 10^{11}$ C/kg

- B doubled, E same $\rightarrow$ v halves; E switched off $\rightarrow$ circle in B
- $v \propto \sqrt{V_a}$: 2 kV $\rightarrow$ 8 kV doubles v
- in the same crossed fields: any particle at v undeflected (alpha too); an electron at $2v$: magnetic force wins

COMMON MISTAKES

✗ $e/m = V/2d^2B^2$ with one V
✓ $E^2/2V_aB^2$: V_a accelerates, V_p on the plates makes E.

✗ Millikan's plates 3.5 cm apart
✓ about **1.5 cm** apart (22 cm across).

✗ a beam always clears the plates
✓ if $y > d/2$ at the end, it **hits a plate**.

✗ drop held still: drag balances weight
✓ no drag: $qE = mg$.

✗ the period in B grows with speed
✓ $T = 2\pi m/Be$, the same.

✗ a magnetic field speeds an electron up
✓ no work; speed unchanged.

✗ the path in an electric field is a circle
✓ a **parabola**; a circle in B.