Edexcel Physics A-level

Topic 11: Nuclear Radiation

Notes

11 - Nuclear Radiation

11.164 - Nuclear binding energy
At the nuclear level **mass and energy are interchangeable** and can be related by the equation, which **applies to all energy changes**:

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

Where **E** is energy, **m** is mass and **c** is the speed of light in a vacuum.

When measuring the mass of a nucleus and the mass of its constituents, you will notice that the mass of the nucleus is always lower, this difference is known as the **mass defect / mass deficit**. **The mass that is "lost" is converted into energy and released** when the nucleons fuse to form a nucleus.

The **binding energy** of a nucleus is the **energy required to separate the nucleus into its constituents (nucleons)** (or the energy released when a nucleus is formed from its constituents).

Nucleus
(smaller mass)

Separated nucleons
(greater mass)

Image source: Rice University,CC BY 4.0
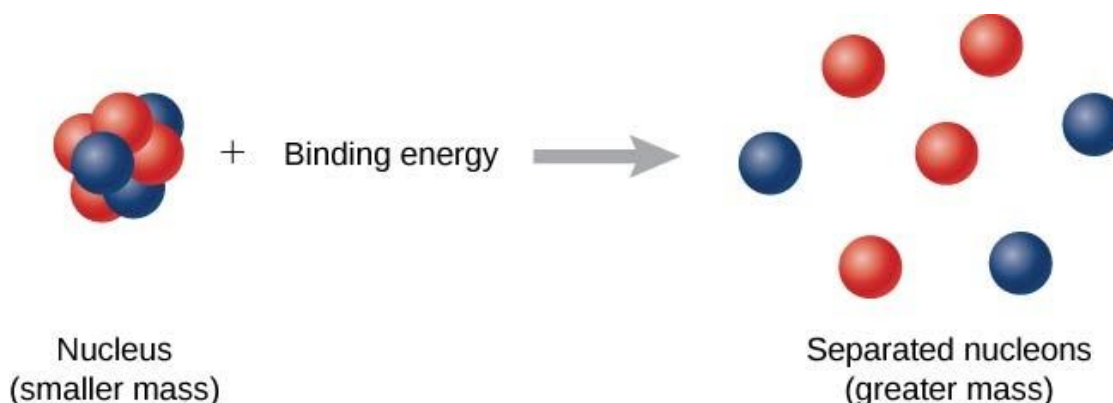
You should be able to use the above equation to calculate mass defect and energy, some example questions are provided in the next section.

11.165 - Atomic mass unit
The change in mass when nucleons fuse is incredibly small, therefore when measuring the mass difference, **atomic mass units** are used. One atomic mass unit (1 u) is defined as 1/12th of the mass of a carbon-12 atom, which is 1.661×10^{-27} kg. You can convert atomic mass units to kg by multiplying them by 1.661×10^{-27} kg, and then use the above equation to find the energy released in joules, however you could also simply use the fact that **a change in 1 u of mass means that 931.5 MeV of energy is released**.

Below are some example calculations, using the formula defined above:
Find the binding energy of a nucleus in eV, given that its mass defect is 0.0647 u.
Method 1: Convert the mass defect into kg and use $E = mc^2$ to find binding energy in joules then convert it to eV.

$$0.0647\, u \ = 0.0647 \times 1.661 \times 10^{-27}\ \text{kg} \ = 1.074667 \times 10^{-28}\ \text{kg}$$

$$E = 1.074667 \times 10^{-28} \times (3 \times 10^8)^2 = 9.672 \times 10^{-12} \text{ J}$$

$$\frac{9.672 \times 10^{-12}}{1.6 \times 10^{-19}} = 6.0 \times 10^7 \text{ eV} = 60 \text{ MeV (2 s.f.)}$$

Method 2: Use the fact that a mass defect of 1 u is equivalent to 931.5 MeV of energy released.

$$0.0647 \times 931.5 = \quad 60 \text{ Mev (2 s.f.)}$$

Find the energy released in MeV when a uranium-235 nucleus splits into barium-144 and krypton-89 and 2 neutrons.

Name	Mass (u)
U-235 nucleus	235.043930
Ba-144 nucleus	143.922953
Kr-89 nucleus	88.91763
Neutron	1.008664

First calculate the mass defect using the information above:

Mass before = 235.043930 u

Mass after = 143.922953 + 88.91763 + 2(1.008664) = 234.857911 u

Mass defect = Mass before - Mass after

Mass defect = 235.043930 - 234.857911 = 0.186019 u

Now multiply the mass defect by 931.5 to get energy released in Mev:

$$0.186019 \times 931.5 = 173 \text{ MeV (3 s.f.)}$$

11.166 - Nuclear fission, nuclear fusion and binding energy per nucleon

Nuclear fission is the **splitting of a large nucleus into two daughter nuclei**. It occurs in very large nuclei, which are unstable (such as uranium), and occurs completely randomly, however it can also be induced. Energy is released during fission because the smaller daughter nuclei have a higher binding energy per nucleon. The image below shows the induced fission of uranium-235.
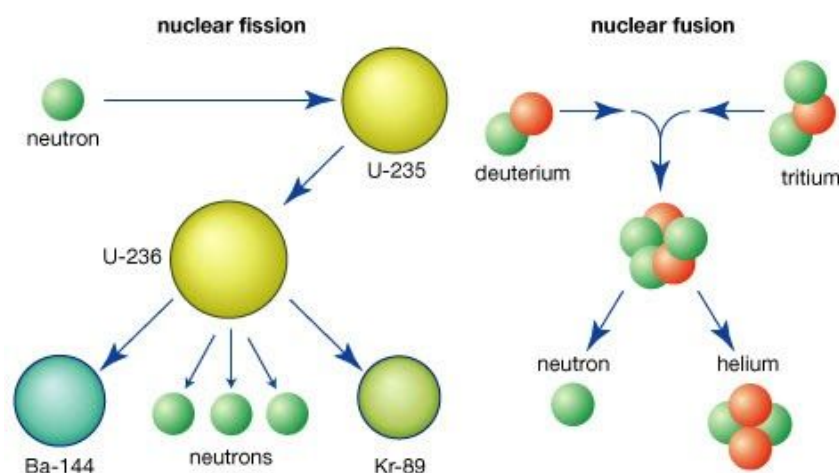

Image source: Padsohot1,CC BY-SA 4.0

Nuclear fusion is the opposite of fission, it is where **two smaller nuclei join together to form one larger nucleus**. It only occurs in fairly small nuclei. Energy is released during fusion because the larger nucleus has a much higher binding energy per nucleon. Fusion releases far more energy than fission however fusion can only occur at **extremely high temperatures** (for example in stars).

The **binding energy per nucleon** is simply the binding energy of a nucleus divided by the number of nucleons in the nucleus. By plotting a graph of **binding energy per nucleon against nucleon number**, you can identify whether an element can undergo fission or fusion. As you can see on the graph, it has a characteristic curve which shows a dramatic difference in binding energy per nucleon for small nuclei. The peak of the curve occurs at a nucleon number of 56; the element iron has the highest binding energy per nucleon, nuclei smaller than iron can undergo fusion, while elements larger than iron can undergo fission.
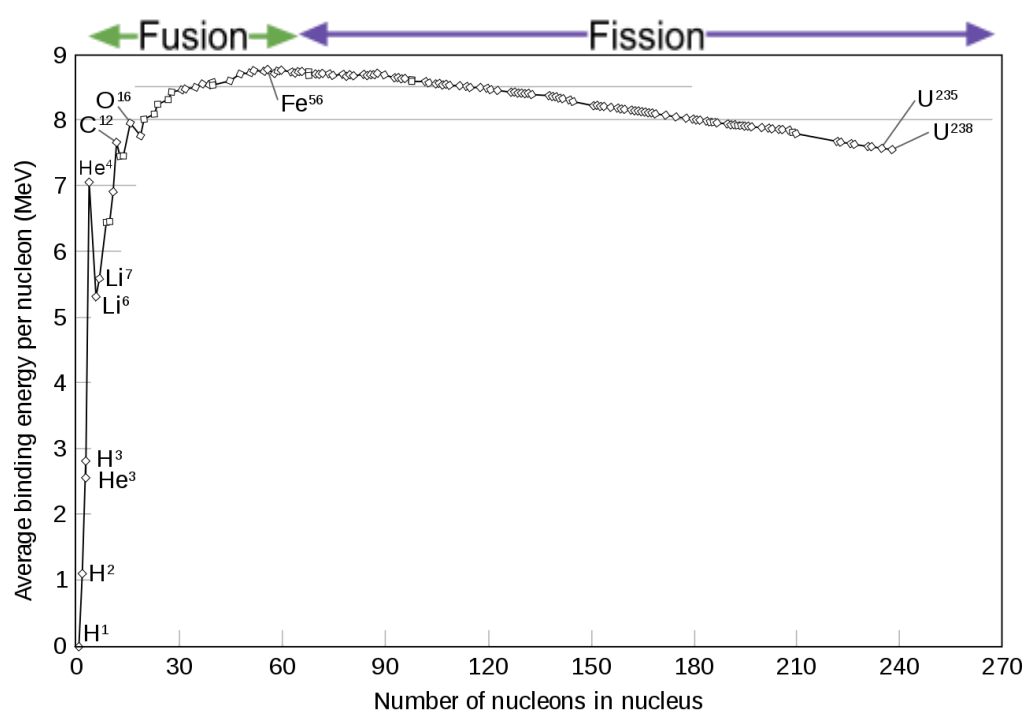
You can also use the above graph to calculate the energy released in a fission or fusion reaction by calculating the change in energy between the nuclei.

11.167 - The mechanism of nuclear fusion
As mentioned previously, nuclear fusion is where **two smaller nuclei join together to form one larger nucleus**.

Fusion can only occur at **extremely high temperatures** because a massive amount of energy is required to overcome the **electrostatic force of repulsion between nuclei**, as nuclei are all positively charged.

Furthermore, in order to **maintain** a fusion reaction, **very high densities of matter** must be used, in order to make sure that there are **enough colliding protons** undergoing fusion.

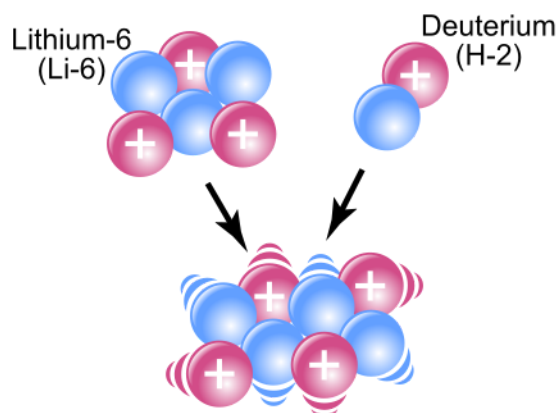The diagram below shows the fusion reaction between lithium and deuterium.

Image source: Sakurambo,CC BY-SA 3.0,Image is cropped

11.168 - Background radiation

Background radiation is around us constantly, therefore when taking readings of the count rate of a radioactive source it is important to measure the background radiation first, then subtract this value to find the **corrected count**, which is the actual count rate caused by the source.

$$Corrected\ count\ =\ Total\ count\ rate\ -\ background\ count$$

There are many sources of background radiation:
- **Radon gas** - which is released from rocks.
- **Artificial sources** - caused by nuclear weapons testing and nuclear meltdowns.
- **Cosmic rays** - enter the Earth's atmosphere from space.
- **Rocks** containing naturally occurring radioactive isotopes.

11.169 - Alpha, beta and gamma radiation

Radiation is where an unstable nucleus emits energy in the form of EM waves or subatomic particles in order to become more stable. There are three types of radiation, all of which have different properties which are summarised in the table below:

Radiation	Nature	Range in air	Ionising	Absorbed by?
Alpha (α)	An alpha particle (helium nucleus / 2 protons and 2 neutrons)	2 - 10 cm	Highly	Paper
Beta (β)	A fast-moving electron	Around 1 m	Weakly	Aluminium foil (around 3 mm)
Gamma (γ)	An electromagnetic wave	Infinite range: follows inverse square law	Very weakly	Several metres of concrete or several inches of lead

Due to their **differing penetrating powers**, the type of radiation emitted from a source can be easily identified using a simple experiment:

1. Using a geiger-muller (GM) tube and counter, find the **background count** when the source is not present.
2. Place the source of radiation close to the GM tube and measure the count rate.
3. Place a **sheet of paper** between the source and GM tube and measure count rate again, if the count rate decreases significantly, then the source is emitting alpha radiation.
4. Repeat the above step using **aluminium foil** and **several inches of lead**. If there is a significant decrease in count rate for aluminium foil, then beta radiation is being emitted and if there is a significant decrease in count rate for the lead block, then gamma radiation is being emitted.

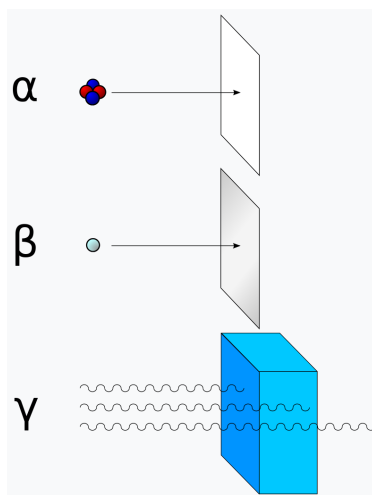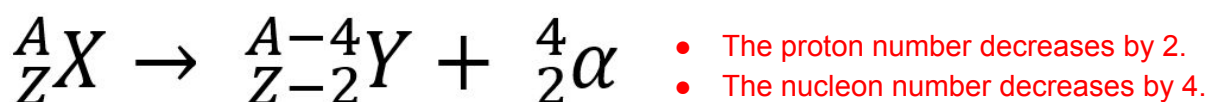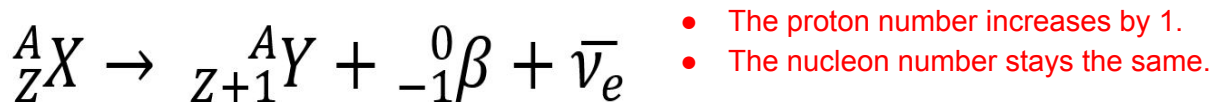Image source: Stannered,CC BY-SA 3.0

11.170 - Nuclear equations

Alpha decay occurs in large nuclei, with too many of both protons and neutrons. A general equation for alpha decay is:

$$^A_Z X \rightarrow \ ^{A-4}_{Z-2}Y + \ ^4_2\alpha$$

- The proton number decreases by 2.
- The nucleon number decreases by 4.

Beta-minus decay occurs in nuclei which are neutron-rich (have too many neutrons). A general equation for beta-minus decay is:

$$^A_Z X \rightarrow \ ^A_{Z+1}Y + \ ^0_{-1}\beta + \overline{\nu}_e$$

- The proton number increases by 1.
- The nucleon number stays the same.

Where ν_e is the symbol for an electron neutrino.

You should be able to interpret and write nuclear equations like the ones given above.

11.172 - The random nature of nuclear decay

Radioactive decay is a **random** and **spontaneous** process meaning you can't predict when the next decay will occur. A given radioactive nucleus will have a **constant decay probability** denoted by the letter λ, and known as the **decay constant**, which is the probability of a nucleus decaying per unit time. This value can be calculated by finding the change in the number of nuclei (ΔN) of a sample over time (Δt), over the initial number of nuclei (N):

$$\frac{\Delta N}{\Delta t} = -\lambda N$$

11.173 - Activity and half-life

Over long periods of time radioactive decay can be described as an exponential decay through the following formula:

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

Where **N** is the number of nuclei, **N_0** is the initial number of nuclei, **λ** is the decay constant and t is time passed.
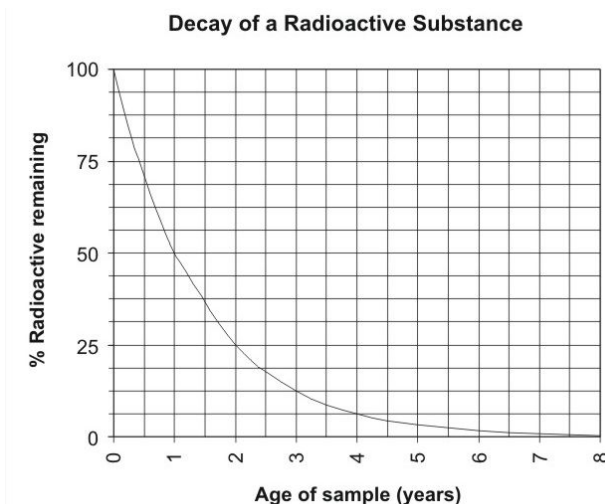

Decay of a Radioactive Substance

Image source: Kurt Rosenkrantz,CC BY-SA 3.0

As the decay is exponential, the time taken for the number of nuclei to halve will be constant, the name for this value is the **half-life ($T_{1/2}$)** of the sample. You can determine this value graphically, by plotting a graph of the number of nuclei against time and measuring the time taken for the sample size to halve, across several half-lives and finding a mean. For example, using the graph above, the time taken to drop to 25% is 2 years, therefore the half-life would be 1 year.

However, a more accurate way to measure half-life is by plotting a **graph of ln (N_0) against time**, which forms a straight line graph, the modulus of the gradient of the line is the decay constant, which can be used to find half-life. This is because:

$ln\,(N) = ln(N_0 e^{-\lambda t})$

$ln(N) = ln(N_0) + ln(e^{-\lambda t})$ Using the log rule: log(AB) = log(A)+log(B)

$ln(N) = ln(N_0) - \lambda t$ Rearrange to the form Y = mx+c

$ln(N) = -\lambda t + ln(N_0)$

Using your measured value of decay constant you can use the following formula, (which is derived by substituting $0.5N_0$ for N in the exponential decay equation and rearranging for time):

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

The above equation can also be used to find the decay constant when the half-life is known:

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

The **activity** of a radioactive sample is the number of nuclei that decay per second, this is proportional to the number of nuclei (N) in the sample, where the decay constant (λ) is the constant of proportionality:

$$A = \lambda N$$

Because activity is directly proportional to the number of nuclei it follows the same exponential decay equation:

$$A = A_0 e^{-\lambda t}$$

Also as they are proportional, the **time taken for activity to halve is equal to the half-life** as well, and as the activity of a sample is much easier to measure than the number of nuclei, this is often used to find the half-life of a sample.

The **decay constant** can be used to **model the decay of a nuclei only when there is a large number of nuclei in a sample**, this is because the decay constant models the number of nuclei decayed by statistical means.