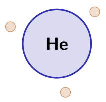
# Nuclear Physics

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

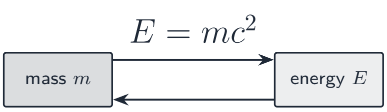
$$E = mc^2, \qquad \Delta E = c^2 \Delta m$$

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

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

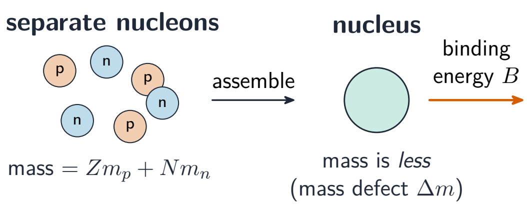
**Helium-4, $\Delta m = 0.0304\,\mathrm{u}$**

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



## The missing mass

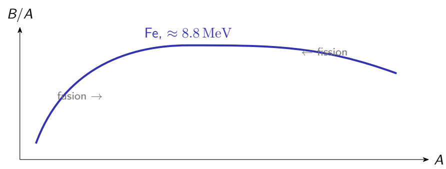
Separated nucleons weigh more than the nucleus they make. That difference is the **mass defect** 质量亏损, and $E = mc^2$ turns it into the binding energy.






## 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

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

needs millions of kelvin to beat electrostatic repulsion

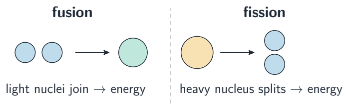
**fission**
核裂变

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. $\Delta m = m_{\text{reactants}} - m_{\text{products}}$ (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



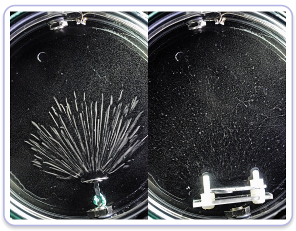
## Random and spontaneous

**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. $\lambda$ 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 $\lambda$ 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 $\Delta m$ 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.** $1/8$