Nuclear and Quantum Physics

IB SL Study Guide

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May 2026 Exam Predictions

How to Use This Guide

- **The Nuclear Atom** — Rutherford's model, nuclear notation, strong nuclear force, nuclear radius
- **Radioactive Decay** — alpha, beta, gamma; balanced nuclear equations; penetration and ionisation
- **Radioactive Half-Life** — decay law, activity, half-life calculations
- **Nuclear Energy** — mass defect, binding energy, fission and fusion, $E = mc^2$
- **Quantum and Wave-Particle Duality** — photoelectric effect, de Broglie wavelength, Bohr model, hydrogen energy levels

Aligned to IB Physics 2025 syllabus — Theme E: Nuclear and Quantum Physics (first assessment 2025)

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Videos on this page: Watch: Photoelectric Effect

Section 1: The Nuclear Atom

Rutherford's Gold Foil Experiment

Before Rutherford (1911), the **Thomson "plum pudding" model** described the atom as a diffuse positive sphere with electrons embedded throughout. The gold foil experiment overturned this model.

MEMORISE THIS

Experimental observations and conclusions:

Observation	Conclusion
Most alpha particles passed straight through the foil	The atom is mostly empty space
A small fraction were deflected at large angles	A concentrated positive charge exists in the atom
A very small fraction (about 1 in 8000) bounced almost straight back	The positive charge is concentrated in a tiny, dense region (the nucleus)

The nuclear model: a tiny, positively charged, dense **nucleus** (containing protons and neutrons) surrounded by orbiting electrons.

EXAM ALERT

"Explain why most alpha particles passed straight through" is worth 2 marks. You need two points: (1) the atom is mostly empty space, (2) electrons are too light to deflect the massive alpha particle significantly. Just writing "mostly empty space" alone earns only 1 mark.

Nuclide Notation and Nuclear Structure

MEMORISE THIS

$^{A}_{Z}X$

Symbol	Name	Definition
A	mass number (nucleon number)	total number of protons + neutrons
Z	atomic number (proton number)	number of protons
$N = A - Z$	neutron number	number of neutrons
X	chemical symbol	determines the element

- **Isotopes**: same Z, different A (same element, different mass number, different number of neutrons)
- Example: carbon-12 ($^{12}_{6}$C) and carbon-14 ($^{14}_{6}$C) are isotopes

Nuclear Radius and the Strong Nuclear Force

The nuclear radius scales with mass number:

MEMORISE THIS

$r = r_0 A^{1/3} \qquad r_0 = 1.2 \times 10^{-15}\ \text{m} = 1.2\ \text{fm}$

This tells us nuclear density is approximately constant for all nuclei ($\rho \approx 2 \times 10^{17}\ \text{kg m}^{-3}$).

Strong nuclear force:

- Acts between all nucleons (protons and neutrons)
- **Attractive** at typical nuclear separations (~ 1 fm); **repulsive** at very short range (< 0.5 fm)
- Very short range: negligible beyond $\sim$ 2–3 fm (unlike gravity and electrostatics)
- **Charge-independent**: same magnitude between p-p, p-n, and n-n pairs

IB TIP

Why do large nuclei become unstable? As Z increases, the electrostatic repulsion between protons (long-range) grows faster than the short-range strong force can compensate. Adding more neutrons initially helps (neutrons contribute to the strong force but not to electrostatic repulsion), but beyond $Z \approx 82$ (lead), no stable nuclei exist — the nucleus undergoes radioactive decay.

Section 2: Radioactive Decay

Types of Radiation

MEMORISE THIS

Type	Symbol	Nature	Charge	Mass	Penetration	Ionising power
Alpha	α	$^4_2$He nucleus	$+2e$	4 u	Stopped by paper / 5 cm of air	Very high
Beta-minus	β^-	electron	$-e$	~ 0	Stopped by a few mm of aluminium	Moderate
Beta-plus	β^+	positron	$+e$	~ 0	Stopped by a few mm of aluminium	Moderate
Gamma	γ	EM photon	0	0	Reduced (not stopped) by thick lead or concrete	Low

Key relationship: penetration is inversely related to ionising power. Alpha particles are the most ionising precisely because they interact strongly with matter and lose energy quickly.

Balanced Nuclear Equations

In all nuclear equations, **two conservation laws apply:**

MEMORISE THIS

1. **Conservation of mass number** (A): the sum of mass numbers is the same on both sides.
2. **Conservation of atomic number** (Z): the sum of atomic numbers is the same on both sides.

Alpha decay — nucleus emits $^4_2$He:

$$^A_ZX \rightarrow ^{A-4}_{Z-2}Y + ^4_2\text{He}$$

Beta-minus decay — a neutron converts to a proton; emits an electron and antineutrino:

$$^A_ZX \rightarrow ^{A}_{Z+1}Y + ^0_{-1}e + \bar{\nu}_e$$

Beta-plus decay — a proton converts to a neutron; emits a positron and neutrino:

$$^A_ZX \rightarrow ^{A}_{Z-1}Y + ^0_{+1}e + \nu_e$$

Gamma emission — accompanies alpha or beta decay; no change in A or Z:

$^A_Z X^* \rightarrow ^A_Z X + \gamma$

WORKED EXAMPLE

Worked Example E1 — Alpha decay of radium-226:

Radium-226 decays by alpha emission. Write the balanced nuclear equation.

$^{226}_{88}\text{Ra} \rightarrow ^{222}_{86}\text{Rn} + ^4_2\text{He}$

Check: Mass numbers: $226 = 222 + 4$ ✓. Atomic numbers: $88 = 86 + 2$ ✓. The daughter nucleus is radon-222.

WORKED EXAMPLE

Worked Example E2 — Beta-minus decay of carbon-14:

Carbon-14 decays by beta-minus emission (used in radiocarbon dating). Write the equation.

$^{14}_{6}\text{C} \rightarrow ^{14}_{7}\text{N} + ^{0}_{-1}e + \bar{\nu}_e$

Check: Mass numbers: $14 = 14 + 0$ ✓. Atomic numbers: $6 = 7 + (-1)$ ✓. The daughter nucleus is nitrogen-14.

EXAM ALERT

You must include the antineutrino ($\bar{\nu}_e$) in beta-minus equations and the neutrino (ν_e) in beta-plus equations to get full marks on Paper 2. Failing to include them is the most common error in nuclear equation questions. Note: the neutrinos have zero charge and zero mass number, so they do not affect the balancing — but their omission costs a mark.

Section 3: Radioactive Half-Life

The Decay Law

Radioactive decay is a **random and spontaneous** process — it cannot be triggered or prevented by chemical or physical means. However, the overall rate of decay follows a precise statistical law.

MEMORISE THIS

Number of undecayed nuclei at time t:

$N = N_0 e^{-\lambda t}$

Activity (decays per second, unit: Bq = becquerel):

$A = A_0 e^{-\lambda t} \qquad A = \lambda N$

Half-life ($t_{1/2}$):

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

Symbol	Meaning
N_0	initial number of undecayed nuclei
λ	decay constant (s^{-1}) — probability of decay per unit time
$t_{1/2}$	time for half the nuclei to decay (or activity to halve)
A	activity (Bq)

All these equations and values are in the **IB data booklet**.

WORKED EXAMPLE

Worked Example E3 — Half-life calculation:

A radioactive source has an initial activity of $A_0 = 3200\ \text{Bq}$ and a half-life of $t_{1/2} = 5.0\ \text{days}$.

(a) Find the activity after 20 days.

20 days = $4 \times t_{1/2}$, so the activity halves four times:

$A = 3200 \times \left(\frac{1}{2}\right)^4 = 3200 \times \frac{1}{16} = 200\ \text{Bq}$

(b) Find the decay constant λ (in s^{-1}).

$t_{1/2} = 5.0\ \text{days} = 5.0 \times 86400 = 432000\ \text{s}$

$\lambda = \frac{\ln 2}{t_{1/2}} = \frac{0.693}{432000} = 1.60 \times 10^{-6}\ \text{s}^{-1}$

Background Radiation

Background radiation is low-level ionising radiation present at all times from natural sources (cosmic rays, radon gas, rocks) and artificial sources (medical equipment, nuclear fallout). In experiments:

MEMORISE THIS

$A_{\text{corrected}} = A_{\text{measured}} - A_{\text{background}}$

Always subtract background before plotting decay curves or calculating half-lives. Background rates are typically quoted in **counts per minute (cpm)**, not becquerels.

IB TIP

Paper 2 graph question: You may be asked to plot $\ln A$ vs t from tabulated data. Since $A = A_0 e^{-\lambda t}$, taking the natural log gives $\ln A = \ln A_0 - \lambda t$ — a straight line with gradient $-\lambda$ and intercept $\ln A_0$. The half-life is then $t_{1/2} = \ln 2/\lambda$. Practise this graph type.

Section 4: Nuclear Energy

Mass Defect and Binding Energy

When nucleons combine to form a nucleus, the mass of the nucleus is **less** than the sum of the individual nucleon masses. This missing mass is the **mass defect**.

MEMORISE THIS

Mass defect:

$\Delta m = Zm_p + Nm_n - m_{\text{nucleus}}$

Binding energy — energy equivalent of the mass defect (Einstein's mass-energy equivalence):

$E_B = \Delta m \cdot c^2$

Using atomic mass units: $1\ \text{u} = 931.5\ \text{MeV}/c^2$, so $E_B(\text{MeV}) = \Delta m(\text{u}) \times 931.5$

Binding energy per nucleon $= E_B/A$ — the stability indicator.

Constant	Value
c	$3.00 \times 10^8\ \text{m s}^{-1}$
1 u	$1.661 \times 10^{-27}\ \text{kg}$
1 eV	$1.60 \times 10^{-19}\ \text{J}$
m_p	$1.0073\ \text{u}$
m_n	$1.0087\ \text{u}$

WORKED EXAMPLE

Worked Example E4 — Binding energy of helium-4:

A ^4_2He nucleus has a measured mass of $4.0015\ \text{u}$.

$m_p = 1.0073\ \text{u}, m_n = 1.0087\ \text{u}.$

Mass of 2 protons + 2 neutrons:

$2(1.0073) + 2(1.0087) = 2.0146 + 2.0174 = 4.0320\ \text{u}$

Mass defect:

$\Delta m = 4.0320 - 4.0015 = 0.0305\ \text{u}$

Binding energy:

$E_B = 0.0305 \times 931.5 = 28.4\ \text{MeV}$

Binding energy per nucleon:

$\frac{E_B}{A} = \frac{28.4}{4} = 7.1\ \text{MeV nucleon}^{-1}$

The Binding Energy Per Nucleon Curve

The graph of binding energy per nucleon (E_B/A) vs mass number (A) is a fundamental result in nuclear physics.

MEMORISE THIS

Key features of the curve:

- Peaks at around **iron-56** ($^{56}_{26}$Fe), $E_B/A \approx 8.8$ MeV nucleon^{-1} — iron is the most stable nucleus
- Light nuclei ($A < 56$): E_B/A increases toward the peak → **fusion releases energy** (products are more stable)
- Heavy nuclei ($A > 56$): E_B/A decreases from the peak → **fission releases energy** (products are more stable)
- Hydrogen-1 (single proton): $E_B/A = 0$ (no binding energy — just one nucleon)

Fission and Fusion

MEMORISE THIS

Nuclear fission: a heavy nucleus (e.g., $^{235}_{92}$U) splits into two smaller fragments, releasing energy and neutrons. The energy released is because the products have higher E_B/A than the original nucleus (products are lower on the curve's right-hand side, but higher in E_B/A).

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{141}_{56}\text{Ba} + ^{92}_{36}\text{Kr} + 3\,^{1}_{0}\text{n} + \text{energy}$$

Nuclear fusion: two light nuclei combine to form a heavier nucleus, releasing energy. Requires extremely high temperature and pressure to overcome electrostatic repulsion.

$$^{2}_{1}\text{H} + ^{3}_{1}\text{H} \rightarrow ^{4}_{2}\text{He} + ^{1}_{0}\text{n} + 17.6\text{ MeV}$$

EXAM ALERT

Exam question: "Explain why both fission of uranium and fusion of hydrogen release energy, using the binding energy per nucleon curve." Model answer: Fission products have higher E_B/A than uranium (moving left toward the peak), so the products are more stable and energy is released. In fusion, the products (e.g., helium) have higher E_B/A than the reactants (hydrogen isotopes), so the products are more stable and energy is released. In both cases: the increase in E_B/A corresponds to the energy released. (3 marks)

Section 5: Quantum and Wave-Particle Duality

The Photoelectric Effect

Classical physics predicted that light of any frequency, if intense enough, could eject electrons from a metal surface. Einstein's 1905 explanation showed this was wrong.

MEMORISE THIS

Photoelectric effect key results:

- Electrons are ejected only if the light frequency exceeds the **threshold frequency** f_0 — regardless of intensity.
- Above f_0, the number of ejected electrons increases with intensity; the **maximum kinetic energy** does not.
- The maximum kinetic energy increases with frequency, not intensity.

Einstein's photon equation:

$E_{K,\max} = hf - \phi$

where:

- $h = 6.63 \times 10^{-34}$ J s (Planck's constant, in data booklet)
- f = frequency of incident light
- $\phi = hf_0$ = work function = minimum energy to free an electron from the surface
- $E_{K,\max}$ = maximum kinetic energy of emitted electrons

Photon energy: $E = hf = \frac{hc}{\lambda}$

WORKED EXAMPLE

Worked Example E5 — Photoelectric effect:

Light of frequency $f = 8.0 \times 10^{14}$ Hz strikes a metal surface with work function $\phi = 2.0$ eV.

(a) Calculate $E_{K,\max}$ in eV.

Photon energy: $E = hf = 6.63 \times 10^{-34} \times 8.0 \times 10^{14} = 5.30 \times 10^{-19}$ J

Convert to eV: $E = 5.30 \times 10^{-19} / 1.60 \times 10^{-19} = 3.31$ eV

$E_{K,\max} = E - \phi = 3.31 - 2.00 = 1.31 \text{ eV} \approx 1.3 \text{ eV}$

(b) Find the threshold frequency f_0.

$f_0 = \frac{\phi}{h} = \frac{2.0 \times 1.60 \times 10^{-19}}{6.63 \times 10^{-34}} = \frac{3.20 \times 10^{-19}}{6.63 \times 10^{-34}} = 4.83 \times 10^{14}$ Hz

⚠ **EXAM ALERT**

Unit conversions are essential in quantum physics. Energies in the data booklet are often in eV; you must convert to joules using $1\text{ eV} = 1.60 \times 10^{-19}$ J before using $E = hf$ (which gives joules). Mixing units without converting is the most common error.

Wave-Particle Duality

Einstein established that light (classically a wave) behaves as particles (photons). de Broglie proposed the converse: particles also have wave properties.

MEMORISE THIS

de Broglie wavelength:

$\lambda = \frac{h}{p} = \frac{h}{mv}$

- All matter has an associated wavelength.
- For macroscopic objects, λ is negligibly small (not observable).
- For electrons and other particles, λ is comparable to atomic spacings $\rightarrow$ electron diffraction is observable.

Evidence for wave-particle duality:

- Photoelectric effect $\rightarrow$ light has particle properties (photons)
- Electron diffraction patterns $\rightarrow$ electrons have wave properties

The Bohr Model and Hydrogen Energy Levels

The **Bohr model** (1913) proposed that electrons orbit the nucleus only in specific allowed circular orbits with quantised angular momentum.

MEMORISE THIS

Hydrogen energy levels:

$E_n = -\frac{13.6\text{ eV}}{n^2} \qquad n = 1, 2, 3, \ldots$

- $n = 1$: ground state, $E_1 = -13.6$ eV
- $n = 2$: first excited state, $E_2 = -3.40$ eV
- $n = \infty$: ionisation level, $E = 0$ (electron is free)
- **Ionisation energy** of hydrogen: 13.6 eV (energy to remove the electron from ground state)

Energy transitions:

When an electron drops from level n_i to n_f (where $n_i > n_f$), a photon is emitted with:

$E_{\text{photon}} = E_{n_i} - E_{n_f} = hf = \frac{hc}{\lambda}$

When a photon is absorbed, the electron moves from a lower to a higher energy level (the photon energy must exactly match the energy gap).

WORKED EXAMPLE

Worked Example E6 — Hydrogen emission line:

An electron in hydrogen drops from $n = 3$ to $n = 1$ (Lyman series, UV). Calculate the wavelength of the emitted photon.

$E_3 = -\frac{13.6}{9} = -1.51 \text{ eV} \qquad E_1 = -13.6 \text{ eV}$

$E_{\text{photon}} = E_3 - E_1 = -1.51 - (-13.6) = 12.09 \text{ eV}$

Convert to joules: $E = 12.09 \times 1.60 \times 10^{-19} = 1.934 \times 10^{-18} \text{ J}$

$\lambda = \frac{hc}{E} = \frac{6.63 \times 10^{-34} \times 3.00 \times 10^{8}}{1.934 \times 10^{-18}} = \frac{1.989 \times 10^{-25}}{1.934 \times 10^{-18}} = 1.03 \times 10^{-7} \text{ m} = 103 \text{ nm}$

This is in the UV region, consistent with the Lyman series.

IB TIP

Emission vs absorption spectra: Emission spectra show bright lines on a dark background (photons emitted when electrons drop). Absorption spectra show dark lines on a continuous spectrum (photons absorbed when electrons jump up). Both show the same set of wavelengths — this is how astronomers determine the composition of stars.

▸Watch: Photoelectric Effect — Khan Academy VIDEO

Exam-Style Practice Questions

Paper 1 Style (MCQ)

Q1. A radioactive sample has a half-life of 12 hours. After 48 hours, what fraction of the original number of nuclei remains undecayed?

A. $\frac{1}{4}$

B. $\frac{1}{8}$

C. $\frac{1}{16}$

D. $\frac{1}{32}$

▶ Answer

Q2. In the photoelectric effect, increasing the intensity of light while keeping its frequency constant above the threshold frequency will:

A. Increase the maximum kinetic energy of emitted electrons.

B. Increase the number of electrons emitted per second.

C. Increase the threshold frequency.

D. Decrease the stopping potential.

▶ Answer

Paper 2 Style (Structured Response)

Q3. Strontium-90 ($^{90}_{38}$Sr) decays by beta-minus emission.

(a) Write the balanced nuclear equation for this decay. [2]

(b) Strontium-90 has a half-life of 28.8 years. Calculate the decay constant in s^{-1}. [2]

(c) A sample of strontium-90 initially contains $N_0 = 5.0 \times 10^{15}$ nuclei. Calculate the initial activity in Bq. [1]

(d) The photoelectric effect is observed when UV light of frequency 1.5×10^{15} Hz shines on a metal surface with work function $\phi = 3.5$ eV. Calculate the maximum kinetic energy of emitted electrons in eV. [3]

▶ Mark-scheme answers

⚠ **EXAM ALERT**

Common Theme E errors that cost marks:

1. Omitting the antineutrino ($\bar{\nu}_e$) in beta-minus equations or neutrino (ν_e) in beta-plus — always include them.
2. Forgetting to convert half-life to seconds before calculating λ — half-lives are often given in days, years, or hours.
3. Confusing mass number and atomic number in nuclide notation — A is on top, Z is below.
4. Mixing up energy in eV and joules — convert using 1 eV $= 1.60 \times 10^{-19}$ J before using $E = hf$.
5. Saying "intensity increases maximum kinetic energy" in the photoelectric effect — intensity only affects the number of electrons, not their maximum kinetic energy.
6. Drawing the binding energy curve with the peak at the wrong position — the maximum is at iron-56 ($A \approx 56$), not at lead or uranium.

May 2026 Exam Predictions

Based on past IB Physics paper patterns, Theme E questions in May 2026 are likely to include:

- **Paper 1 MCQ:** Half-life fractional decay question (find what fraction remains after n half-lives), or a question on which type of radiation is stopped by a given thickness of material.
- **Paper 2 Short Answer:** A balanced nuclear decay equation (write the daughter nucleus and decay product symbols), followed by a half-life or decay constant calculation. Typically 4–5 marks.
- **Photoelectric effect:** Numerical calculation of $E_{K,\text{max}}$ plus an "explain why increasing intensity does not increase $E_{K,\text{max}}$" question (2 marks qualitative). This combination appears in roughly 60% of recent papers.
- **Binding energy:** Calculate the binding energy per nucleon and use the curve to explain whether a reaction releases or absorbs energy. Often paired with a fission equation.
- **Energy levels:** Given an energy level diagram for hydrogen or a hypothetical atom, calculate the photon wavelength for a given transition.

IB TIP

The two most reliably tested quantitative skills in Theme E: (1) writing and balancing nuclear equations (practise the conservation rules until they are automatic), and (2) the photoelectric effect calculation using $E_{K,\text{max}} = hf - \phi$. Both appear in almost every recent exam paper. Master these two skills first.