

# Nuclear and Quantum Physics

IB SL Study Guide

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## 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

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

**Jump to section:** The Nuclear Atom · Radioactive Decay · Half-Life · Nuclear Energy · Quantum Physics · Practice Questions

**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:**

<b>Observation</b>	<b>Conclusion</b>
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



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 ( ${}^{12}_6\text{C}$ ) and carbon-14 ( ${}^{14}_6\text{C}$ ) are isotopes

## Nuclear Radius and the Strong Nuclear Force

The nuclear radius scales with mass number:

### MEMORISE THIS

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

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 ( $\sim 1 \text{ fm}$ ); **repulsive** at very short range ( $< 0.5 \text{ fm}$ )
- Very short range: negligible beyond  $\sim 2\text{--}3 \text{ fm}$  (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	$\alpha$	${}^4_2\text{He}$ nucleus	$+2e$	4 u	Stopped by paper / 5 cm of air	Very high
Beta-minus	$\beta^-$	electron	$-e$	$\sim 0$	Stopped by a few mm of aluminium	Moderate
Beta-plus	$\beta^+$	positron	$+e$	$\sim 0$	Stopped by a few mm of aluminium	Moderate
Gamma	$\gamma$	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.

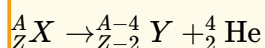
### Balanced Nuclear Equations

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

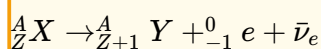
#### MEMORISE THIS

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

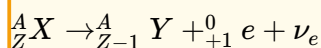
**Alpha decay** — nucleus emits  ${}^4_2\text{He}$ :



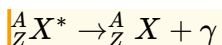
**Beta-minus decay** — a neutron converts to a proton; emits an electron and antineutrino:



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



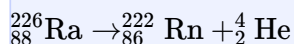
**Gamma emission** — accompanies alpha or beta decay; no change in  $A$  or  $Z$ :



### WORKED EXAMPLE

#### Worked Example E1 — Alpha decay of radium-226:

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

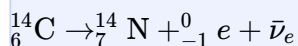


Check: Mass numbers:  $226 = 222 + 4$  ✓. Atomic numbers:  $88 = 86 + 2$  ✓. The daughter nucleus is radon-222.

### 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.



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 ( $\nu_e$ ) 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):

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

**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

$\lambda$  decay constant ( $\text{s}^{-1}$ ) — 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  $A_0 = 3200$  Bq and a half-life of  $t_{1/2} = 5.0$  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  $\lambda$  (in  $\text{s}^{-1}$ ).

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

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

## 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

$$c = 3.00 \times 10^8 \text{ m s}^{-1}$$

$$1 \text{ u} = 1.661 \times 10^{-27} \text{ kg}$$

$$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$

$$m_p = 1.0073 \text{ u}$$

$$m_n = 1.0087 \text{ u}$$

#### WORKED EXAMPLE

##### Worked Example E4 — Binding energy of helium-4:

A  ${}^4_2\text{He}$  nucleus has a measured mass of 4.0015 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

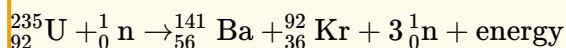
#### Key features of the curve:

- Peaks at around **iron-56** ( ${}_{26}^{56}\text{Fe}$ ),  $E_B/A \approx 8.8 \text{ MeV nucleon}^{-1}$  — 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)

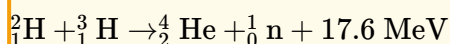
## Fission and Fusion

### MEMORISE THIS

**Nuclear fission:** a heavy nucleus (e.g.,  ${}_{92}^{235}\text{U}$ ) 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  $E_B/A$ ).



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



### 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.

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

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

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

(b) Find the threshold frequency  $f_0$ .

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

## EXAM ALERT

**Unit conversions are essential in quantum physics.** Energies in the data booklet are often in eV; you must convert to joules using  $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$  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,  $\lambda$  is negligibly small (not observable).
- For electrons and other particles,  $\lambda$  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:**

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

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

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

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

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 ( ${}^{90}_{38}\text{Sr}$ ) 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  $\text{s}^{-1}$ . [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  $1.5 \times 10^{15}$  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 ( $\nu_e$ ) in beta-plus — always include them.
2. Forgetting to convert half-life to seconds before calculating  $\lambda$  — 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  $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$  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  $E_{K,\max}$  plus an “explain why increasing intensity does not increase  $E_{K,\max}$ ” 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  $E_{K,\max} = hf - \phi$ . Both appear in almost every recent exam paper. Master these two skills first.