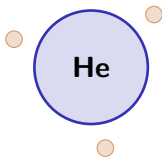


Nuclear Physics

A2 Physics ■ Topic 23

A-Level Physics



What we will cover

- 1 Mass–energy equivalence
- 2 Mass defect and binding energy
- 3 Fusion and fission
- 4 Radioactive decay
- 5 Recap



Mass and energy are the same thing

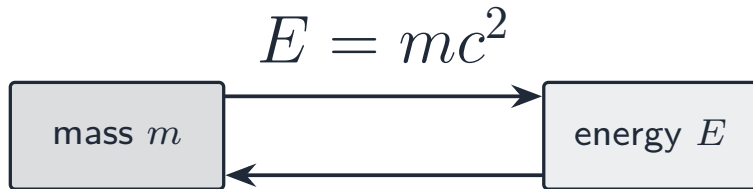
Mass–energy equivalence , from special relativity:

$$E = mc^2, \quad \Delta E = c^2 \Delta m$$

$c = 3.00 \times 10^8 \text{ m s}^{-1}$. Nuclear masses are tiny but c^2 is huge, so a small mass change is a large energy. The conversion you will use again and again:

$$1 \text{ u} \longleftrightarrow 931 \text{ MeV}$$

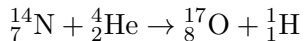
The exchange rate



A mass of one atomic mass unit is worth 931.5 MeV – which is why nuclear energies are quoted in MeV and chemical ones in eV.

1 u $\leftrightarrow$ 931 MeV. Nuclear masses are tiny and c^2 is enormous, so a mass change too small to weigh releases an energy you can measure.

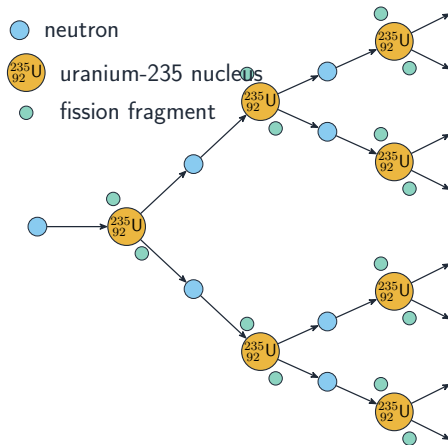
Balancing a nuclear reaction



Nucleon number is conserved (top: $14 + 4 = 17 + 1$) and charge is conserved (bottom: $7 + 2 = 8 + 1$).

To fill in an unknown: identify the species, then balance the top and bottom numbers.

Balancing a nuclear reaction, in detail



In an uncontrolled chain reaction each fission of uranium-235 releases neutrons that cause more

Nuclear fusion and fission



A nuclear power station releases energy by nuclear fission.



A nucleus weighs less than its parts

The mass of a **nucleus** is less than its Z **protons** plus N neutrons, $Zm_p + Nm_n$. The difference is the **mass defect** :

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

That missing mass was released as **binding energy** when the nucleus formed:

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

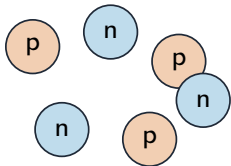
Helium-4, $\Delta m = 0.0304 \text{ u}$

$$B = 0.0304 \times 931 \approx 28 \text{ MeV}$$

The missing mass

Separated nucleons weigh **more** than the nucleus they make. That difference is the **mass defect**, and $E = mc^2$ turns it into the binding energy.

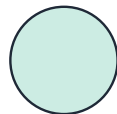
separate nucleons



$$\text{mass} = Zm_p + Nm_n$$

assemble
→

nucleus

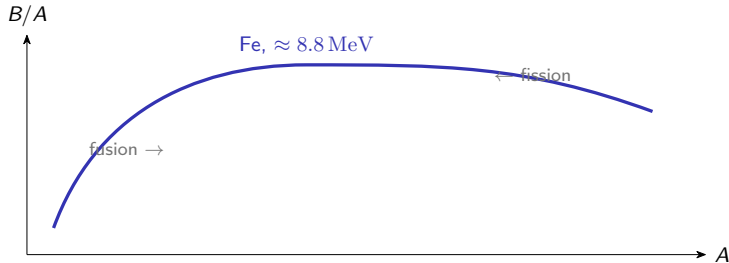


mass is *less*
(mass defect Δm)

binding
energy B
→

Binding energy per nucleon peaks at iron

B/A (MeV per nucleon) measures how tightly each nucleon is held.



Iron-56 is the most stable nucleus. Light nuclei sit to the left; heavy nuclei sit to the right.

Reading the binding-energy curve

the shape

dome-shaped: rising steeply from hydrogen, **peaking at iron**, then falling slowly

why it peaks

the **strong nuclear force** is short-range, so beyond about iron the electrostatic repulsion of the protons wins

to the left of iron

fusion moves nuclei up the curve and releases energy

to the right

fission moves them up too – both directions run downhill in energy

mass-energy equivalence

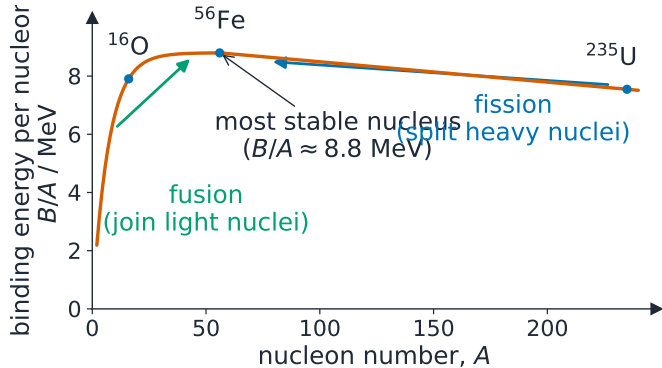
$E = \Delta mc^2$ converts the mass defect into the energy released

in every equation

nucleon number, **conservation of charge** and energy must all balance

Binding energy per nucleon measures **stability**, not total energy. Iron is the most stable nuclide, which is why stars stop there.

Binding energy per nucleon vs nucleon number



binding energy per nucleon peaks near ^{56}Fe

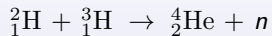
Binding energy per nucleon peaks near iron ($A \approx 56$); lighter and heavier nuclei are less tightly bound



Energy is released towards the iron peak

fusion

two light nuclei join



needs millions of kelvin to
beat electrostatic repulsion

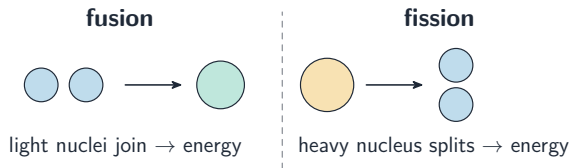
fission

a heavy nucleus splits

extra neutrons can cause more
fissions – a **chain reaction**

needs a **critical mass**

Both directions run downhill to iron



Fusion joins light nuclei; **fission** splits heavy ones. Both move nucleons **towards** the iron peak, and both release the difference in binding energy.

Calculating the energy released

- 1 total mass of the reactants
- 2 total mass of the products
- 3 $\Delta m = m_{\text{reactants}} - m_{\text{products}}$ (positive when energy is released)
- 4 $\Delta E = c^2 \Delta m$, or in u: $\Delta E \text{ (MeV)} = \Delta m \text{ (u)} \times 931$

Mass decreases by 0.020 u

$$\Delta E = 0.020 \times 931 \approx 19 \text{ MeV}$$

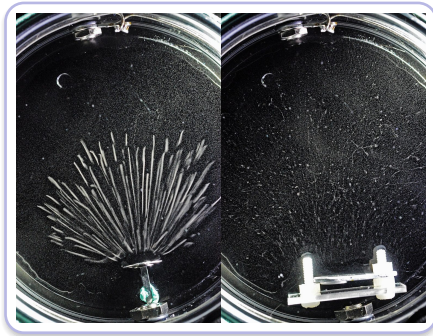


Random and spontaneous

Spontaneous – no outside trigger. Rate is not changed by temperature, pressure or chemical state.

Random – you cannot predict when a given nucleus will decay, only the probability. Evidence: the count rate **fluctuates**.

Seeing single decays



Each track is one decay – unpredictable individually, precisely regular in bulk. A **Geiger counter** beside a source clicks at uneven intervals, never a steady stream, which is the evidence that decay is random.

Activity, decay constant, exponential

$$A = \lambda N$$

A is **activity** (decays per unit time), in **becquerel** (Bq). λ is the **decay constant** – probability per unit time that a nucleus decays.

$$N = N_0 e^{-\lambda t}, \quad A = A_0 e^{-\lambda t}$$

The same **fraction** decays in each interval – that is what makes it **exponential decay** .

Half-life

Half-life $t_{1/2}$ is the time for N (or A , or the count rate) to fall to half:

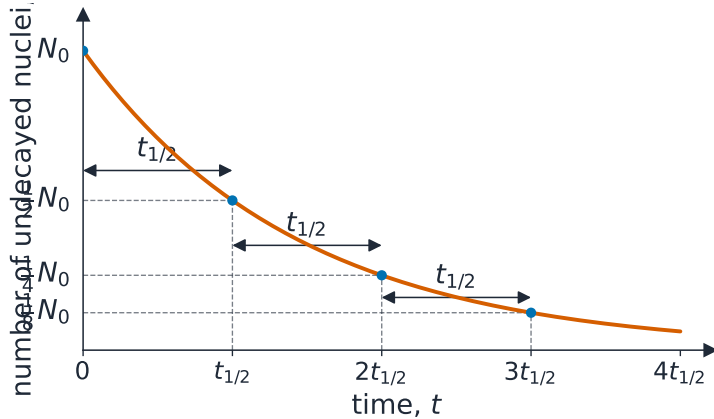
$$\lambda = \frac{\ln 2}{t_{1/2}} \approx \frac{0.693}{t_{1/2}}$$

After n half-lives the surviving fraction is $(1/2)^n$. After 5 half-lives, about 3% remains.

$$t_{1/2} = 6.0 \text{ hours}$$

$$6.0 \text{ h} = 21600 \text{ s, so } \lambda = 0.693/21600 \approx 3.2 \times 10^{-5} \text{ s}^{-1}$$

Half-life, in detail



$$N = N_0 e^{-\lambda t} \cdot T_{1/2} = \ln 2 / \lambda$$

The number of undecayed nuclei falls by half in each half-life

Activity, decay constant and half-life

activity

$A = \lambda N$ – decays per second, in becquerel

λ

the decay constant: the **probability per second** that any one nucleus decays

fixed per nuclide

λ never changes for a given **radionuclide** – so a **larger sample has proportionally larger activity**

the link

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

the units

convert the half-life to **seconds** first: $6.0 \text{ h} = 21\,600 \text{ s}$

the decay law

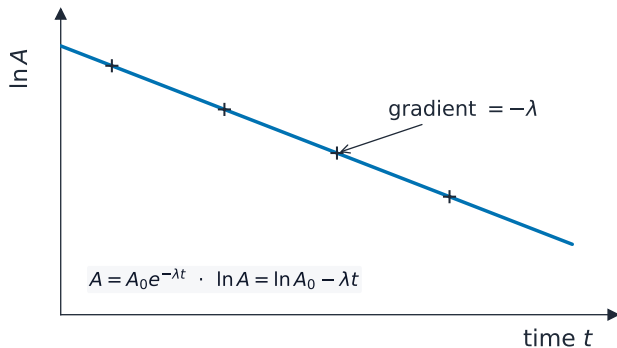
$N = N_0 e^{-\lambda t}$, and the same form for A and for count rate

Decay is **random and spontaneous**: unaffected by temperature, pressure or chemical state. Only the number of nuclei present changes the activity.

Finding λ from data

$$\lambda = \frac{1}{t} \ln \frac{A_0}{A}, \quad \ln A = \ln A_0 - \lambda t$$

A plot of $\ln A$ against t is a straight line of gradient $-\lambda$.



A graph of $\ln A$ against time is a straight line of gradient $-\lambda$

Exam tips

- $E = mc^2$; **the mass defect** is the mass lost when nucleons bind, released as binding energy.
- **Binding energy per nucleon** peaks near iron – both fusion (light nuclei) and fission (heavy nuclei) move towards it and release energy.
- Activity $A = \lambda N$; decay is exponential $N = N_0 e^{-\lambda t}$; half-life $t_{1/2} = \ln 2 / \lambda$.
- Balance nuclear equations by conserving **nucleon number and proton number**.



Topic 23 – key takeaways

1 $E = mc^2$

1 u $\leftrightarrow$ 931 MeV; balance A and Z

2 Binding

B/A peaks at iron; fusion and fission move towards it

3 Decay

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

4 Half-life

$t_{1/2} = \ln 2 / \lambda$; random and spontaneous

Check yourself

- 1 Why does a small Δm release a lot of energy?
- 2 Which nucleus sits at the peak of the B/A curve?
- 3 Fusion and fission both release energy – why?
- 4 After 3 half-lives, what fraction remains?

Answers 1. c^2 is huge 2. iron-56 3. both move towards the iron peak 4. $1/8$