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A2 PHYSICS

Complete Formula & Concept Sheet

Cambridge International A Level — 9702

Topics 12 – 25 · 20-Page Edition

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Topic 12 Motion in a Circle

Angular quantities

Angular displacement:

$$\theta = s / r \qquad (\text{rad})$$

Angular speed:

$$\omega = \Delta\theta / \Delta t = 2\pi / T = 2\pi f$$

Linear speed in a circle:

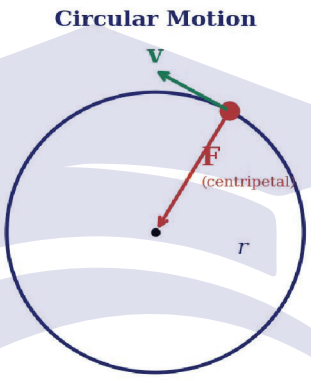
$$v = r\omega$$

1 revolution = 2π rad = 360°
Period T (s): time for one full revolution
Frequency f (Hz): revolutions per second
Direction of v is always tangent to the circle.

Centripetal acceleration & force

$$a = v^2 / r = r\omega^2 = v\omega$$
$$F = mv^2 / r = mr\omega^2$$

F is always directed **towards the centre**. It does no work on the object (perpendicular to v) so the speed is constant in uniform circular motion.



Velocity is tangential; net force points to the centre.

Common contexts

- Horizontal circle on a string: $T = mv^2/r$
- Vertical loop, top: $mg + T = mv^2/r$; bottom: $T - mg = mv^2/r$
- Conical pendulum: $\tan\theta = v^2/(rg)$
- Banked track (no friction): $\tan\theta = v^2/(rg)$
- Car over a hill (just leaves road): $mg = mv^2/r$

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Topic 13 Gravitational Fields (Part 1)

Newton's law of gravitation

$$F = G M m / r^2 \qquad \text{(attractive)}$$

$G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}. Acts between any two point masses; for spherical bodies treat mass as concentrated at the centre (for $r \geq R$).

Gravitational field strength

$$g = F / m = G M / r^2$$

Vector quantity, units N kg^{-1} (= m s^{-2}). Direction: towards the mass producing the field.

On Earth's surface

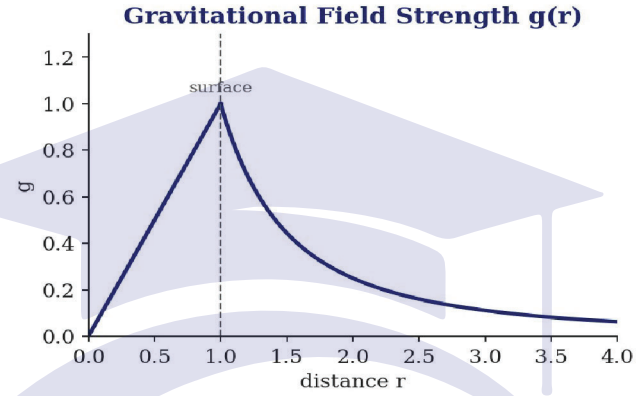
$$g_o = G M_E / R_E^2$$

Above the surface, g decreases as $1/r^2$ where r is measured from the centre of the Earth.

Inside a uniform sphere

$$g_{inside} \propto r$$

Outside a sphere acts as if all mass were at the centre.



g varies linearly with r inside, and as $1/r^2$ outside.

Orbits

For a satellite in a circular orbit: gravitational pull provides centripetal force.

$$G M m / r^2 = m v^2 / r \Rightarrow v = \sqrt{(GM / r)}$$

$$T^2 = 4\pi^2 r^3 / (G M) \qquad \text{(Kepler's 3rd law)}$$

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Topic 13 Gravitational Fields (Part 2)

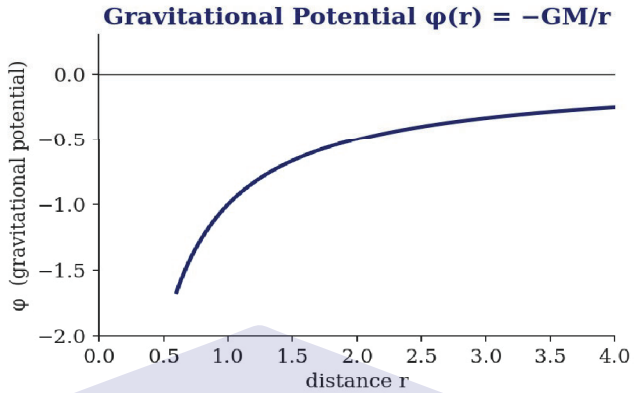
Gravitational potential φ

$$\varphi = -GM/r \qquad (\text{J kg}^{-1})$$

Work done per unit mass to bring a small mass from infinity to that point. Always negative — taken as 0 at infinity.

Potential energy

$$U = m\varphi = -GMm/r$$



φ approaches 0 at infinity and → −∞ near the mass.

Field & potential link

$$g = -d\varphi/dr \qquad (g = -\text{gradient of } \varphi)$$

The minus sign shows the field points from high to low potential.

Escape speed

Speed at which KE = |PE| at the surface:

$$\tfrac{1}{2} m v_e^2 = GMm/R \Rightarrow v_e = \sqrt{(2GM/R)}$$

Geostationary orbit

- Period T = 24 h, equatorial, same direction as Earth's rotation.
- Radius from centre ≈ 4.23×10^7 m (height ≈ 3.6×10^7 m).
- Stays above one fixed point on Earth — used for communications.

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Topic 14 Temperature & Thermal Properties

Temperature scales

$$T\,(\mathrm{K}) = \theta\,(^{\circ}\mathrm{C}) + 273.15$$

0 K = absolute zero — no kinetic energy of random motion. The thermodynamic (Kelvin) scale is independent of any substance.

Thermometers (key idea)

- Thermometric property: a measurable quantity that varies with T (e.g. resistance, emf, length, pressure).
- Calibration: two fixed points (e.g. ice point and steam point) at known temperatures.
- Resistance thermometer: wide range, accurate. Thermocouple: small junctions, fast response, can measure high T. Liquid-in-glass: simple, limited range.

Internal energy

Internal energy U = sum of (random) kinetic + potential energies of all the molecules.

- KE depends on absolute temperature.
- PE depends on intermolecular separation (state of matter).

Specific heat capacity (no change of state)

$$Q = m\,c\,\Delta T \qquad (\mathrm{J})$$

c = energy needed per kg to raise temperature by 1 K. Units: J kg^{-1} K^{-1}.

Specific latent heat (change of state)

$$Q = m\,L$$

- L_f = specific latent heat of fusion (solid ↔ liquid)
- L_v = specific latent heat of vaporisation (liquid ↔ gas)

During a change of state, T does not change — energy goes into PE of molecules (breaking bonds).

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Topic 15 Ideal Gases

Mole and Avogadro's number

$$N = n N_A \qquad N_A = 6.02 \times 10^{23}\ \text{mol}^{-1}$$

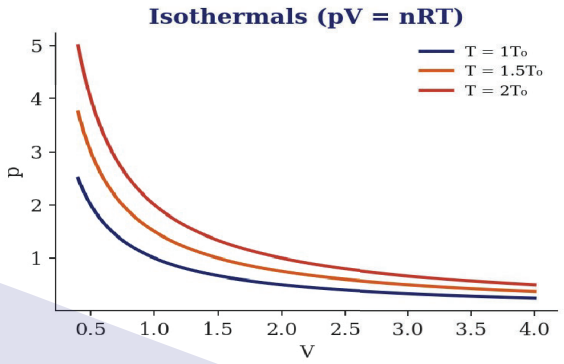
Equation of state

$$p V = n R T = N k T$$

$R = 8.31\ \text{J mol}^{-1}\ \text{K}^{-1}$; $k = R/N_A = 1.38 \times 10^{-23}\ \text{J K}^{-1}$.

Gas laws (special cases)

Boyle: $pV = \text{const}$ (T fixed)
Charles: $V/T = \text{const}$ (p fixed)
Pressure: $p/T = \text{const}$ (V fixed)



Kinetic theory of gases

Assumptions:

- Molecules are point particles in random motion.
- Collisions are elastic, of negligible duration.
- Intermolecular forces are negligible (except during collisions).
- Volume of molecules « volume of the container.

$$p V = \tfrac{1}{3} N m \langle c^2 \rangle$$

$\langle c^2 \rangle$ = mean square speed of molecules; m = mass of one molecule.

Mean translational KE of a molecule

$$\tfrac{1}{2} m \langle c^2 \rangle = (3/2)\, k T$$

Hence the total internal energy of an ideal monatomic gas:

$$U = N \cdot (3/2)\, k T = (3/2)\, n R T$$

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Topic 16 Thermodynamics — First Law

First law of thermodynamics

$$\Delta U = q + w$$

ΔU = increase in internal energy ; q = heat supplied **to** the system ; w = work done **on** the system.

Work done on/by a gas

$$w_{on\ gas} = -p\,\Delta V \qquad \text{(constant pressure)}$$

If the gas expands (ΔV > 0), work is done **by** the gas → w on gas is negative.

Special processes (ideal gas)

Isothermal (T constant)

- ΔU = 0 → q = − w
- pV = constant
- Heat absorbed equals work done by the gas.

Adiabatic (q = 0)

- ΔU = w → temperature changes
- Compression heats the gas; expansion cools it.

Isobaric (p constant)

- w on gas = − p ΔV
- Q = n C_p ΔT (for ideal gas)

Isochoric (V constant)

- w = 0 → ΔU = q
- All heat goes into raising T.

Reading p–V diagrams

- Area under a p–V curve = work done by the gas.
- Closed cycle: net work = enclosed area; ΔU over a cycle = 0.

For an ideal gas, U depends only on T — so along an isothermal, ΔU = 0.

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Topic 17 Oscillations — SHM (Part 1)

Defining condition for SHM

$$a = -\omega^2 x$$

Acceleration is **proportional to displacement** from the equilibrium position and **directed back towards it**.

Solutions of SHM

$$x = x_0 \cos(\omega t) \quad \text{(start at amplitude)}$$
$$x = x_0 \sin(\omega t) \quad \text{(start at equilibrium)}$$
$$v = \pm\omega\sqrt{(x_0^2 - x^2)}$$
$$v_{max} = \omega x_0, \quad a_{max} = \omega^2 x_0$$

$$\omega = 2\pi / T = 2\pi f$$

Phase relations

- v leads x by π/2 (90°)
- a leads v by π/2 ; a is π out of phase with x

Examples of SHM systems

Mass on a spring

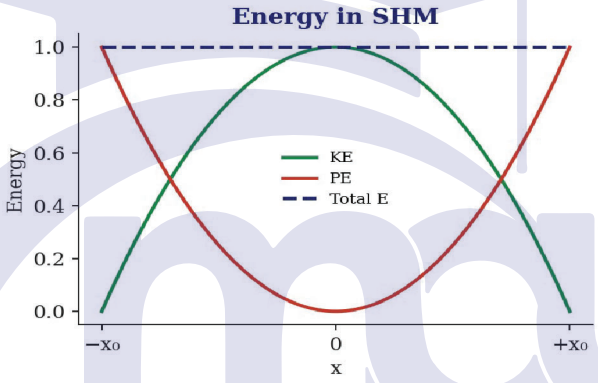
$$T = 2\pi\sqrt{(m / k)}$$

Simple pendulum (small θ)

$$T = 2\pi\sqrt{(L / g)}$$

Energy in SHM

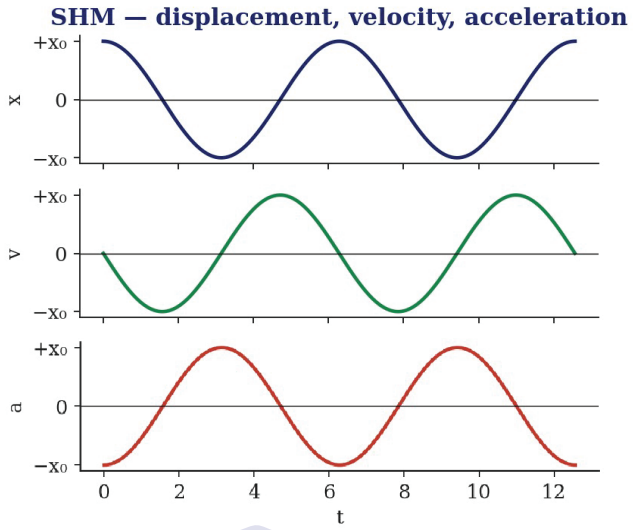
$$KE = \tfrac{1}{2} m \omega^2 (x_0^2 - x^2)$$
$$PE = \tfrac{1}{2} m \omega^2 x^2$$
$$\text{Total } E = \tfrac{1}{2} m \omega^2 x_0^2 \quad \text{(constant)}$$



KE and PE interchange; total mechanical energy is constant.

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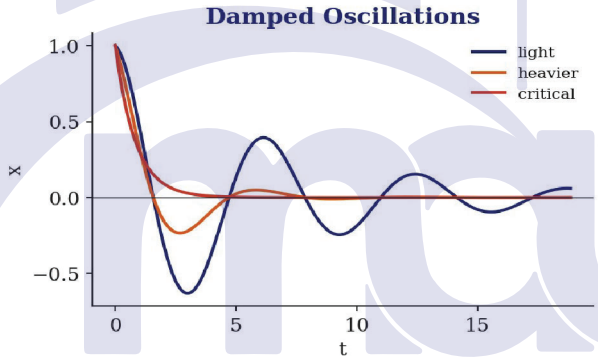
Topic 17 Oscillations — SHM (Part 2)



Displacement, velocity and acceleration vs. time for SHM.

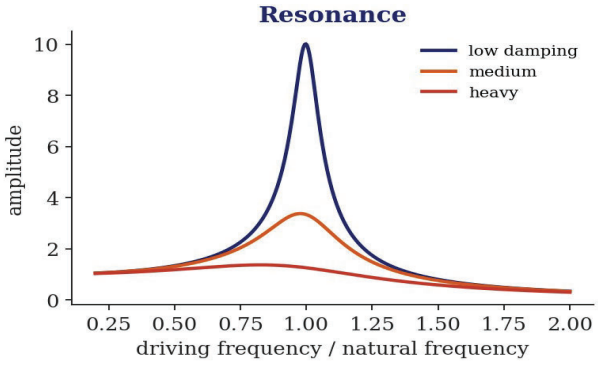
Damping

- **Light damping:** amplitude decays exponentially; period almost unchanged.
- **Critical damping:** returns to equilibrium in the shortest time without oscillating (e.g. car suspensions, door dampers).
- **Heavy (over) damping:** returns slowly without oscillating.



Forced oscillation & resonance

- Forced: driven by an external periodic force at frequency f.
- **Resonance:** amplitude is maximum when driving frequency equals the natural frequency f_0.
- Heavier damping → smaller, broader resonance peak shifted slightly below f_0.



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Topic 18 Electric Fields (Part 1)

Coulomb's law

$$F = Q_1 Q_2 / (4\pi\varepsilon_0 r^2)$$

$\varepsilon_0 = 8.85 \times 10^{-12}$ F m^{-1} ; $k = 1/(4\pi\varepsilon_0) \approx 8.99 \times 10^9$ N m^2 C^{-2}. Repulsive for like charges, attractive for unlike.

Electric field strength

$$E = F / Q \qquad (N\ C^{-1} = V\ m^{-1})$$

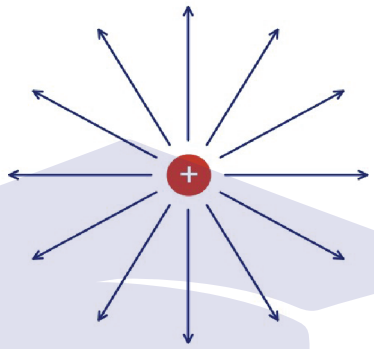
Point charge

$$E = Q / (4\pi\varepsilon_0 r^2)$$

Uniform field (parallel plates)

$$E = V / d$$

Field of a Point Charge (radial)



Radial field of a positive point charge.

Field-line rules

- Lines start on + charges and end on − charges.
- Tangent gives field direction; closer lines = stronger field.
- Lines never cross; meet conductor surfaces at right angles.

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Topic 18 Electric Fields (Part 2)

Electric potential V

$$V = Q / (4\pi\varepsilon_0 r) \qquad \text{(taken as 0 at infinity)}$$

Work done per unit positive charge to bring it from infinity to a point. Scalar quantity ($J\,C^{-1} = V$).

Potential energy of two point charges

$$U = Q_1 Q_2 / (4\pi\varepsilon_0 r)$$

Field – potential relationship

$$E = -dV / dx$$

Field points from high to low potential. On a graph of V against r, E is the (negative) gradient.

Comparison: gravitational vs electric

- $g = GM/r^2$ ↔ $E = Q/(4\pi\varepsilon_0 r^2)$
- $\varphi = -GM/r$ ↔ $V = Q/(4\pi\varepsilon_0 r)$
- F gravity always attractive.
- F electric attractive or repulsive.
- Field strength inverse-square in both.
- Potential inverse in r, scalar in both.

Charged particle in a uniform field

- Force $F = QE$ → acceleration $a = QE/m$
- Parabolic path if entering with velocity perpendicular to E (similar to projectile motion).

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Topic 19 Capacitance

Definition

$$C = Q / V \qquad (1\ F = 1\ C\ V^{-1})$$

Capacitors in combination

In parallel

$$C_{total} = C_1 + C_2 + \ldots$$

Same V across each. Q adds.

In series

$$1/C_{total} = 1/C_1 + 1/C_2 + \ldots$$

Same Q on each. V adds.

Energy stored

$$W = \tfrac{1}{2} Q V = \tfrac{1}{2} C V^2 = \tfrac{1}{2} Q^2 / C$$

Equal to the area under a Q–V graph (a triangle).

Charging & discharging through resistor R

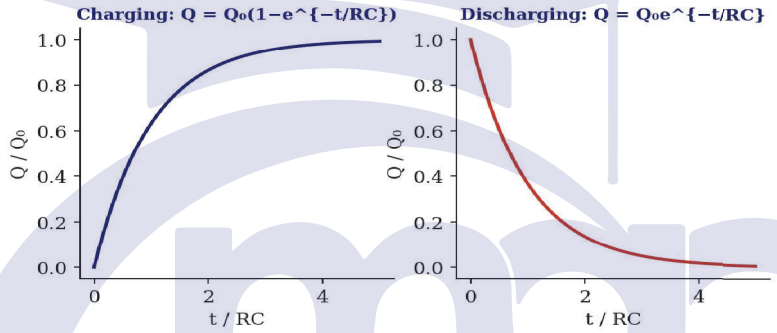
Charging

$$Q = Q_0 (1 - e^{(-t/RC)})$$
$$V = V_0 (1 - e^{(-t/RC)})$$
$$I = I_0 e^{(-t/RC)}$$

Discharging

$$Q = Q_0 e^{(-t/RC)}$$
$$V = V_0 e^{(-t/RC)}$$
$$I = I_0 e^{(-t/RC)}$$

Time constant $\tau = RC$ (s). After one τ, Q falls to $1/e \approx 37\%$ of Q_0 (or rises to 63% when charging).



Exponential charge build-up and discharge.

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Topic 20 Magnetic Fields (Part 1)

Force on a current-carrying conductor

$$F = B I L \sin\theta$$

θ = angle between current and field. Maximum when current is perpendicular to B (sin θ = 1).

Tesla

1 T = 1 N A^{-1} m^{-1}: the flux density that produces 1 N on each metre of a wire carrying 1 A perpendicular to B.

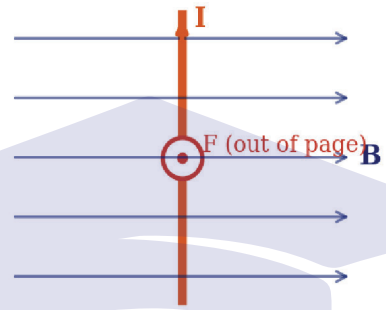
Force on a moving charge

$$F = B Q v \sin\theta$$

Force is always perpendicular to v → no work done → speed unchanged → circular motion (in a uniform field).

$$r = m v / (B Q)$$

F = BIL (Fleming's LH rule)

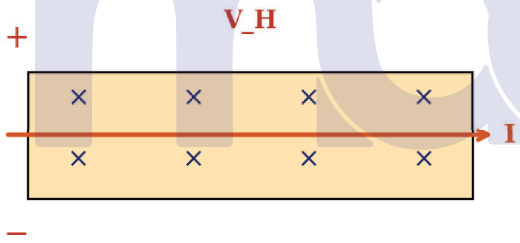


Fleming's left-hand rule: thuMb–Force, First–Field, seCond–Current.

Hall effect (semiconductor of thickness t, n carriers per m^3)

$$V_H = B I / (n t q)$$

Hall Effect: V_H = BI / (ntq)



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Topic 20 Magnetic Fields (Part 2) — EM Induction

Magnetic flux

$$\Phi = B\,A\cos\theta \qquad (\text{Wb} = \text{T m}^2)$$

Flux linkage $N\Phi$ for an N-turn coil

Faraday's law

$$\varepsilon = -\,d(N\Phi)/dt$$

Magnitude of induced emf equals the rate of change of flux linkage.

Lenz's law

The induced current flows in the direction such that its effect **opposes the change** which produced it (consequence of conservation of energy — explains the minus sign in Faraday's law).

Practical contexts

- Straight wire of length L moving at speed v perpendicular to B: $\varepsilon = BLv$
- Coil rotating in B: $\varepsilon = NBA\omega\sin(\omega t)$ → alternating emf
- Search coil: connected to oscilloscope; the alternating flux through the coil induces an emf used to investigate magnetic field patterns and strengths.

Investigating Φ–t and ε–t graphs

- ε is the negative gradient of the flux-linkage graph (NΦ vs t).
- Where NΦ has a turning point (max or min) → ε = 0.
- Where NΦ changes most rapidly (steepest gradient) → |ε| is maximum.

Conservation of energy & Lenz's law

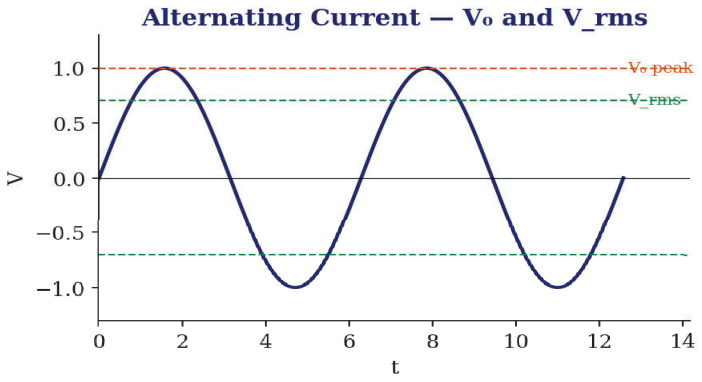
- Pushing a magnet into a coil: induced current opposes the motion (you do positive work against the induced force) → kinetic energy converted to electrical energy in the coil.
- This is the fundamental link between Lenz's law and conservation of energy.

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Topic 21 Alternating Currents

Sinusoidal a.c.

$$I = I_o \sin(\omega t) \qquad V = V_o \sin(\omega t)$$
$$\omega = 2\pi f, \quad T = 1/f$$



Peak, peak-to-peak, rms

$$I_{rms} = I_o / \sqrt{2}, \quad V_{rms} = V_o / \sqrt{2}$$

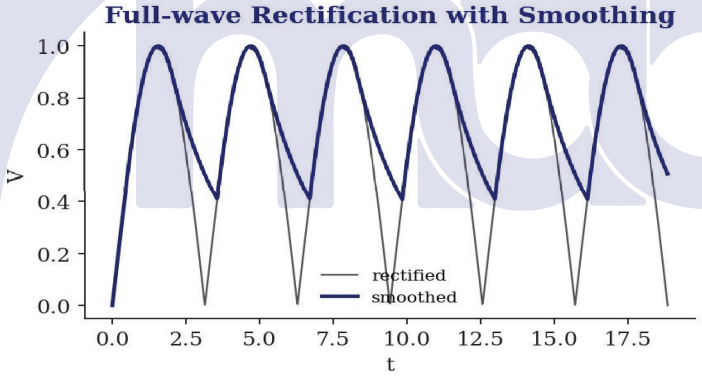
rms (root-mean-square) is the d.c. equivalent — produces the same average power dissipation in a resistor.

Mean power in a resistor

$$\langle P \rangle = \tfrac{1}{2} I_o V_o = I_{rms} V_{rms} = I_{rms}^2 R = V_{rms}^2 / R$$

Rectification

- **Half-wave:** single diode — only half of each cycle passes; output not smooth, half the average current.
- **Full-wave (bridge of 4 diodes):** both halves used; doubles average output.
- **Smoothing:** a capacitor in parallel with the load — charges quickly, then supplies current as the rectified voltage drops, leaving a small ripple.



Rectified output (grey) and capacitor-smoothed output (navy).

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Topic 22 Quantum Physics

Photon energy

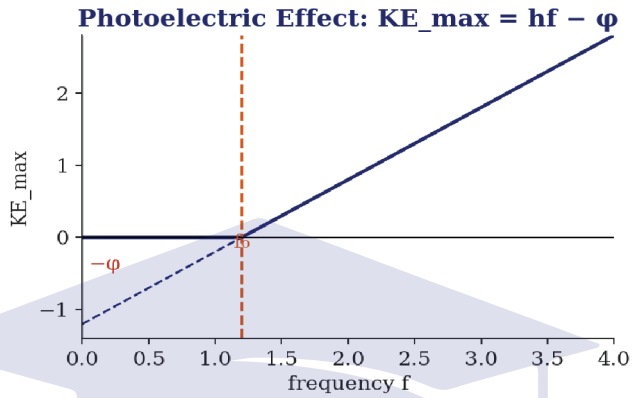
$$E = h f = h c / \lambda$$

$h = 6.63 \times 10^{-34}$ J s. Photons are discrete packets of EM energy.

Photoelectric effect

$$h f = \varphi + KE_{max}$$

- **Threshold frequency f_0:** $\varphi = h f_0$; below f_0 no electrons emitted however bright the light.
- KE_{max} depends on f, not intensity. Intensity affects the rate of emission.
- Confirms the particle nature of EM radiation.



Gradient = h ; x-intercept = f_0 ; y-intercept = $-\varphi$.

Wave-particle duality (de Broglie)

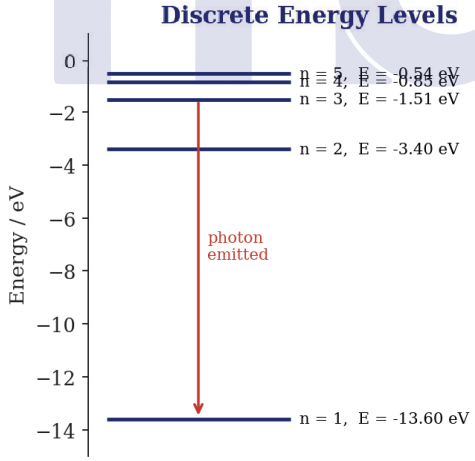
$$\lambda = h / p = h / (m v)$$

Electrons diffract through a thin crystal — direct evidence that particles have wave properties.

Atomic line spectra

$$h f = E_1 - E_2$$

Discrete photons are emitted/absorbed only when an electron transitions between fixed energy levels — explaining sharp emission/absorption lines.



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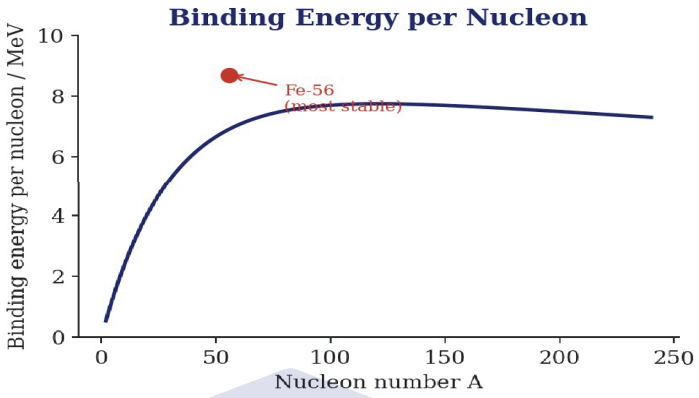
Topic 23 Nuclear Physics

Mass defect & binding energy

$$\Delta m = Z\,m_p + (A - Z)\,m_n - m_nucleus$$

$$E = \Delta m\,c^2 \qquad (E = \text{energy released when the nucleus is formed})$$

Binding energy per nucleon is a measure of nuclear stability.



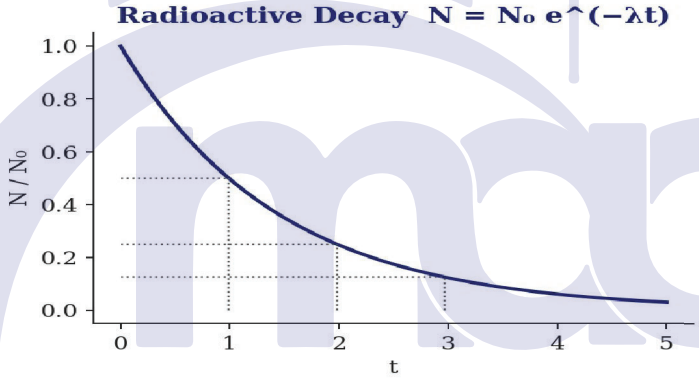
Peak around Fe-56 — fusion of light nuclei or fission of heavy nuclei releases energy.

Radioactive decay

$$\frac{dN}{dt} = -\lambda N$$

$$N = N_0\,e^{(-\lambda t)} \qquad A = A_0\,e^{(-\lambda t)}$$

$$t_{1/2} = \ln 2 / \lambda = 0.693 / \lambda$$



Activity

$$A = \lambda N \qquad (\text{Bq} = \text{decays per second})$$

Decay is a **random** and **spontaneous** process — exact moment of an individual decay cannot be predicted; statistical behaviour follows the exponential law.

α, β, γ at a glance

- α: $^4_2$He nucleus; high ionising power; stopped by paper; deflected slightly by E and B fields.
- β^-: fast electron from neutron→proton; medium ionising; stopped by ~3 mm Al; deflected oppositely to α.
- γ: high-energy photon; weak ionising; reduced by thick Pb; not deflected by E or B.

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Topic 24 Medical Physics

Production of ultrasound (piezoelectric crystal)

- Alternating p.d. across a crystal causes it to vibrate at its natural frequency, generating ultrasound (f > 20 kHz).
- Reflected ultrasound makes the crystal vibrate, generating an a.c. p.d. — the same crystal acts as transmitter and receiver.

Acoustic impedance & reflection

$$Z = \rho c \qquad (\text{kg m}^{-2}\,\text{s}^{-1})$$

$$I_r / I_o = (Z_2 - Z_1)^2 / (Z_2 + Z_1)^2$$

Coupling gel removes air gap (huge Z mismatch) so most of the ultrasound enters tissue.

Attenuation in matter

$$I = I_o e^{(-\mu x)}$$

μ = linear absorption coefficient. Half-value thickness $x_{½} = \ln 2 / \mu$.

X-ray imaging

- X-rays produced when fast electrons strike a metal target. Continuous (bremsstrahlung) + characteristic line spectrum.
- Contrast: bones (high μ) absorb more than tissue → appear lighter on the film.
- Sharpness improved by small focal spot, contrast by Cu/Al filters and contrast media (e.g. barium).
- **CT scan:** rotates X-ray source/detector around patient; computer reconstructs 3-D image — high contrast and depth, but high dose.

PET (positron-emission tomography)

- Tracer emits positrons; positron + electron → 2 γ photons (511 keV) in opposite directions.
- Coincidence detection locates the annihilation; map of metabolic activity (e.g. ^{18}F-FDG).

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Topic 25 Astronomy & Cosmology

Standard candles & luminosity

$$F = L / (4\pi d^2) \qquad \text{(radiant flux intensity)}$$

L = total power emitted (W); F = power received per m^2 at the observer.

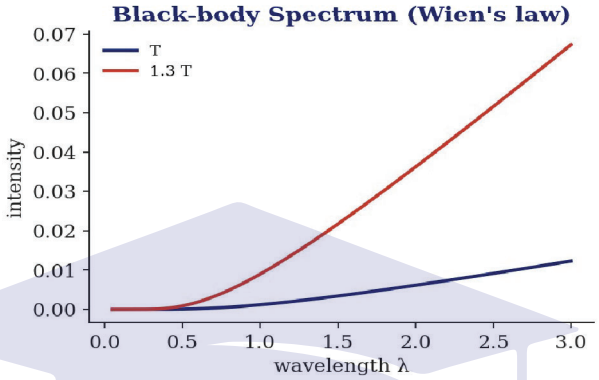
Stefan–Boltzmann law

$$L = 4\pi R^2 \sigma T^4$$

$\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}. Combined with Wien's law it gives R if T and L are known.

Wien's displacement law

$$\lambda_{max} T = 2.9 \times 10^{-3} \text{ m K}$$



Hotter bodies peak at shorter wavelengths (bluer).

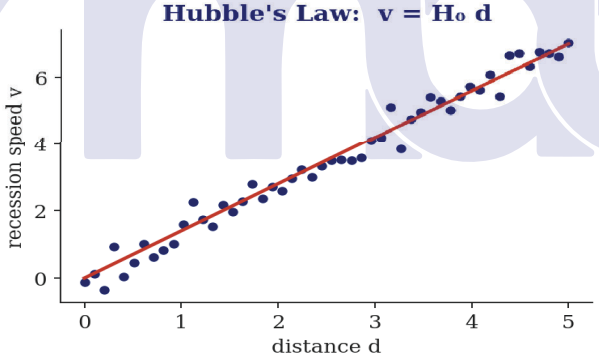
Doppler shift for light (v « c)

$$\Delta\lambda / \lambda \approx \Delta f / f \approx v / c$$

Galaxies show **redshift** (λ longer) → moving away.

Hubble's law and the Big Bang

$$v = H_0 d$$



Age of Universe ≈ $1 / H_0$. Hubble's law and the cosmic microwave background (~2.7 K) are key evidence for the Big Bang.

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Topic R Constants, Conversions & Final Tips

Data — Cambridge 9702

- $c = 3.00 \times 10^{8}$ m s^{-1}
- $\varepsilon_0 = 8.85 \times 10^{-12}$ F m^{-1}
- $e = 1.60 \times 10^{-19}$ C
- $h = 6.63 \times 10^{-34}$ J s
- $u = 1.66 \times 10^{-27}$ kg
- $m_e = 9.11 \times 10^{-31}$ kg
- $m_p = 1.67 \times 10^{-27}$ kg
- N_A = 6.02×10^{23} mol^{-1}
- $R = 8.31$ J mol^{-1} K^{-1}
- $k = 1.38 \times 10^{-23}$ J K^{-1}
- $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}
- $g = 9.81$ N kg^{-1}
- $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}
- Wien: $\lambda_{max} T = 2.9 \times 10^{-3}$ m K
- $H_0 \approx 2.4 \times 10^{-18}$ s^{-1}
- Earth: $M = 6.0 \times 10^{24}$ kg, $R = 6.4 \times 10^{6}$ m

Common conversions

- 1 eV = 1.60×10^{-19} J ; 1 MeV = 1.60×10^{-13} J
- 1 u → 931.5 MeV (mass-energy equivalence)
- Angle: 1° = π/180 rad ; ω in rad s^{-1}

Exam-day tips from Sir MAC

- **Direction matters:** vectors (E, F, g, B, v) need both magnitude and direction. State the direction!
- **Always check units:** substitute base units into your final formula to check it's dimensionally consistent.
- **Significant figures:** answers to 2 or 3 s.f., matching the data given.
- **Graph questions:** name the axes, scales, plot points, line of best fit, calculate gradient/intercept with units.
- **State, explain, deduce:** 'state' = one-line answer; 'explain' = reasoning needed; 'show that' = include all working with the given data.
- **Definitions:** learn them word-for-word — they are guaranteed marks.

Best of luck — Sir Mahad · Physics with MAC

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