WJEC (Eduqas) Physics A-level

Topic 3.6: Nuclear Decay

Notes

This work by PMT Education is licensed under CC BY-NC-ND 4.0

Radioactivity

Some elements in the universe are said to be **unstable**, meaning that if left for a long enough time they will inevitably decay to form a more stable element. This process is called **nuclear decay,** as the nucleus of the decaying atom changes during the decay.

Nuclear decay has a **probabilistic nature**. It is impossible to predict exactly when a single nucleus will decay. Radioactive substances tend to contain a large number of individual atoms, so instead we can predict what **proportion** of these atoms (on average) will have decayed after a certain time.

There are three general ways in which a nucleus can decay: alpha, beta and gamma.

Alpha Decay

The unstable nucleus emits an **alpha particle**, which is identical to a helium nucleus containing 2 protons and 2 neutrons. The nucleus then becomes lighter and more stable.

Alpha Decay generally happens to larger elements which are unstable due to the **proton-proton repulsion** between nucleons in the nucleus. Larger elements contain more protons so are generally more unstable than lighter atoms.

We can express nuclear decay in an equation form, which contains the ‘reactants’ and ‘products’ of the reaction. We represent nuclei in the following way:

$$^{A}_{Z}X$$

Here ‘A’ is the number of nucleons in the nucleus (**nucleon number**), ‘Z’ is the number of protons (**atomic number**) and ‘X’ is the chemical symbol for the element. For example we can write Carbon-12 as:

$$^{12}_{6}C$$

All alpha decays take the following form:

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

The new nucleus ‘Y’ formed by the decay will have 4 fewer nucleons and 2 fewer protons. The α symbol represents the alpha particle ejected by the decay.

For example Uranium-238 can undergo alpha decay to form Thorium-234:

$$^{238}_{92}U \rightarrow \, ^{234}_{90}Th + \, ^{4}_{2}\alpha$$

CC BY NC ND

All quantities such as **baryon number, lepton number and charge are all conserved** in nuclear decay.

Beta Decay

A neutron in the nucleus decays into a proton, ejecting an electron in the process. This electron is referred to as a **beta particle**.

Nuclei which have too many neutrons relative to their protons will undergo beta decay in order to become more stable.

Seeing as the number of protons in the nucleus changes, the element formed by the decay is different to the original. Beta decay will always take the from of:

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}\beta + \bar{\nu}_e$$

We can see that in beta decay **the nucleus number is unchanged,** but the atomic number increases by 1. Once again we can see that charge and baryon number are conserved, and in order to conserve lepton number an **anti-electron neutrino** is produced.

Electrons have a small mass but receive a relatively large amount of kinetic energy during the decay, meaning **beta particles are emitted at very high speeds.**

Gamma Decay

A single gamma photon is emitted, with no change to the composition of the nucleus.

Just as electrons which orbit nuclei can exist in excited energy states, **the protons and neutrons inside a nucleus can exist in their own excited states.** When these nucleons transition to a lower energy level a gamma photon is emitted, similar to how an orbital electron emits a photon when moving to a lower energy level.

Gamma decay can be represented as:

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z}X + \gamma$$

Where the γ symbol represents the emitted gamma photon. Notice there is **no change to the composition of the nucleus.**

Detecting Radiation

The three forms of radiation behave very differently, which is no surprise seeing as they have a range of masses and charges.

This table summarises the important properties of each kind of radiation.

Radiation	Range in air	Ionising	Deflected by electric and magnetic fields?	Absorbed by?
Alpha (α)	2 - 10 cm	Highly	Yes	Paper
Beta (β)	Around 1 m	Weakly	Yes	Aluminium foil (around 3 mm)
Gamma (γ)	Infinite range: follows inverse square law	Very weakly	No	Several metres of concrete or several inches of lead

Alpha particles contain 4 nucleons, which compared to particles like electrons makes them very heavy particles. **This means alpha particles move slowly in comparison to the other two forms of radiation.** Slower particles are more likely to collide with particles in air, and so **alpha particles lose their energy very quickly** resulting in their short range.

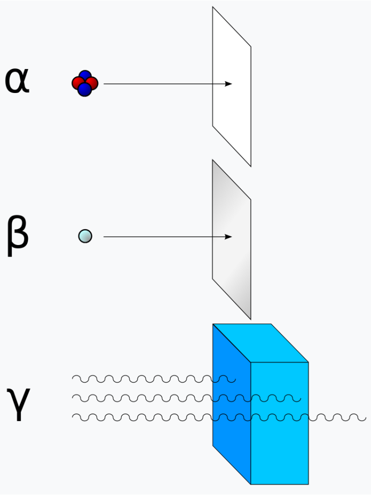
Beta radiation on the other hand is **much faster** and so has a longer range. Gamma particles are essentially electromagnetic radiation, so they move at the speed of light and will effectively never be stopped by air.

How **ionising** a particle is a measure of its ability to **remove electrons from other atoms.** Alpha particles carry a strong positive, giving them the ability to essentially 'rip' electrons away from atoms which they come into contact with. Energy is transferred from an alpha particle to an electron in order to ionise it, which is why alpha particles lose their energy and are stopped so rapidly.

Alpha and Beta are both charged particles meaning they will interact with electric and magnetic fields.

The **different penetrating power** of each radiation type enables the radiation given off by a source to be analyzed by following this procedure:

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**.



Rate of Nuclear Decay

Imagine if we had a sample of radioactive material on a table. Measuring the amount of radiation being emitted from the material over time would show us that it is **decreasing.** This is because t**he number of decays that we detect each second is proportional to the number of undecayed atoms left in the sample.** Intuitively, we would expect to see twice as much radiation being emitted from a sample which was twice as large. We can express this fact in equation form:

$$A = \lambda N$$

A is the **activity (the number of decays detected each second),** N is the **number of undecayed atoms in the sample** and λ is the constant of proportionality referred to as the **decay constant.**

The activity is measured in **'Becquerels'** with symbol **Bq. 1 Bq is defined to be the activity of a sample in which one atom decays each second.** This means it must have units of s^{-1} .

Every decay corresponds to one less undecayed atom, therefore the **activity is the rate at which** N **is decreasing**. Meaning:

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

The equation on the right is enough information to tell us exactly how N depends on time. **The rate that** N **decreases is proportional to** N, so when N gets smaller, the rate at which N decreases becomes slower, so N decreases more slowly and so on. **This is an example of exponential decay.**

Therefore, we can find N in terms of the time elapsed:

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

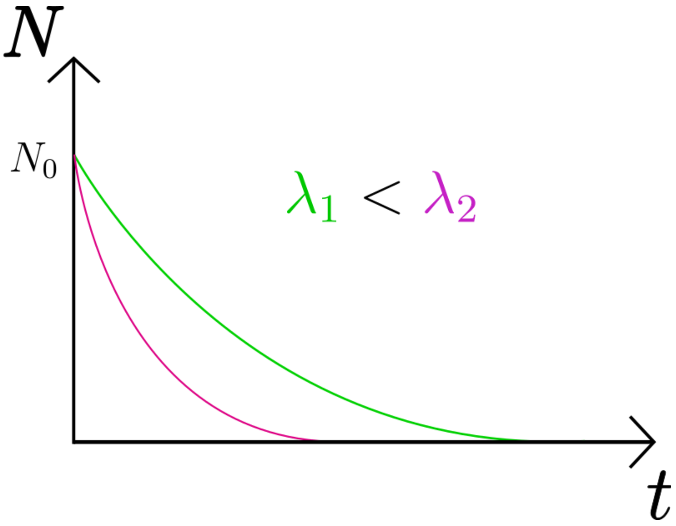
N_0 is the initial amount of undecayed atoms when t is zero. As mentioned previously, N is proportional to A, which means that the activity must also exponentially decay in the same way:

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

Once again, here A_0 is the initial activity of the sample.

Exponential Decay Graphs

The following graph shows the number of undecayed atoms for two different samples:



Both samples start with the same number of undecayed atoms N_0 . Initially both start to decay very rapidly, then slow down as time as time increases until eventually N 'tends' towards 0. In theory, N never actually reaches exactly 0, but for a real sample of radioactive atoms there will be a time when all of the atoms have decayed.

The pink line represents a decaying sample where the atoms have a **large decay constant** λ_2. These atoms are **more unstable** and hence decay much faster than the other sample with smaller decay constant λ_1.

The Half-Life

The decay constant is one way of expressing how unstable a radioactive nucleus is. Another value which does this is the half-life. **The half-life is the average amount of time it takes for half of a radioactive sample to decay.**

For example, suppose we started with 1000 identical radioactive atoms with a small half-life of 1 minute. From the definition of the half-life, after 1 minute we would expect 500 undecayed atoms to be left. After another minute we would expect 250, after another minute 125 and so on.

We can find the half-life by using the equation for N over time:

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

After one half-life, we expect half of the initial atoms to remain. This means that:

$$\frac{N_0}{2} = N_0 e^{-\lambda T_{1/2}}$$

Here we have set the time to be equal to the half-life $T_{1/2}$ .Cancelling the N_0's and flipping both sides gives:

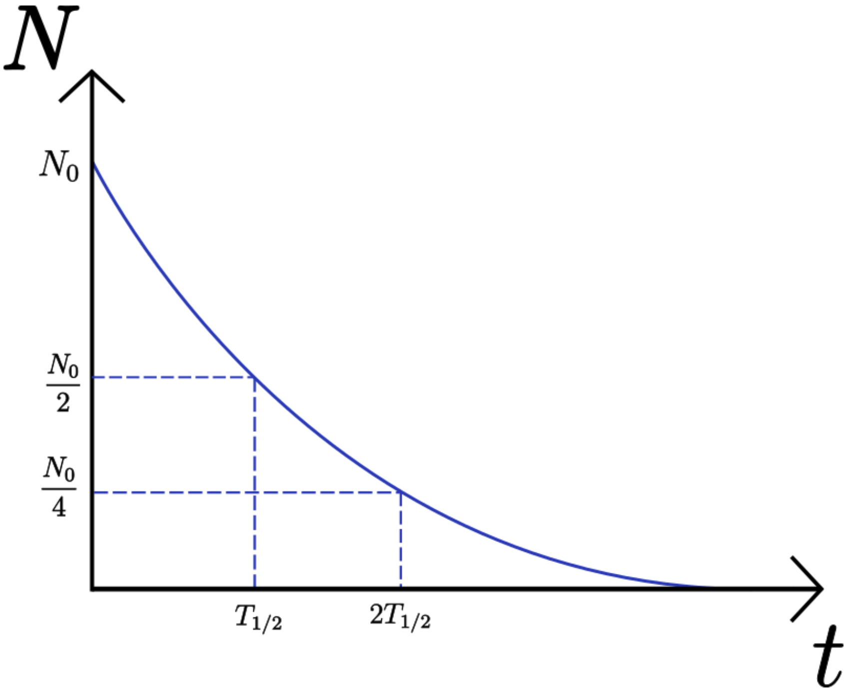
$$2 = e^{\lambda T_{1/2}}$$

Taking the natural logarithm of both sides of this equation allows for it to be written in terms of the half life:

$$\lambda T_{1/2} = \ln(2) \ \Rightarrow T_{1/2} = \frac{\ln(2)}{\lambda} \approx \frac{0.693}{\lambda}$$

If the decay constant is large then we would expect the sample to decay very quickly. This is reflected in this equation; when the decay constant increases the half-life shall be made smaller.

When drawing decay curves, it can be useful to draw on the **half-life intervals**, as is done in this graph:



This helps to make it clear that because of the shape of the exponential decay curve, **the value of N takes the same length of time to halve each time.**

If N halves after each half-life has passed, then another equation which might be useful is the following:

$$N = \frac{N_0}{2^X}$$

Here 'X' is the number of half-lives which has passed. Note that this formula works even when 'X' isn't an integer, like if 1.5 half-lives have passed.

Since N is proportional to the activity there is a similar equation for the activity:

$$A = \frac{A_0}{2^X}$$