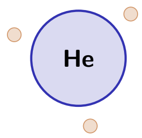
Nuclear Physics

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

1 Mass-energy

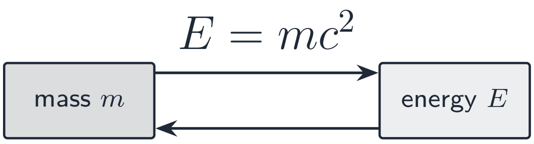
Mass and energy are the same thing

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

$c = 3.00 \times 10^8\,\mathrm{m\,s^{-1}}$. 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:

$$1\,\mathrm{u} \;\longleftrightarrow\; 931\,\mathrm{MeV}$$

The exchange rate



A mass of one atomic mass unit is worth $931.5\,\mathrm{MeV}$ — which is why nuclear energies are quoted in MeV and chemical ones in eV.

Balancing a nuclear reaction

$${}^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H}$$

Nucleon number 核子数 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.

2 Binding energy

A nucleus weighs less than its parts

The mass of a **nucleus** 原子核 is less than $Zm_\mathrm{p} + Nm_\mathrm{n}$. The difference is the **mass defect** 质量亏损:

$$\Delta m = (Zm_\mathrm{p} + Nm_\mathrm{n}) - m_\mathrm{nucleus}$$

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

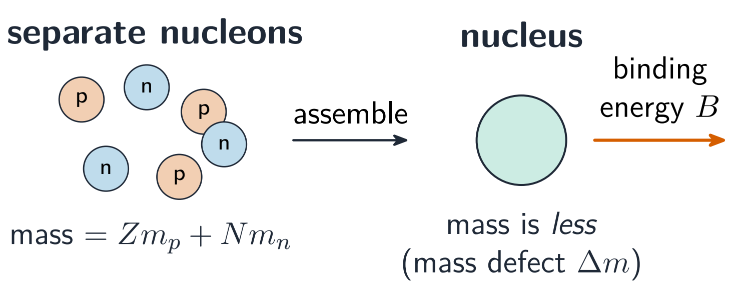
$$B = \Delta m \cdot c^2$$

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

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

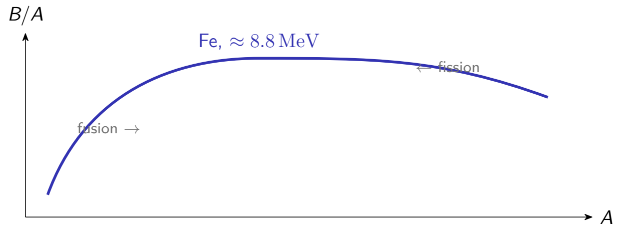
The missing mass

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



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.

3 Fusion and fission

Energy is released towards the iron peak

fusion
核聚变

two light nuclei join

$^2_1\mathrm{H} + ^3_1\mathrm{H} \rightarrow ^4_2\mathrm{He} + n$

needs millions of kelvin to beat electrostatic repulsion

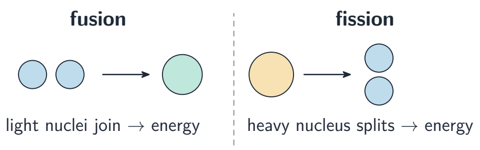
fission
核裂变

a heavy nucleus splits

extra neutrons can cause more fissions – a **chain reaction** 链式反应

needs a **critical mass** 临界质量

Both directions run downhill to iron



Fusion 聚变 joins light nuclei; **fission** 裂变 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. $\Delta m = m_{\mathrm{reactants}} - m_{\mathrm{products}}$ (positive when energy is released)
4. $\Delta E = c^2 \Delta m$, or in u: $\Delta E\ (\mathrm{MeV}) = \Delta m\ (\mathrm{u}) \times 931$

Mass decreases by $0.020\,\mathrm{u}$

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

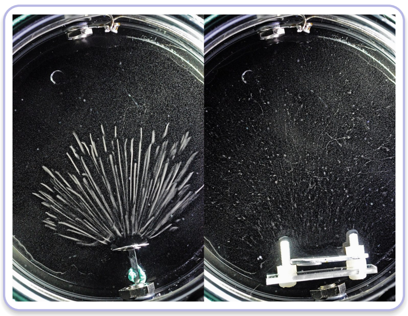
4 Radioactive decay

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.

Activity, decay constant, exponential

$$A = \lambda N$$

A is **activity** 活度 (decays per unit time), unit Bq. λ is the **decay constant** 衰变常数 – probability per unit time that a nucleus decays.

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

The same fraction decays in each time interval – that is why it is exponential.

Half-life

Half-life 半衰期 $t_{1/2}$ 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.

$t_{1/2} = 6.0$ hours

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

Finding λ from data

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

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

5 Recap

Topic 23 – key takeaways

1 $E = mc^2$

$1\,\mathrm{u} \leftrightarrow 931\,\mathrm{MeV}$; 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.** $1/8$