Nuclear physics

Mass-energy equivalence, nuclear equations, mass defect and binding energy, binding energy per nucleon, fusion and fission, the random nature of decay, activity and the decay constant, half-life, and exponential decay.

23.1 Mass defect and nuclear binding energy

Mass and energy

Mass and energy are equivalent:

$$E = mc^2$$

So a change in energy means a change in mass: $\Delta E = c^2 \Delta m$. A nuclear reaction that releases energy leaves the products with less total mass.

Nuclear equations

Nucleon number and proton number balance on both sides:

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

Mass defect and binding energy

- **Mass defect:** the difference between the total mass of the separate nucleons and the mass of the nucleus. The nucleus is always lighter.
- **Binding energy:** the energy needed to separate a nucleus completely into its individual nucleons. It equals c^2 × the mass defect.

TRY IT

A helium-4 nucleus has mass 4.0015 u. Find its binding energy. Proton: 1.0073 u; neutron: 1.0087 u. Total of the separate nucleons $= 2(1.0073) + 2(1.0087) = 4.0320$ u. Mass defect $= 0.0305$ u $= 0.0305 \times 1.66 \times 10^{-27} = 5.06 \times 10^{-29}$ kg. $E = 5.06 \times 10^{-29} \times (3.0 \times 10^{8})^2 = 4.6 \times 10^{-12}$ J, about 28 MeV.

Binding energy per nucleon

A higher binding energy per nucleon means a more **stable** nucleus. The peak is near iron-56.

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Fusion and fission

	Fusion	Fission
What happens	two light nuclei join	a heavy nucleus splits into two lighter ones and some neutrons
Where on the curve	left of the peak	right of the peak
Example	hydrogen to helium in stars	uranium-235 in a reactor

In both, the products have a greater binding energy per nucleon than the starting nuclei, and that is why they release energy. Energy released is $c^2\Delta m$, or the increase in total binding energy.

Fusion needs very high temperatures, so that the positive nuclei are moving fast enough to overcome their electrostatic repulsion.

23.2 Radioactive decay

Spontaneous and random

- **Random:** you cannot predict which nucleus will decay next or when, though each one has a constant probability per unit time.
- **Spontaneous:** decay is not affected by external factors such as temperature or pressure.

The **fluctuations** in the count rate from a radioactive source are evidence for its randomness.

Activity and the decay constant

Activity A is the number of decays per unit time, measured in becquerels (1 Bq = 1 decay per second).

The **decay constant** λ is the probability per unit time that a nucleus will decay.

$$A = \lambda N$$

Half-life

Half-life $t_{1/2}$ is the time taken for the number of undecayed nuclei of a nuclide (or the activity) to fall to half.

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

Exponential decay

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

where x can be the **activity**, the **number of undecayed nuclei**, or the **received count rate**.

TRY IT

A source has an activity of 800 Bq and a half-life of 6.0 hours. Find its activity after 15 hours. $\lambda = 0.693/6.0 = 0.1155$ h^{-1}. $A = 800e^{-0.1155\times 15} = 800e^{-1.73} = 142$ Bq.

TRY IT

Find the number of nuclei in a source of activity 1200 Bq with half-life 30 s. $\lambda = 0.693/30 = 0.0231$ s^{-1}. $N = A/\lambda = 5.2 \times 10^4$.

Taking logs gives $\ln A = \ln A_0 - \lambda t$. So a plot of $\ln A$ against t is a straight line with gradient $-\lambda$.

NOTE

Exam tip: subtract the background count from every reading before using it. Use consistent units for λ and t; for $A = \lambda N$ in Bq, λ must be in s^{-1}.

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