

Nuclear physics

A-Level Physics 9702 · Topic 23 revision notes · A2

Mass-energy equivalence, mass defect and binding energy, the binding energy per nucleon curve behind fission and fusion, and the exponential law of radioactive decay.

12 definitions to learn word for word, 10 equations in their own column, 6 diagrams and graphs. Read it, cover it, test yourself.

1. 23.1a Mass-energy equivalence, mass defect and binding energy
2. 23.1b Binding energy per nucleon, fission and fusion
3. 23.2a Random decay, activity and the decay constant
4. 23.2b Exponential decay and half-life

Definitions (mark-scheme wording) Equations Exam traps

23.1a Mass-energy equivalence, mass defect and binding energy

Definitions

Mass-energy equivalence: mass and energy are equivalent; a change in energy ΔE corresponds to a change in mass Δm given by $\Delta E = c^2 \Delta m$.

Mass defect: the difference between the total mass of the separate nucleons and the mass of the nucleus.

Binding energy: the minimum energy needed to separate a nucleus completely into its individual protons and neutrons (the energy equivalent of the mass defect).

Unified atomic mass unit (u): one twelfth of the mass of a carbon-12 atom ($1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}$).

Equations

$$E = mc^2$$

mass-energy equivalence
J

$$\Delta E = c^2 \Delta m$$

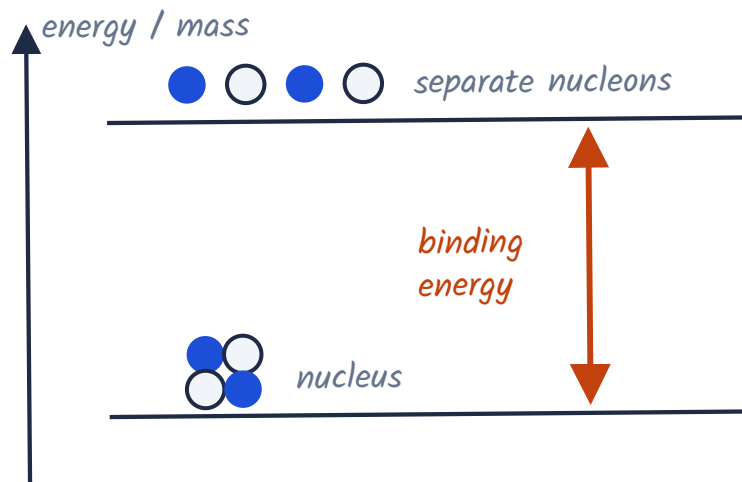
energy for mass change Δm
J

$$\Delta m = 2m_p + (A - Z)m_n - M$$

mass defect of a nucleus of mass M
kg or u

Key points

- ✓ A nucleus has **less mass** than its separate nucleons: the mass defect.
- ✓ Energy is released when a nucleus forms; that energy must be **supplied** to pull it apart.
- ✓ Mass defect = $2m_p + (A - Z)m_n - m_{\text{nucleus}}$
- ✓ $1 \text{ u} \approx 931.5 \text{ MeV}$ of energy; work in kg and J if unsure.
- ✓ Energy released in a reaction = (mass of reactants - mass of products) $\times c^2$.
- ✓ Released energy appears as kinetic energy of products and as γ -ray photons.



Separate nucleons have more energy (and mass) than the bound nucleus; the gap is the binding energy $= c^2 \times \text{mass defect}$ (blue = protons, white = neutrons).

Watch out!

- ! The nucleus is **lighter** than its parts, not heavier.
- ! Binding energy is energy **needed** to separate a nucleus, not energy stored inside it.
- ! Use nuclear masses, or consistent atomic masses (electrons then cancel); do not mix them.

23.16 Binding energy per nucleon, fission and fusion

Definitions

Binding energy per nucleon: the binding energy of a nucleus divided by the number of nucleons in it.

Nuclear fission: the splitting of a large (heavy) nucleus into two smaller nuclei of similar mass, with release of energy (and neutrons).

Nuclear fusion: the joining of two light nuclei to form a heavier nucleus, with release of energy.

Equations

$$\text{BE per nucleon} = \text{BE} / A$$

A = nucleon number

MeV

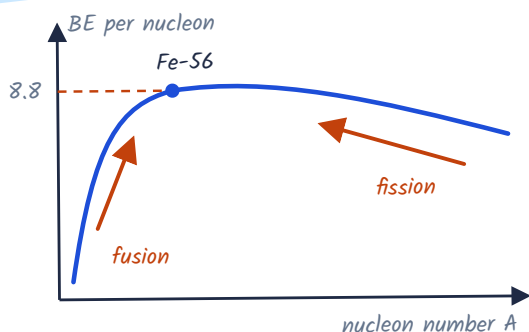
$$E_{\text{released}} = \sum \text{BE}_{\text{products}} - \sum \text{BE}_{\text{reactants}}$$

energy from a nuclear reaction

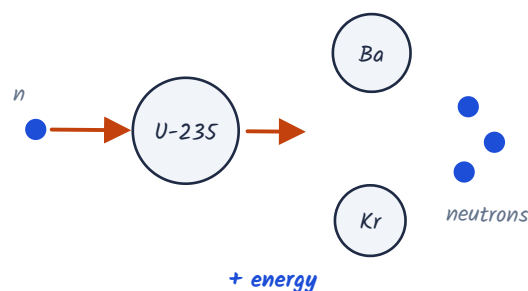
MeV

Key points

- ✓ Higher binding energy per nucleon = **more stable** nucleus.
- ✓ The curve peaks near **iron-56** (about 8.8 MeV per nucleon).
- ✓ Energy is released when binding energy per nucleon **increases**: products are more tightly bound.
- ✓ **Fusion** of light nuclei (left of the peak) and **fission** of heavy nuclei (right of the peak) both release energy.
- ✓ Energy released = total BE of products - total BE of reactants.
- ✓ Fusion needs very high temperature so nuclei overcome electrostatic repulsion; fission is triggered by neutron absorption.



Binding energy per nucleon against A: fusion and fission both move towards the iron peak and release energy.



Fission: a slow neutron is absorbed by U-235, which splits into two daughter nuclei plus 2 or 3 neutrons, releasing energy.

Watch out!

- ! Fusing nuclei **heavier than iron** absorbs energy; energy comes out only when BE per nucleon rises.
- ! Products have **greater** binding energy but **less** total mass than the reactants.

23.2a Random decay, activity and the decay constant

Definitions

Random (decay): it cannot be predicted which nucleus will decay next, or when a given nucleus will decay.

Spontaneous (decay): decay is not affected by external factors such as temperature, pressure or chemical state.

Activity (A): the number of nuclei that decay per unit time (1 Bq = 1 decay per second).

Decay constant (λ): the probability that an individual nucleus will decay per unit time.

Equations

$$A = \lambda N$$

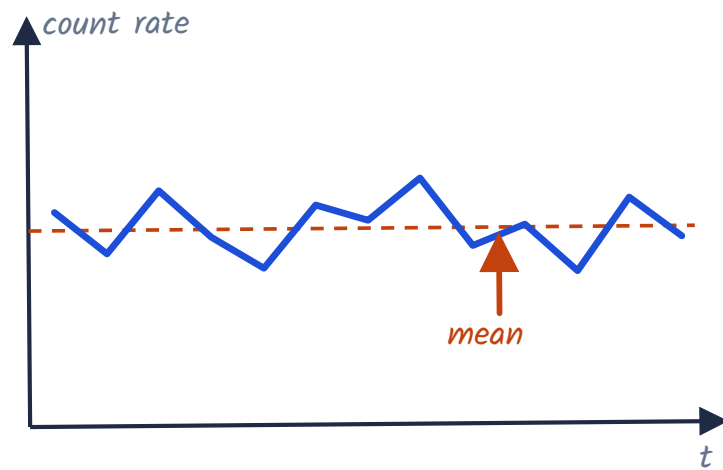
activity = decay constant $\times$ number of undecayed nuclei
Bq (s^{-1})

$$A = -dN/dt$$

activity is the rate of decrease of N
Bq

Key points

- ✓ Evidence for randomness: the **count rate fluctuates** about a mean value.
- ✓ Each nucleus has the same probability of decaying per second, so **activity $\propto$ number of undecayed nuclei**.
- ✓ Measured count rate is less than the activity: the detector catches only some emissions; subtract **background** count.
- ✓ Large λ means rapid decay and a **short half-life**.
- ✓ Number of nuclei $N = (\text{mass} / \text{molar mass}) \times N_A$.



Count rate from a long-lived source over time: random fluctuations about a steady mean.

Watch out!

- ! Random does not mean unpredictable in bulk: for large N the decay **rate** is predictable.
- ! Correct count rates for background radiation before using them.

23.26 Exponential decay and half-life

Definitions

Half-life ($t_{1/2}$): the mean time taken for half of the active nuclei in a sample to decay.

Key points

- ✓ N , A and count rate all fall **exponentially** with the same half-life.
- ✓ After n half-lives the fraction remaining is $(\frac{1}{2})^n$.
- ✓ Half-life is **constant** for an isotope, independent of the starting amount.
- ✓ Straight-line test: **$\ln A$ against t** is linear with **gradient $-\lambda$** and intercept $\ln A_0$.
- ✓ Read $t_{1/2}$ from a decay curve at several points and average.
- ✓ Undecayed nuclei fall as N ; daughter nuclei grow as $N_0 - N$.

Equations

$$x = x_0 e^{-\lambda t}$$

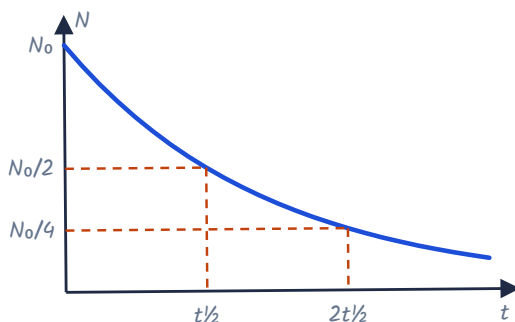
$x = N, A$ or count rate

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

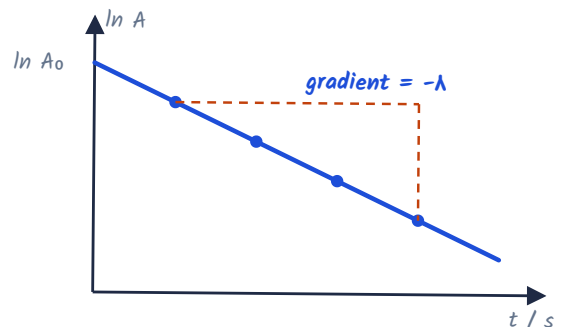
decay constant and half-life
 s^{-1}

$$\ln A = \ln A_0 - \lambda t$$

log form: gradient $-\lambda$



Exponential decay: every half-life halves what remains, N_0 to $N_0/2$ to $N_0/4$.



$\ln A$ against t : a straight line with gradient $-\lambda$, so $t_{1/2} = \ln 2 / \lambda$.

Watch out!

- ! $\lambda = 0.693/t_{1/2}$, not $1/t_{1/2}$. Units must match: λ in s^{-1} needs t in s .
- ! Half-life is not half the time for the sample to decay completely; it never fully decays.
- ! Gradient of $\ln A$ against t is $-\lambda$; drop the minus sign only when quoting λ .

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