IB DP PHYSICS · THEME E NUCLEAR AND QUANTUM PHYSICS · E.3 · ~7 MIN READ

E.3 Radioactive decay

Isotopes and nuclear stability, the strong force, mass defect and binding energy, the binding-energy-per-nucleon curve, alpha, beta and gamma decay, neutrinos, half-life and activity, background radiation, and (HL) the decay constant and exponential decay.

Nuclear stability | Mass defect & binding energy | BE per nucleon | α, β, γ decay | Neutrinos | Half-life | Activity | Decay constant (HL)

RS by Riyaz Sir
mentorriyaz.in

No tag = **SL and HL** HL ONLY HL students only DATA BOOKLET given in the exam

M1 A1 how marks are awarded highlight = comes up again and again Test yourself at the end

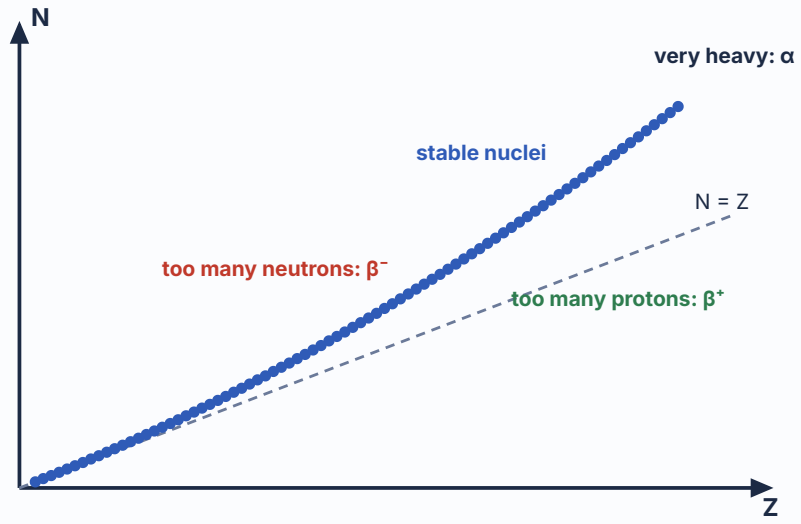
IN 30 SECONDS

- Protons repel each other, but the **strong nuclear force** (attractive, very short range) holds the nucleus together. Too many protons or neutrons makes a nucleus **unstable**.
- A nucleus has less mass than its separate nucleons. This **mass defect** Δm is the **binding energy** $E = \Delta mc^2$. Iron-56 has the highest binding energy per nucleon: the most stable.
- Unstable nuclei decay **randomly** and **spontaneously** by α, β^-, β^+ or γ emission. **Half-life** is the time for half the nuclei (or the activity) to go.
- **HL:** $N = N_0e^{-\lambda t}$, $A = \lambda N$ and $T_{½} = \ln 2/\lambda$; the β energy spectrum as evidence for neutrinos.

BY THE END YOU CAN

- Use nuclear notation to write balanced decay equations for α, β^-, β^+ and γ.
- Describe the strong force and use an N–Z chart to predict decay type.
- Calculate mass defect and binding energy, and interpret the binding-energy-per-nucleon curve.
- Compare the properties of α, β and γ radiation and describe background radiation.
- Use half-life with graphs and calculations.
- Use the decay constant, $N = N_0e^{-\lambda t}$ and $A = \lambda N$. HL
- Explain how the β energy spectrum shows that neutrinos exist. HL

1 Nuclear stability



Stable nuclei lie on a band that bends away from N = Z, because large nuclei need extra neutrons to dilute the proton repulsion.

- **Strong nuclear force:** attractive between all nucleons, about 10^{-15} m range, repulsive at even shorter distances. Light nuclei are stable with N ≈ Z; heavy nuclei need N > Z.

2 Mass defect and binding energy

Binding energy — the energy needed to separate a nucleus completely into its individual protons and neutrons (equivalently, the energy released when it forms).

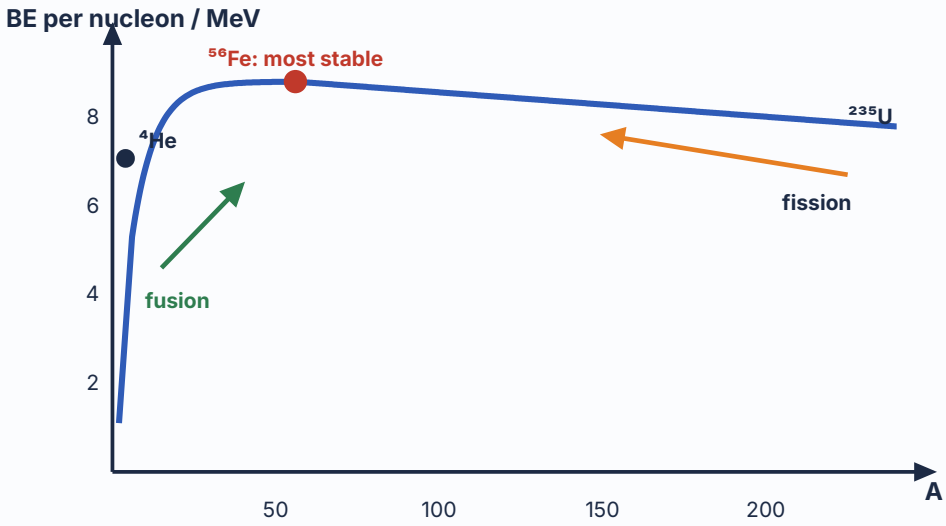
$$E = mc^2$$ DATA BOOKLET

$1\ u = 931.5\ MeV\ c^{-2}$

WORKED EXAMPLE

Find the binding energy per nucleon of helium-4 (nuclear mass 4.001506 u; m_p = 1.007276 u, m_n = 1.008665 u).

1. mass of nucleons = 2(1.007276) + 2(1.008665) = 4.031882 u M1
2. Δm = 4.031882 − 4.001506 = 0.030376 u A1
3. **E = 0.030376 × 931.5 = 28.3 MeV, so 7.07 MeV per nucleon** A1



Moving towards the peak (by fusion from the left or fission from the right) releases energy.

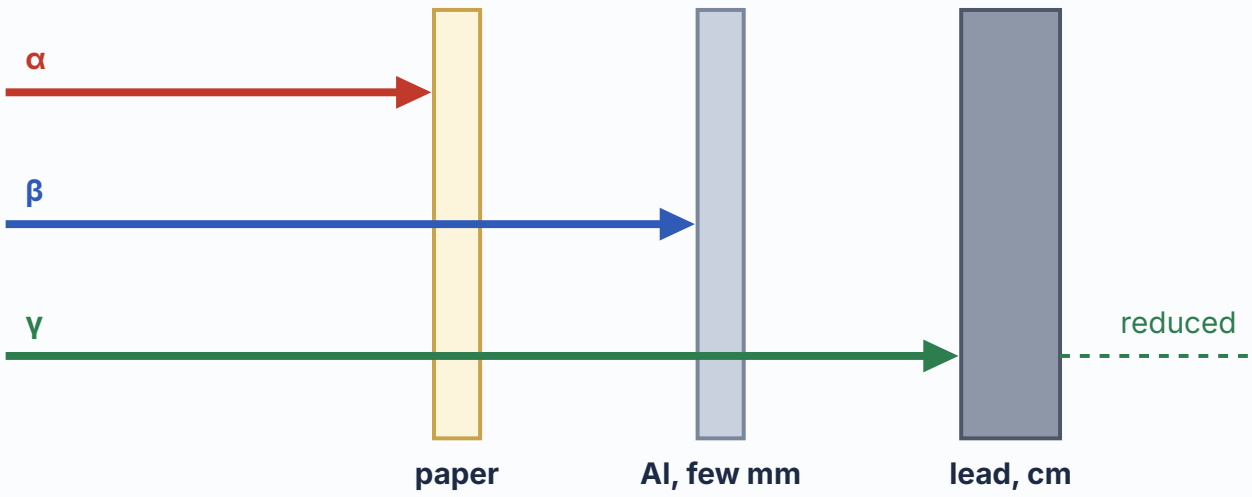
COMMON MISTAKE

Thinking a larger total binding energy means a "heavier = less stable" nucleus. Stability is about binding energy **per nucleon**.

3 Types of decay

Type	What leaves	Change	Example
alpha α	$^{4}_{2}$He nucleus	A − 4, Z − 2	$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}\alpha$
beta-minus β^-	electron + antineutrino	n → p: A same, Z + 1	$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e + \bar{\nu}$
beta-plus β^+	positron + neutrino	p → n: A same, Z − 1	$^{22}_{11}Na \rightarrow {}^{22}_{10}Ne + {}^{0}_{+1}e + \nu$
gamma γ	photon	no change in A or Z	after α or β, the excited nucleus drops to its ground state

- **Balancing:** both A and Z must add up on each side. Charge, nucleon number and (with the neutrino) lepton number are conserved.



Each radiation stopped by a different thickness of material.

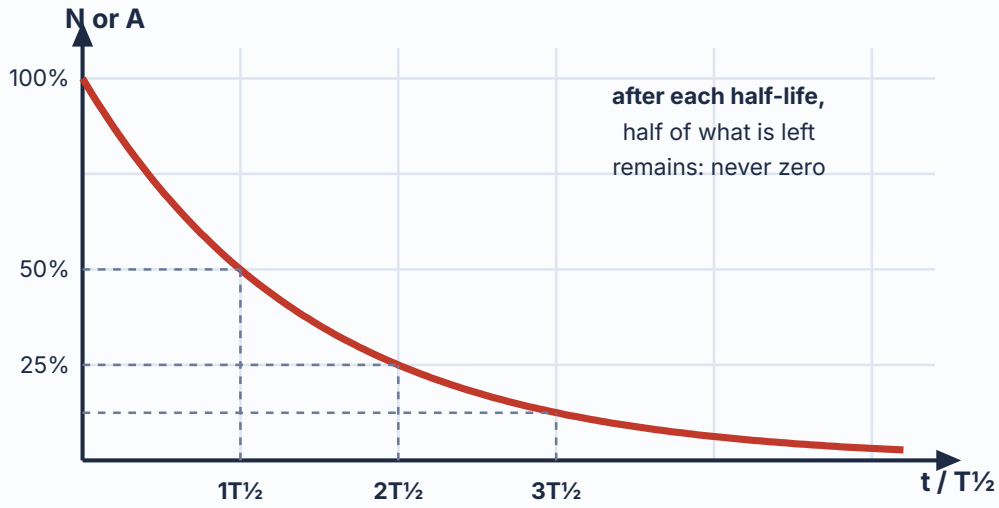
	α	β	γ
ionising	strongly	moderately	weakly
range in air	a few cm	about 1 m	very long (intensity falls with distance)
stopped by	paper or skin	a few mm of aluminium	reduced by cm of lead
deflected by fields	yes (positive)	yes (opposite way, more)	no

- **Background radiation** comes from rocks (radon gas is the largest part), cosmic rays, food, medical uses and nuclear industry. Subtract it from every count rate you measure.

4 Half-life

Half-life $T_{½}$ — the time for half of the undecayed nuclei in a sample to decay, or for the activity to halve.

Activity A — the number of decays per second, in becquerels (Bq).



Random decay of many nuclei gives a smooth exponential curve.

WORKED EXAMPLE

A sample of 80 mg has a half-life of 6.0 hours. How much is left after one day?

1. 24 h = 4 half-lives M1
2. **80 → 40 → 20 → 10 → 5.0 mg** A1

- **Random:** you cannot predict when a given nucleus decays, only the probability. **Spontaneous:** temperature, pressure and chemistry do not change it.

EXAM TIP

Count rates on graphs include background. Subtract it before reading a half-life off the curve.

5 The decay constant HL

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

λ = decay constant, the probability per second that a nucleus decays

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

activity

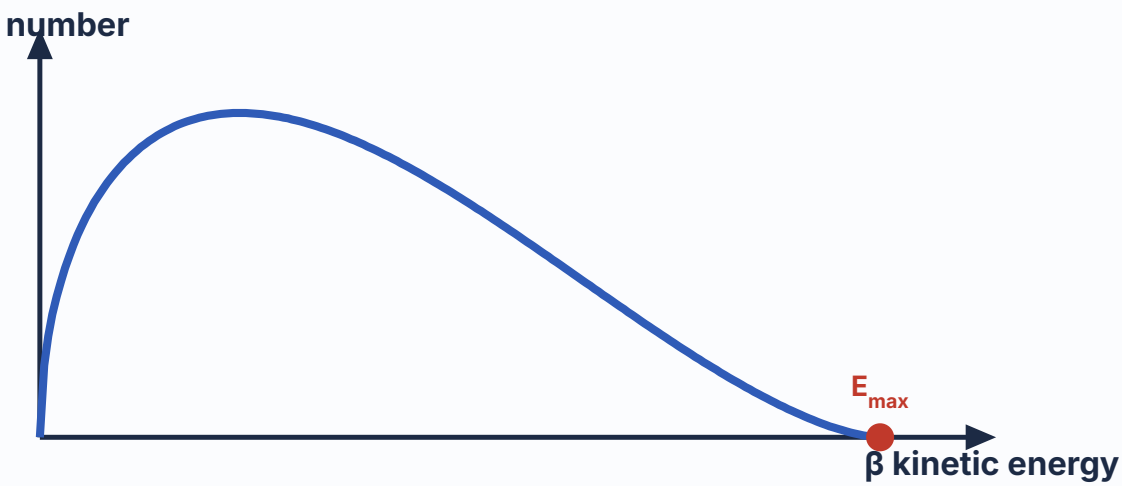
$$T_{½} = \frac{\ln 2}{\lambda}$$ DATA BOOKLET

WORKED EXAMPLE

A wooden object has 40 % of the carbon-14 activity of living wood ($T_{½}$ = 5730 years). How old is it?

1. $\lambda = \ln 2/5730 = 1.21 \times 10^{-4}\ \text{yr}^{-1}$ M1
2. $0.40 = e^{-\lambda t} \Rightarrow t = \ln(1/0.40)/\lambda$ M1
3. **$t = 7.6 \times 10^3$ years** A1

- **Very long half-lives** (uranium, about 10^9 years) are found from A = λN: count the activity and the number of nuclei (from the mass), then λ = A/N.



A continuous spread: the missing energy is carried by a neutrino.

If β decay made only two particles, every electron would have the same energy. It doesn't.

- **Neutrino evidence:** β particles have a continuous range of energies up to a maximum. Energy and momentum are conserved only if a third, almost undetectable particle (the neutrino, or antineutrino in β^-) takes the rest.

LINKING QUESTION

Binding energy explains why both fission (E.4) and fusion (E.5) release energy. Radioactive decay is also a source of the Earth's internal heat.

IDEA FOR YOUR IA / EXPLORATION

Model radioactive decay with dice (or a spreadsheet), or measure the "half-life" of beer froth or a discharging capacitor, and compare with the exponential model.

Test yourself — cover the answers first

QUICK CHECK

1. What force holds the nucleus together?
2. What changes in β^- decay?
3. Which radiation is most ionising?
4. A count rate falls from 800 to 100 in 30 minutes. What is the half-life?
5. Which nucleus has the highest binding energy per nucleon?
6. HL Find λ for a half-life of 8.0 days, in s^{-1}.

EXAM-STYLE

7. Complete: $^{226}_{88}Ra \rightarrow ? + {}^{4}_{2}He$, and $^{90}_{38}Sr \rightarrow ? + {}^{0}_{-1}e + \bar{\nu}$
8. HL A source has activity 4.0×10^5 Bq and half-life 30 years. How many radioactive nuclei does it contain?

Show answers

1. the strong nuclear force
2. a neutron becomes a proton: Z rises by 1, A stays the same
3. alpha
4. 3 half-lives, so 10 minutes
5. iron-56 (or nickel-62)
6. $\ln 2/(8.0 \times 86\,400) = 1.0 \times 10^{-6}\ s^{-1}$
7. $^{222}_{86}Rn$
   $^{90}_{39}Y$
8. $\lambda = \ln 2/(30 \times 3.15 \times 10^7) = 7.3 \times 10^{-10}\ s^{-1}$
   $N = A/\lambda = 4.0 \times 10^5/7.3 \times 10^{-10}$
   $= \mathbf{5.5 \times 10^{14}}$ **nuclei**

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