REAL-LIFE PHYSICS

Particles and Waves

Teacher guide

For the Higher Physics workbook



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Blewis LEARNING

Using the workbooks

The Higher Physics workbook for **Particles and Waves** has eight topics. Every topic has learning pages, a practical the learner plans and evaluates (with uncertainties), a brain break and an exam-style check-up.

PRACTICALS

Learners plan each investigation (variables, prediction, kit, risk, method), take repeat readings, work out averages, draw graphs with their own scales, and write conclusions and evaluations.

PRACTICAL SAFETY

Every practical has a Stay safe table and a teacher note with hazards, adapted versions and common problems. The Stay safe tables and these notes are a starting point, not a complete risk assessment: the teacher or school must risk assess every practical for their own learners, room and kit before use, following their employer's policies and national guidance (in Scotland, SSERC). Always check learners' care plans and medical information. High-voltage supplies and tubes are teacher-only; radioactive sources and nuclear processes are covered by data or simulations; lasers are class 2 only and never looked into.

NO LAB, NO KIT, OR A LEARNER ABSENT

Each practical includes example results so learners can still complete the results, graph, conclusion and evaluation.

EVIDENCE

The practicals develop the skills needed for the assignment and for questions on experimental work in the exam; the learn pages and check-ups build knowledge and problem solving. The skills tracker at the back of each workbook can be signed off as you go. Always check the latest course documents and your centre's arrangements.

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TEACHER NOTES

Practical 1: The charge to mass ratio of the electron

Time	One 50-minute lesson for processing, graph and evaluation. A teacher demonstration of a deflection or fine-beam tube (about 10 minutes) adds interest.
Kit	Data practical: calculator, ruler, the sample data. Optional demonstration: fine-beam or deflection tube, EHT supply, Helmholtz coils, safety screen.
Prep	If you demonstrate, check the tube and EHT supply in advance and dim the room so the beam is visible.
Expected results	v^2 rises in proportion to V; gradient about 3.5×10^{11} $m^2\ s^{-2}\ V^{-1}$, giving $e/m \approx 1.75 \times 10^{11}$ C/kg, within about 1 % of the accepted value.
Level	H derives the linear relationship, processes data, draws the graph, finds a gradient, compares with an accepted value and evaluates.

Safety and inclusion

- EHT supplies and vacuum tubes are teacher-only: shrouded leads, current-limited supply, safety screen, switch off before handling. Tubes can implode if knocked.
- The data practical needs no lab, so every learner can take part fully; offer graph paper with pre-drawn axes if needed.
- Risk assess for your own class, room and kit, following your employer's policies and SSERC guidance.

Common problems

- **Using kV as V:** convert 2.5 kV to 2500 V.
- **Plotting v against V:** gives a curve; plot v^2 against V.
- **Gradient from two data points:** use two well-separated points on the line of best fit.

No lab, no time, or a learner absent?

The whole practical runs from the data given in the workbook.

Assessment link

Practises assignment skills: processing raw data, plotting a linear graph, finding a gradient, percentage uncertainty and comparing with a referenced value.

Answers: Topic 1

Topic 1: Forces on charged particles (Higher)

1 Electric fields and work

1 Straight, parallel, evenly spaced lines from the top (positive) plate to the bottom (negative) plate, arrows pointing down; lines bulge slightly at the edges.

2 $W = Q\,V = 1.60 \times 10^{-19} \times 4500 = 7.2 \times 10^{-16}$ J

3 One volt is one joule of work done per coulomb of charge moved between two points ($1\ V = 1\ J\ C^{-1}$).

2 Accelerating charges

1 $W = Q\,V = 1.60 \times 10^{-19} \times 800 = 1.3 \times 10^{-16}$ J; $\frac{1}{2} \times 9.11 \times 10^{-31} \times v^2 = 1.3 \times 10^{-16}$; $v = 1.7 \times 10^{7}$ m/s

2 $E_k = \frac{1}{2} \times 1.673 \times 10^{-27} \times (5.0 \times 10^{5})^2 = 2.1 \times 10^{-16}$ J; $V = E_k \div Q = 2.1 \times 10^{-16} \div 1.60 \times 10^{-19} =$ 1307 V, so 1300 V

3 $E_k = W = Q\,V = 1.60 \times 10^{-19} \times 1000 = 1.6 \times 10^{-16}$ J

3 Magnetic fields and accelerators

1 Right hand (negative charge): first finger into the page, second finger to the right, thumb points **down** the page: the force is downwards.

2 It curves the opposite way (upwards); it curves much less (larger radius) because its mass is about 1800 times greater.

3 The force is always at right angles to the velocity, so it does no work on the particle: its kinetic energy, and so its speed, stays the same; only the direction changes.

Practical 1: The charge to mass ratio of the electron

Variables: independent = accelerating p.d.; dependent = speed of the electrons; controlled = the same tube and speed-measuring method (or the same particle, the electron).

Physics: $e\,V = \frac{1}{2}\,m\,v^2$, so $v^2 = (2e/m)\,V$. Plot v^2 against V: a straight line through the origin with gradient 2e/m.

Hazards (real experiment), e.g. glass vacuum tube could implode (teacher handles it, safety screen); hot filament (do not touch; allow to cool).

v^2 values: 500 V: $v^2 = 1.77 \times 10^{14}$ m²/s²; 1000 V: $v^2 = 3.46 \times 10^{14}$ m²/s²; 1500 V: $v^2 = 5.29 \times 10^{14}$ m²/s²; 2000 V: $v^2 = 7.08 \times 10^{14}$ m²/s²; 2500 V: $v^2 = 8.70 \times 10^{14}$ m²/s².

Graph: straight line through the origin. Gradient ≈ 3.50×10^{11} m² s^{-2} V^{-1} (accept 3.4 to 3.6 × 10^{11}).

Percentage uncertainty in the smallest speed = $0.02 \times 10^{7} \div 1.33 \times 10^{7} \times 100 = 1.5$ %.

6 e/m = gradient ÷ 2 ≈ 1.75×10^{11} C/kg; percentage difference ≈ 0.4 % (about 1 %) (accept values consistent with the candidate's gradient).

7 v^2 is directly proportional to V (straight line through the origin), as $Q\,V = \frac{1}{2}\,m\,v^2$ predicts; e/m ≈ 1.75×10^{11} C/kg, close to the accepted 1.76×10^{11} C/kg.

8a A graph uses all the readings, averages out random uncertainty and shows up any anomalous point. 8b e.g. the voltmeter reading consistently high or low (a calibration or zero error) makes every v^2 value wrong in the same direction and shifts the line, giving a wrong gradient; or the electrons not starting from rest.

Check-up

1 B (1)

2 (a) $W = Q\,V$ (1); $W = 1.60 \times 10^{-19} \times 25\,000$ (1); $W = 4.0 \times 10^{-15}$ J (1). (b) $\frac{1}{2}\,m\,v^2 = W$ (1); $0.5 \times 9.11 \times 10^{-31} \times v^2 = 4.0 \times 10^{-15}$ (1); $v = 9.4 \times 10^{7}$ m/s (1).

3 $Q\,V = \frac{1}{2}\,m\,v^2$ so $3.20 \times 10^{-19} \times 2000 = 0.5 \times 6.64 \times 10^{-27} \times v^2$ (1); $v = 4.39 \times 10^{5}$ m/s ≈ 4.4×10^{5} m/s (1).

4 Open-ended (3). Good answer, e.g. the magnetic force is perpendicular to the velocity so it does no work and cannot increase the energy (only electric fields accelerate the particles); but magnetic fields are needed to bend the beam round a ring so particles pass the accelerating gaps many times, to focus the beam and to steer it into collisions; stronger fields are needed as the particles get faster. 3: good understanding; 2: reasonable; 1: limited; 0: none.

TEACHER NOTES

Practical 2: Is energy missing in beta decay?

Time	One 50-minute lesson: prediction, graph, uncertainty and discussion.
Kit	Data practical: calculator, ruler, the sample data. Optional: a radioactive-decay / beta-spectrum simulation to show random counts and the shape of the spectrum.
Prep	Load and test the simulation in advance. No radioactive sources are needed for this practical.
Expected results	A broad, continuous spectrum peaking near 0.5 MeV with an end-point near 1.7 MeV. Learners should conclude that a third particle is needed to carry the missing energy.
Level	H predicts from conservation of energy, plots and interprets data, finds a mean and random uncertainty, and evaluates.

Safety and inclusion

- Radioactive sources are for teacher or technician use only, under your local rules: tongs, arm's length, minimal time, sources returned and checked in.
- The data practical needs no lab; learners who are unable to attend can do it in full.
- Risk assess for your own class, room and kit, following your employer's policies and SSERC guidance.

Common problems

- **Bar chart against line graph:** either is acceptable here, but the energy axis is continuous, so a smooth curve is best.
- **Thinking the peak is the maximum energy:** the maximum (end-point) energy is where the curve reaches zero.

No lab, no time, or a learner absent?

The whole practical runs from the data in the workbook.

Assessment link

Practises assignment skills: prediction from theory, graphing, uncertainty in repeated measurements, and comparing with a referenced source.

Answers: Topic 2

Topic 2: The Standard Model (Higher)

1 Scale and the fundamental particles

1 (a) 10^{-14} m (accept 10^{-15}) (b) 10^{7} m

2 $8 \times 10^{-6} \div 1 \times 10^{-10} = 8 \times 10^{4}$, so about 5 orders of magnitude (accept 4 to 5).

3 e.g. charm (+⅔) or strange (−⅓); muon (−1) or muon neutrino (0).

2 Hadrons and their charges

1 Delta-plus-plus: +2, baryon; Omega-minus: −1, baryon; Antiproton: −1, baryon; Negative pion: −1, meson; Neutral kaon: 0, meson.

2 Hadrons are made of quarks; a lepton is a fundamental particle that is not made of quarks.

3 Forces, antimatter and the neutrino

1 (a) photon (b) gluon

2 They annihilate: their mass is converted into energy, released as (two) gamma photons.

3 A down quark changes into an up quark (so a neutron becomes a proton), through the weak force (W boson).

4 The electrons had a continuous range of energies, not one value, so some energy appeared to be missing; to conserve energy (and momentum) a third, undetected particle had to carry the rest: the (anti)neutrino.

Practical 2: Is energy missing in beta decay?

1a Same energy: with two particles, conservation of energy and momentum fixes how the energy is shared, so every electron would have one fixed energy. 1b (i) a single spike at one energy; (ii) a spread of energies from zero up to a maximum.

Hazards (real experiment), e.g. contamination if a source is damaged (inspect sources, never handle with fingers, wash hands); time near the source (keep exposure short; keep distance).

Graph: a smooth hump rising from about 60 at 0.1 MeV to a peak of about 120 near 0.5 MeV, falling to almost zero at about 1.7 MeV.

5 Mean = 121; random uncertainty = (127 − 115) ÷ 5 = 2.4, so 121 ± 2.

6a About 1.7 MeV (accept 1.6 to 1.8 MeV). 6b Three: the electrons have a continuous spread of energies from near zero to a maximum, not one energy. 6c It is carried by the (anti)neutrino (and a very small amount by the recoiling nucleus).

7a Radioactive decay is random, so counts vary; a longer count gives larger numbers and a smaller percentage uncertainty. 7b 2.4 ÷ 121 × 100 = 2.0 %.

Check-up

1 B (1)

2 (a) −⅓ + (−⅓) + (−⅓) = −1 (1 for correct quark charges, 1 for the sum). (b) Baryon, because it is made of three quarks (1).

3 (a) W or Z boson (1). (b) Beta decay (1).

4 A fundamental particle that is not made of quarks, such as the electron or a neutrino (1). Antimuon: +1 (1).

5 Open-ended (3). Good answer, e.g. antiparticles are routinely made in accelerators and in beta-plus decay; positrons are used in PET scans in hospitals, where the gamma photons from annihilation are detected; we rarely see antimatter because it annihilates as soon as it meets ordinary matter; why the Universe has so much more matter than antimatter is still an open question. For comparison, annihilation of an electron and positron at rest gives 1.6×10^{-13} J.

TEACHER NOTES

Practical 3: Which fuel gives most energy per kilogram?

Time	One 50-minute lesson. A spreadsheet speeds up the calculations and is good assignment practice.
Kit	Data practical: calculator or spreadsheet, ruler, the mass data in the workbook.
Prep	None. You could show a short video of a tokamak or a reactor control room for context.
Expected results	Energy per reaction about 2.8×10^{-11} J (fission), 2.8×10^{-12} J (D–T) and 5.3×10^{-13} J (D–D). Per kilogram: about 7×10^{13} J/kg (fission), 3.4×10^{14} J/kg (D–T) and 8×10^{13} J/kg (D–D).
Level	H plans a multi-step calculation, processes data, presents it, concludes and evaluates the effect of precision.

Safety and inclusion

- No practical hazards. Some learners may be anxious about nuclear topics: keep discussion factual and balanced.
- A spreadsheet or calculator template helps learners who find long calculations hard.

Common problems

- **Forgetting a neutron:** count every particle on both sides, including the three neutrons in fission.
- **Rounding early:** keep five significant figures until after the subtraction.
- **Energy per kilogram:** divide by the mass of the fuel nuclei only (not the neutron that triggers fission).

No lab, no time, or a learner absent?

The whole practical runs from the data in the workbook.

Assessment link

Practises assignment skills: processing data from a source, presenting it in a suitable chart, drawing a conclusion and discussing precision.

Answers: Topic 3

Topic 3: Nuclear reactions (Higher)

1 Nuclear equations

1 $^{210}_{84}Po \rightarrow {}^{206}_{82}Pb + {}^{4}_{2}He$

2 A = 236 − 140 − 2 = 94; Z = 92 − 54 = 38 (strontium-94)

3 $^{131}_{53}I \rightarrow {}^{131}_{54}Xe + {}^{0}_{-1}e$ (+ antineutrino)

4 Induced: the uranium nucleus splits after absorbing a neutron.

2 Mass into energy

1 $E = m c^2 = 3.2 \times 10^{-28} \times (3.00 \times 10^{8})^2 = 2.9 \times 10^{-11}$ J

2 Mass lost = (3.3436 + 5.0074) − (6.6447 + 1.6749) = 0.0314×10^{-27} kg = 3.14×10^{-29} kg; E = 2.83×10^{-12} J

3 Power stations and fusion reactors

1 $P = 8.0 \times 10^{19} \times 2.8 \times 10^{-11} = 2.2 \times 10^{9}$ W

2 The nuclei are positively charged and repel; they must be moving extremely fast (very high kinetic energy, so very high temperature) to get close enough to fuse.

3 At over 100 million °C any wall would melt or vaporise and cool the plasma; the plasma is made of charged particles, so a magnetic field can exert forces on them and keep them away from the walls.

Practical 3: Which fuel gives most energy per kilogram?

Prediction, e.g. D–T fusion, because it loses the largest fraction of its mass.

Plan: mass lost = total mass before − total mass after; $E = m c^2$; energy per kg = E ÷ mass of the fuel nuclei in one reaction.

Headings: Reaction, Mass lost (kg), Energy per reaction (J), Mass of fuel (kg), Energy per kg (J/kg).

Results: Fission of uranium-235: mass lost 3.09×10^{-28} kg, energy 2.78×10^{-11} J, per kg 7.1×10^{13} J/kg; D–T fusion: mass lost 3.14×10^{-29} kg, energy 2.83×10^{-12} J, per kg 3.4×10^{14} J/kg; D–D fusion: mass lost 5.90×10^{-30} kg, energy 5.31×10^{-13} J, per kg 7.9×10^{13} J/kg.

Uncertainty: the mass lost is a tiny difference between two large, nearly equal numbers, so many significant figures are needed or the difference disappears in rounding.

6 D–T fusion releases the most energy per kilogram (about 3.4×10^{14} J/kg), roughly four or five times more than U-235 fission or D–D fusion.

7a The uranium nucleus is much more massive, so per kilogram there are far fewer reactions; D–T fusion loses a bigger fraction of its fuel mass (about 0.4 %) than fission (about 0.08 %). 7b m = $1.0 \times 10^{15} \div 3.38 \times 10^{14}$ = 3.0 kg (about 3 kg).

8a e.g. it is very hard to reach and keep the temperature and pressure needed; the plasma is unstable and difficult to confine; reactors so far use more energy than they produce; materials are damaged by neutrons; tritium is scarce. 8b The rounded masses would make the mass lost very inaccurate, possibly zero or even negative, so the energies would be badly wrong.

Check-up

1 C (1)

2 a = 240 − 134 − 3 = 103 (1); b = 94 − 52 = 42 (1)

3 (a) $E = m c^2$ (1); $E = 4.6 \times 10^{-30} \times (3.00 \times 10^{8})^2$ (1); $E = 4.1 \times 10^{-13}$ J (1). (b) number per second = P ÷ E (1); $= 4.0 \times 10^{8} \div 4.14 \times 10^{-13}$ (1); $= 9.7 \times 10^{20}$ reactions per second (accept 9.7 to 9.8 × 10^{20}) (1).

4 Open-ended (3). Good answer, e.g. fusion fuel (deuterium from sea water) is plentiful and the energy per kilogram is huge with no carbon dioxide and little long-lived waste; but no fusion power station yet produces more energy than it uses; containing a plasma at over 100 million °C with magnetic fields is very difficult; it may be decades before it is commercial, so other low-carbon sources are needed now.

TEACHER NOTES

Practical 4: Does a small lamp obey the inverse square law?

Time	One 50-minute lesson in pairs: about 20 minutes for readings, the rest for processing and the graph.
Kit per group	Small 12 V lamp (a compact filament or LED bulb) in a holder, low-voltage supply, light meter or light sensor with logger, metre stick, blackout or a cardboard tunnel lined with black paper.
Prep	Blackout the lab or make dark tunnels. Check meters read in W m^{-2} (or use lux and treat the readings as proportional to irradiance).
Expected results	$I \times d^2$ roughly constant (within a few per cent) beyond about 0.2 m; I against $1/d^2$ is a straight line through the origin. Very close to the lamp the law fails because the bulb is not a point source.
Level	H plans the investigation, repeats, finds means, random and percentage uncertainties, plots a linear graph and evaluates.

Safety and inclusion

- Lamps get hot: no touching, cool before moving. Low voltage only.
- Darkened room: clear floors and bags, keep a dim light by the door, and check for learners who are anxious in the dark or have visual impairments (a dark box on the bench avoids blacking out the room).
- Risk assess for your own class, room and kit, following your employer's policies and SSERC guidance.

Common problems

- **No background reading:** the graph line misses the origin.
- **Measuring to the wrong point:** measure to the filament and the sensor face.
- **Plotting I against d:** gives a curve; plot against $1/d^2$.

No lab, no time, or a learner absent?

The sample results let learners do the full analysis.

Assessment link

A classic assignment topic: learners can compare their gradient-based conclusion with published information on the inverse square law, with references.

Answers: Topic 4

Topic 4: Inverse square law (Higher)

1 Irradiance

1 $P = I A = 920 \times 2.4 = 2208$ W (2.2×10^3 W)

2 $I = P / A = 1.8 \times 10^{-3} \div 4.0 \times 10^{-4} = 4.5$ W m^{-2}

3 0.18 × 2208 = 397 W, so 4.0×10^2 W

2 The inverse square law

1 $6.0 \times 1.5^2 = I_2 \times 0.50^2$, $I_2 = 54$ W m^{-2}

2 $6.0 \times 1.5^2 = 1.5 \times d_2^2$, $d_2 = 3.0$ m

3 A laser beam hardly spreads out, so the power stays on almost the same area as the distance increases.

3 Testing the law with a graph

1 $I \times d^2$ = 1.80, 1.81, 1.80, 1.79 W: all about 1.8 W, so the irradiance is inversely proportional to d^2 (allowing for experimental uncertainty).

2 Every reading is 0.6 W m^{-2} too high, so the line is shifted up: it is still straight but no longer passes through the origin (positive intercept); a systematic error.

3 $I_2 = I_1(d_1/d_2)^2 = I_1 \times (1/3)^2 = I_1/9 = 0.11\ I_1$, about 11 %.

Practical 4: Does a small lamp obey the inverse square law?

Variables: change the distance; measure the irradiance; keep the same: the lamp and its p.d., the light meter, the room darkness, the meter facing the lamp.

Prediction: a quarter, because the same power is spread over four times the area.

Equipment: small lamp, low-voltage supply, light meter, metre stick. Not needed: stopwatch, thermometer.

Hazards, e.g. darkened room (trip hazard: clear bags and stools, use a dim torch to move about); mains-powered meter or leads (keep away from water, check cables).

Method key points: blackout blinds or a dark box; take a background reading with the lamp off and subtract it; measure from the filament to the sensor; at least five distances, three readings each; mean; calculate $1/d^2$ and plot I against $1/d^2$.

Headings: d (m), I_1, I_2, I_3 (W m^{-2}), mean I (W m^{-2}), $1/d^2$ (m^{-2}).

Sample results: 0.25 m: mean 14.43 W m^{-2}, $1/d^2$ = 16.0 m^{-2}; 0.35 m: mean 7.36 W m^{-2}, $1/d^2$ = 8.2 m^{-2}; 0.45 m: mean 4.43 W m^{-2}, $1/d^2$ = 4.9 m^{-2}; 0.55 m: mean 2.97 W m^{-2}, $1/d^2$ = 3.3 m^{-2}; 0.65 m: mean 2.12 W m^{-2}, $1/d^2$ = 2.4 m^{-2}. $I \times d^2$ is about 0.90 W in every case.

Graph: straight line through the origin, gradient ≈ 0.90 W.

Random uncertainty at 0.25 m = (14.6 − 14.2) ÷ 3 = ±0.13 W m^{-2} (0.9 %). Percentage uncertainty in d = 0.005 ÷ 0.25 × 100 = 2 %, which is larger (and doubles to 4 % in d^2).

8 A straight line through the origin, so I is directly proportional to $1/d^2$: the lamp obeys the inverse square law.

9a e.g. stray light (blackout, background subtracted); measuring to the glass instead of the filament (measure to the filament); lamp not a point source (use a smaller lamp or larger distances). 9b The same ±0.005 m is a bigger fraction of a small distance, and squaring doubles the percentage.

Check-up

1 $P = I A$ (1); $P = 360 \times 2.5 \times 10^{-4}$ (1); $P = 0.090$ W (1)

2 $I_1 d_1^2 = I_2 d_2^2$ (1); $0.80 \times 50^2 = I_2 \times 2000^2$ (1); $I_2 = 5.0 \times 10^{-4}$ W m^{-2} (1)

3 $32 \times 0.50^2 = 8.0$ (1); $8.0 \times 1.0^2 = 8.0$, so $I d^2$ is the same (1)

4 Open-ended (3). Good answer, e.g. irradiance falls with the square of distance, so to give the same irradiance at twice the distance needs four times the power, not twice; but lamps are not point sources and street lights are aimed with reflectors, so the law only applies roughly; what we see also depends on the eye adapting and on reflection from the road.

TEACHER NOTES

Practical 5: Measuring Planck's constant with LEDs

Time	One 50-minute lesson in pairs.
Kit per group	Five LEDs of known wavelength (not white or UV), 1 kΩ resistor, 0 to 6 V variable supply, digital voltmeter, black tube to look through.
Prep	Label each LED with its peak wavelength from the supplier's data sheet. Darken the room. Test each LED glows below 3 V.
Expected results	Striking p.d. from about 1.9 V (red) to 2.6 V (blue); V against 1/λ is a straight line; h usually comes out within about 10 % of 6.63×10^{-34} J s.
Level	H plans, repeats, processes into a linear graph, finds a gradient, compares with the accepted value and discusses random and systematic uncertainty.

Safety and inclusion

- Low voltage only; always a series resistor. Do not use UV or high-power LEDs. Never look into bright LEDs at full current.
- Risk assess for your own class, room and kit, following your employer's policies and SSERC guidance.

Common problems

- **Wavelength in nm:** convert to metres before finding 1/λ.
- **Turning the p.d. up too fast:** overshoots the first glow.

Assessment link

A popular assignment: learners compare their value of h with an accepted value and discuss the main uncertainties, with references.

Answers: Topic 5

Topic 5: Wave–particle duality (Higher)

1 Photons and the photoelectric effect

1 $E = h f = 6.63 \times 10^{-34} \times 6.0 \times 10^{14} = 4.0 \times 10^{-19}$ J

2 $f = E / h = 5.0 \times 10^{14}$ Hz; $\lambda = v / f = 3.00 \times 10^{8} \div 5.0 \times 10^{14} = 6.0 \times 10^{-7}$ m (603 nm)

2 Threshold frequency and work function

1 f_0 = work function ÷ h = $3.65 \times 10^{-19} \div 6.63 \times 10^{-34} = 5.51 \times 10^{14}$ Hz

2 $E_k = h f - h f_0 = 6.63 \times 10^{-34} \times 7.5 \times 10^{14} - 3.65 \times 10^{-19} = 1.3 \times 10^{-19}$ J

3 Brighter or bluer?

1 (a) It doubles (twice as many photons each second). (b) No change (each photon has the same energy).

2 Each red photon has less energy than the work function of zinc (its frequency is below f_0); an electron absorbs only one photon, so making the light brighter only adds more photons that are each too weak.

3 Electrons are released immediately and only above a threshold frequency, however low the irradiance; this is explained by each photon (a particle of energy h f) giving its energy to a single electron, not by a spread-out wave.

4 e.g. interference or diffraction.

Practical 5: Measuring Planck's constant with LEDs

Variables: change the wavelength (colour of LED); measure the striking p.d.; keep the same: the method of judging the first glow, the darkness of the room, the protective resistor.

Graph: V against 1/λ; gradient = h c / e.

Equipment: variable d.c. supply, voltmeter, leads and resistor, LEDs. Not needed: light gate, stopwatch.

Hazards, e.g. LED leads are sharp (handle carefully); darkened room (clear walkways).

Method key points: LED in series with a protective resistor, voltmeter across the LED; darken the room and look down a black tube; raise the p.d. slowly from zero and record when the LED just glows; repeat three times and find the mean; repeat for each colour.

Headings: λ (nm), V_1, V_2, V_3 (V), mean V (V), 1/λ (m^{-1}).

Sample results: 470 nm: mean 2.63 V, $1/\lambda = 2.13 \times 10^6$ m^{-1}; 525 nm: mean 2.38 V, $1/\lambda = 1.90 \times 10^6$ m^{-1}; 590 nm: mean 2.10 V, $1/\lambda = 1.69 \times 10^6$ m^{-1}; 625 nm: mean 1.99 V, $1/\lambda = 1.60 \times 10^6$ m^{-1}; 660 nm: mean 1.89 V, $1/\lambda = 1.52 \times 10^6$ m^{-1}.

Graph: straight line; gradient ≈ 1.22×10^{-6} V m; intercept ≈ 0.04 V (close to zero).

8 h = gradient × e ÷ c ≈ 6.52×10^{-34} J s; percentage difference ≈ 2 % (accept values consistent with the candidate's gradient).

Uncertainties: scale reading ±0.01 V (digital) = 0.53 % of 1.89 V; random = (1.90 − 1.88) ÷ 3 = ±0.007 V = 0.35 %. The scale-reading uncertainty is larger.

9a Mostly systematic: an observer tends to see the glow at the same slightly late (or early) point every time, so all readings are shifted the same way; there is also a small random part because the judgement varies from reading to reading.

Check-up

1 $f = v / \lambda = 3.00 \times 10^{8} \div 550 \times 10^{-9} = 5.45 \times 10^{14}$ Hz (1); E = h f (1); $E = 6.63 \times 10^{-34} \times 5.45 \times 10^{14}$ (1); $E = 3.62 \times 10^{-19}$ J (1)

2 (a) $h f = 6.63 \times 10^{-34} \times 9.20 \times 10^{14} = 6.10 \times 10^{-19}$ J (1), which is greater than the work function, 4.60×10^{-19} J, so electrons are released (1). (b) $E_k = h f - h f_0$ (1); $E_k = 6.10 \times 10^{-19} - 4.60 \times 10^{-19}$ (1); $E_k = 1.50 \times 10^{-19}$ J (1)

3 No change (1).

4 Open-ended (3). Good answer, e.g. light really does show wave behaviour (interference, diffraction, gratings), but the photoelectric effect can only be explained if light arrives as photons, each with energy h f; neither model alone explains everything, so we use wave–particle duality; electrons and other particles also show wave behaviour (electron diffraction), so it is not just an exception for light.

TEACHER NOTES

Practical 6: Measuring the wavelength of laser light

Time	One 50-minute lesson in small groups.
Kit per group	Class 2 red laser (or a laser pointer of known class 2 rating), 300 lines/mm grating in a holder, matt white screen or wall, metre stick and 2 m tape, retort stand.
Prep	Check every laser is class 2 and labelled. Set the beam height below seated eye level. Remove reflective objects from the bench.
Expected results	At 1.5 m with 300 lines/mm and 650 nm: x ≈ 0.30 m (m = 1), 0.64 m (m = 2), 1.08 m (m = 3); λ within about 1 % of the label value.
Level	H plans, measures, repeats, processes using trigonometry, compares percentage uncertainties and evaluates.

Safety and inclusion

- Class 2 lasers only; never look into the beam; beam below eye level; no reflective jewellery; follow SSERC laser guidance and your local rules.
- Learners can be seated; one learner can mark the spots while another measures.
- Risk assess for your own class, room and kit, following your employer's policies.

Common problems

- **Lines per mm:** convert to lines per metre before finding d.
- **Calculator in radians:** set it to degrees.
- **Grating not square to the beam:** the spots on each side are at different distances.

Assessment link

Good assignment practice: compare with the manufacturer's value and discuss which uncertainty dominates.

Answers: Topic 6

Topic 6: Interference (Higher)

1 Coherent waves and interference

1 Sources with the same frequency (and wavelength) and a constant phase difference.

2 Path difference = 5.5 − 4.0 = 1.5 m = 3 λ (a whole number of wavelengths), so Q is a maximum.

3 Only waves can interfere (superpose to cancel and reinforce); particles cannot add to give nothing.

2 Predicting maxima and minima

1 (m + ½) λ = 2.5 λ = 7.5 cm, so λ = 3.0 cm

2 λ = v / f = 340 ÷ 680 = 0.50 m; first minimum: path difference = ½ λ = 0.25 m

3 The wavelength gets shorter, so a smaller change in path difference is needed between quiet spots: they get closer together.

4 The light from two separate torches is not coherent: the phase difference changes randomly and very quickly, so any pattern moves too fast to see.

3 Diffraction gratings

1 $d = 1 \div 300\,000 = 3.33 \times 10^{-6}$ m; $3.33 \times 10^{-6} \times \sin\theta = 2 \times 650 \times 10^{-9}$; θ = 23.0°

2 More lines per mm means a smaller d; since sin θ = m λ / d, a smaller d gives a bigger angle for each order.

Practical 6: Measuring the wavelength of laser light

Measure: distance from grating to screen D, distance x from the central spot to each order; calculate θ and λ. Keep the same: the laser, the grating, the screen distance, the grating at right angles to the beam.

Physics: $\tan\theta = x / D$, so $\theta = \tan^{-1}(x / D)$; $\lambda = d \sin\theta / m$.

Equipment: class 2 laser, grating, metre stick or tape, ruler. Not needed: prism, thermometer.

Hazards, e.g. reflections from shiny surfaces (remove watches and jewellery, matt screen); trailing laser lead (tidy it).

Method key points: grating square to the beam; screen 1 to 2 m away; measure D; measure x to each order on both sides (half the distance between the two m-th order spots is more accurate); repeat; λ for each order; mean.

Headings: order m, x_1, x_2, x_3 (m), mean x (m), θ (°), λ (nm).

Sample results: m = 1: mean x = 0.298 m, θ = 11.2°, λ = 650 nm; m = 2: mean x = 0.635 m, θ = 22.9°, λ = 650 nm; m = 3: mean x = 1.083 m, θ = 35.8°, λ = 650 nm. Mean λ = 650 nm.

7a about 0.0 %. Uncertainty in D = 0.3 %; in x for m = 1 = 0.7 %: the x uncertainty dominates for the first order.

8 The wavelength is about 650 nm, in agreement with the label value of 650 nm.

9a Larger angles and distances mean the same absolute uncertainty is a smaller percentage. 9b e.g. measure between the two m-th order spots on either side and halve it; use a longer screen distance; mark spot centres with a sharp pencil.

Check-up

1 B (1)

2 $d = 1 \div 500\,000 = 2.00 \times 10^{-6}$ m (1); d sin θ = m λ (1); $2.00 \times 10^{-6} \times \sin 13.9° = 1 \times \lambda$ (1); $\lambda = 4.80 \times 10^{-7}$ m (480 nm) (1)

3 For m = 5, sin θ = 5λ / d = 1.20 (1), which is greater than 1, so there is no fifth-order maximum (1)

4 Each colour has a different wavelength, so each is diffracted to a different angle in each order (1); red has the longest wavelength, so the largest θ (1).

5 Open-ended (3). Good answer, e.g. energy is conserved: it is redistributed, not destroyed; at minima the waves cancel, but at maxima the amplitude doubles and the energy is four times as much; averaged over the whole pattern the energy is the same as without interference; the waves pass through each other and carry on unchanged.

TEACHER NOTES

Practical 7: The hydrogen spectrum

Time	One 50-minute lesson: about 15 minutes viewing, the rest for processing and matching.
Kit	Hydrogen discharge tube and its high-voltage supply (teacher operated), hand spectroscopes with wavelength scales (or gratings and a scale), optional sodium and neon tubes and a filament lamp for comparison.
Prep	Warm up the tube; darken the room; position it so learners view from about 1 m away in turn.
Expected results	Lines near 656, 486 and 434 nm (a faint 410 nm line may be seen). Photon energies 3.03, 4.09 and 4.58 × 10^{-19} J, matching E_2, E_3 and E_4 falling to E_1.
Level	H observes, records repeated readings, processes them into photon energies, links them to energy levels, finds uncertainties and evaluates.

Safety and inclusion

- Discharge tube supplies are high voltage: teacher only, shrouded connections, switch off before changing tubes; tubes get hot.
- Never let learners point spectroscopes at the Sun. Short viewing times near UV-emitting tubes.
- Learners with visual impairments can use the sample data or a camera phone image of the spectrum.
- Risk assess for your own class, room and kit, following your employer's policies and SSERC guidance.

Common problems

- **Signs:** take the higher level minus the lower level to get a positive gap.
- **nm:** convert to metres before using E = h c / λ.

Assessment link

Practises assignment skills: raw data, means with uncertainty, processing, and comparison with a referenced data table.

Answers: Topic 7

Topic 7: Spectra (Higher)

1 Three kinds of spectrum

1 A line emission spectrum: a few bright lines (mainly an intense yellow double line) on a dark background.

2 White light from the hot surface passes through cooler gases in the Sun's outer layers; atoms there absorb photons of particular energies (wavelengths), leaving dark lines.

3 They compare the dark (absorption) lines in the star's spectrum with the line patterns of elements measured in the laboratory: each element has its own set.

2 Energy levels and photons

1 $E_3 - E_1 = -1.36 - (-5.45) = 4.09 \times 10^{-19}$ J; $f = 4.09 \times 10^{-19} \div 6.63 \times 10^{-34} = 6.17 \times 10^{14}$ Hz

2 Six: each pair of levels gives one gap ($E_3 \rightarrow E_2$, $E_3 \rightarrow E_1$, $E_3 \rightarrow E_0$, $E_2 \rightarrow E_1$, $E_2 \rightarrow E_0$, $E_1 \rightarrow E_0$).

3 The Bohr model and ionisation

1 21.8×10^{-19} J $= 2.18 \times 10^{-18}$ J (from E_0 up to zero).

2 $f = 3.00 \times 10^8 \div 486 \times 10^{-9} = 6.17 \times 10^{14}$ Hz; $E = h f = 4.09 \times 10^{-19}$ J; gap $= -1.36 - (-5.45) = 4.09 \times 10^{-19}$ J: the same.

3 Its energy does not match any gap between levels exactly, so no electron can take it in; only photons with exactly the right energy are absorbed.

4 The dark lines are at exactly the wavelengths of the hydrogen emission lines, so hydrogen atoms in the outer layers must be absorbing those photons.

Practical 7: The hydrogen spectrum

1 Three bright lines (red, blue-green, violet) on a dark background: line emission, because it comes from a hot, low-pressure gas.

2 Red has the lowest photon energy, so it comes from the smallest gap among the visible lines: $E_2 \rightarrow E_1$.

Hazards, e.g. UV from the discharge tube (view through the spectroscope, not at close range for long); hot tube (do not touch; teacher only); darkened room (clear walkways).

Headings: line colour, λ_1, λ_2, λ_3 (nm), mean λ (nm), photon energy (J).

Results: red: mean 656 nm, $E = 3.03 \times 10^{-19}$ J, $E_2 \rightarrow E_1$; blue-green: mean 486 nm, $E = 4.09 \times 10^{-19}$ J, $E_3 \rightarrow E_1$; violet: mean 434 nm, $E = 4.58 \times 10^{-19}$ J, $E_4 \rightarrow E_1$.

Red line: random uncertainty $= (657 - 655) \div 3 = \pm 0.7$ nm, percentage ≈ 0.10 %. The scale-reading uncertainty (± 0.5 nm, 0.08 %) is slightly smaller, so the random uncertainty dominates.

6 The lines are produced when electrons in hydrogen atoms drop from higher energy levels (E_2, E_3, E_4) to E_1, each emitting one photon whose energy equals the gap.

7a Yes: each mean is within about 1 nm of the accepted value, about the size of the uncertainty. 7b E_1.

8a e.g. the scale in the spectroscope may be slightly misaligned or poorly calibrated, so every reading is shifted the same way. 8b A grating spectrometer measures the angle precisely (to fractions of a degree) and the lines are very sharp, so the wavelength is found to a fraction of a nanometre.

Check-up

1 $E_2 - E_1 = -3.62 - (-7.96) = 4.34 \times 10^{-19}$ J (1); $f = E \div h = 6.55 \times 10^{14}$ Hz (1); $\lambda = v / f$ (1); $\lambda = 4.58 \times 10^{-7}$ m (1)

2 $E = h f = 6.63 \times 10^{-34} \times 3.29 \times 10^{15} = 2.18 \times 10^{-18}$ J (1), equal to the energy from E_0 to zero (2.18×10^{-18} J), so the atom can just be ionised (1).

3 Electrons can only occupy certain energy levels, so only certain energy gaps exist (1); each photon has energy equal to a gap, $E = h f$, so only certain frequencies and wavelengths are emitted (1).

4 Open-ended (3). Good answer, e.g. the Bohr model correctly explains line spectra and predicts hydrogen wavelengths well, so it is useful; it fails for atoms with more electrons and does not explain why orbits are fixed, and quantum mechanics replaced fixed orbits with probability clouds; but simple models are a good first step that make the main idea (quantised energy levels) clear, as long as their limits are taught.

TEACHER NOTES

Practical 8: The refractive index of a glass block

Time	One 50-minute lesson in pairs.
Kit per group	Ray box with single slit and low-voltage supply, semicircular glass (or acrylic) block, A3 paper, protractor, sharp pencil, ruler.
Prep	Dim the room. Check ray boxes give a fine single ray. Acrylic blocks (n ≈ 1.49) work as well as glass.
Expected results	sin θ_1 against sin θ_2 is a straight line through the origin with gradient about 1.5; critical angle about 41° to 42°.
Level	H plans, measures, repeats, processes into a linear graph, makes and tests a prediction, and evaluates uncertainties.

Safety and inclusion

- Ray boxes get hot; low voltage only. Check blocks for chipped edges.
- Learners with fine-motor difficulties can use a large protractor, polar graph paper, or work with a partner who marks the ray.
- Risk assess for your own class, room and kit, following your employer's policies and SSERC guidance.

Common problems

- **Measuring from the surface:** angles are measured from the normal.
- **Ray not at the centre:** it refracts at the curved face as well and the results drift.
- **Calculator in radians:** set it to degrees.

Assessment link

Good assignment practice: compare the measured refractive index with a published value for the block material, with a reference.

Answers: Topic 8

Topic 8: Refraction of light (Higher)

1 Refractive index

1 sin θ_2 = sin 40° ÷ 1.33; θ_2 = 29°

2 n = sin 35° ÷ sin 22° = 1.53

2 Speed, wavelength and frequency

1 v = $3.00 \times 10^8 \div 2.42 = 1.24 \times 10^8$ m/s

2 λ_2 = 680 ÷ 1.33 = 511 nm; the frequency is unchanged.

3 Critical angle and total internal reflection

1 sin θ_c = 1 ÷ 1.33; θ_c = 48.8°

2 50° is greater than the critical angle (41.1°), so no light refracts out: it is totally internally reflected and stays inside the fibre.

Practical 8: The refractive index of a glass block

Variables: change the angle in air θ_1; measure the angle in glass θ_2; keep the same: the block, the colour of light, the ray aimed at the centre of the flat face.

Graph: sin θ_1 against sin θ_2; gradient = n.

Equipment: ray box and slit, protractor, semicircular glass block, sharp pencil, low-voltage supply. Not needed: stopwatch.

Hazards, e.g. glass block edges (handle carefully, report chips); darkened room (clear walkways).

Method key points: draw round the block on paper, mark the centre of the flat face and draw the normal; aim the ray at the centre at each θ_1; mark the rays with crosses, remove the block, join up and measure θ_2; three repeats; for the critical angle, send the ray in through the curved face and turn it until the refracted ray just skims the flat face.

Headings: θ_1 (°), θ_2 (°) three times, mean θ_2 (°), sin θ_1, sin θ_2.

Sample results: 10°: mean θ_2 = 6.7°, sin θ_1 = 0.174, sin θ_2 = 0.116; 20°: mean θ_2 = 13.3°, sin θ_1 = 0.342, sin θ_2 = 0.231; 30°: mean θ_2 = 19.5°, sin θ_1 = 0.500, sin θ_2 = 0.334; 40°: mean θ_2 = 25.3°, sin θ_1 = 0.643, sin θ_2 = 0.428; 50°: mean θ_2 = 30.7°, sin θ_1 = 0.766, sin θ_2 = 0.510; 60°: mean θ_2 = 35.3°, sin θ_1 = 0.866, sin θ_2 = 0.578.

Graph: straight line through the origin; n = gradient ≈ 1.50. Predicted critical angle = $\sin^{-1}$(1 ÷ 1.50) ≈ 42°.

Uncertainty: 0.5° ÷ 6.7° × 100 ≈ 8 %; the same ± 0.5° is a much bigger fraction of a small angle.

9a Yes: 42° agrees closely with the prediction of about 42° (within about 1°, which is the measuring uncertainty). 9b e.g. use a narrower slit for a fine ray; mark the ray far from the block; use a larger protractor or a sheet of polar graph paper.

Check-up

1 n = sin θ_1 / sin θ_2 (1); n = sin 60° / sin 38° (1); n = 1.41 (1)

2 v_1/v_2 = n (1); $v_2 = 3.00 \times 10^8 \div 1.41$ (1); $v_2 = 2.13 \times 10^8$ m/s (1)

3 sin θ_c = 1 ÷ 1.60 = 0.625 (1); θ_c = 38.7°, about 39° (1)

4 The refractive index of glass depends on frequency (1): violet light has a larger n than red, so it is refracted more and the colours separate (1).

5 Open-ended (3). Good answer, e.g. light stays in the fibre only if it strikes the edge at more than the critical angle; at a sharp bend the angle of incidence becomes smaller and can fall below the critical angle, so light escapes (signal loss); fibres therefore have a minimum bend radius; cladding with a lower refractive index protects the reflection.

About the author

C. Blewis has taught for 17 years, including 10 years in Additional Support Needs (ASN) provision, teaching sciences, maths, PE and more.

In many schools, especially smaller and specialist settings, teachers are often asked to teach outside their own subject. These books are written for them, and for the young people they teach: clear, practical and ready to use from the first lesson.