Radioactivity

Rutherford Scattering

The Experiment

- Fired α particles at a very thin piece of gold leaf
- The particles mostly passed through the gold leaf, but some were deflected at large angles (this meant that there was a positively charged nucleus that repelled the α particle) which contradicted the plum pudding model
- Most α particles passed through because atom's are mostly free space

α, β, γ Radiation

α Radiation

- Two protons and two neutrons bound together (helium nucleus)
- Weakly penetrating
- Easily absorbed
- Positively charged
- Can only be emitted by a nuclei with an atomic number greater than 60
- It is the most ionising of the 3

Applications of α radiation

- Fire alarms
  - The alpha particles cannot penetrate through the smoke which sets off the alarm.

β Radiation

- Electrons (β^-/e^-) or positrons (β^+/e^+) that are emitted from an unstable nucleus
- Moderately penetrative
- Positively or negatively charged
- β^+ emitted by proton rich nuclei
- β^- emitted by neutron rich nuclei
- Is less ionising than α but more ionising than γ

Applications of β radiation

- Measuring thickness
  - β particles cannot penetrate trough more than ~5mm of aluminium or 30cm of air, this can be used to gauge the thickness of aluminium sheets during manufacturing
- Medical PET scanning

γ Radiation

- Does not change the proton or nucleon number of a nucleus
- Makes the nucleus more stable by its emission
- Highly penetrative
- Can be absorbed by several centimetres of lead, many metres of air and can travel through a vacuum indefinitely
- Is the least ionising of the 3
- Part of the electromagnetic spectrum
- Follows the inverse square law

$$intensity \propto \frac{1}{distance^2}$$

Applications of γ radiation

- Medical imaging
- Cancer treatments
- Sterilising medical equipment
- Irradiate food to kill harmful bacteria

Background Radiation

Sources of background radiation: - Radon gas - Buildings (brick) - Cosmic rays - Medical procedures - Food and drink

It is important to always account for the skew caused by background radiation

Safety Considerations

- Wear goggles and gloves
- Radioactive sources should be pointed away from people
- Use tongs to handle radioactive sources to prevent contamination
- Put the source away when not in use to reduce exposure time
- Keep the source in a lead-lined box

Radioactive Decay

The decay of a radioactive substance is random and spontaneous. To measure decay, we must look at the count rate over a long time to see if it decreases

The probability that a given nucleus will decay in a given time is proportional to the number of nuclei. The equation for calculating the rate of decay is:

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

Where λ is the decay constant, N is the number of nuclei and t is time in seconds.

The equation for the decay constant is:

$$\frac{ln2}{T_{\frac{1}{2}}} = \lambda$$

Where $T_{\frac{1}{2}}$ is the half-life of the isotope and λ is the decay constant.

Radioactive decay has a negative exponential relationship between the number of nuclei and time.

The exponential equation for this is:

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

Where N_0 is the initial number of nuclei.

The activity of a sample can be found using the decay constant and the number of nuclei. The equation for this is:

$$A = \lambda N$$

Similarly, the relationship between activity and time is also a negative exponential:

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

Nuclear Instability

Some isotopes are more stable than others, unstable isotopes decay radioactively to become more stable.

Atoms usually decay through α or β decay until they reach a stable point.

α decay reduces the atom by two neutrons and two protons.

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

α could also be written as ${}^{4}_{2}He$

β^- decay reduces the atom by one neutron and increases by one proton.

$${}^{A}_{B}X \rightarrow^{A}_{B+1} Y + \beta^- + \overline{v}$$

β^+ decay reduces the atom by one proton and increase by one neutron.

$${}^{A}_{B}X \rightarrow^{A}_{B-1} Y + \beta^+ + v$$

Excitation

In an atom, an electron can gain energy and be promoted to a higher energy level.

When the electron returns to the original level, the energy is released as electromagnetic waves.

Nuclei also have excited states. This is because of the different arrangements of protons and neutrons within a nucleus.

When the protons and neutrons rearrange to a lower energy state, the excess energy is released as γ radiation.

(we have not done anything below here, but it is on the revision list)

Nuclear Radius

In Rutherford's particle scattering experiment he determined the radius of the nucleus.

The α particles in Rutherford's experiment had a kinetic energy of 5.3 MeV

The gold nucleus in the experiment does work on the α particle to slow it down. Eventually, the α particle has 0 kinetic energy and then is repelled.

The closest point of approach is where the $kinetic\ energy = electrostatic\ potential\ energy\ gained$.

The formula for electrostatic potential energy is:

$$PE = \frac{Qq}{4\pi\epsilon_0 r}$$

where r is the distance of separation of the charges Q and q, and ϵ_0 is a constant.

Electron Diffraction Experiment

This is an alternative method of finding the radius of a nucleus.

The electron can behave like a wave, with the de Broglie wavelength given by:

$$\lambda = \frac{h}{p}$$

Where λ is the wavelength, h is Planck's constant and p is the momentum of the electron.

Liquid Drop Model of the Nucleus

In the liquid drop model, the nucleus is assumed to be of a constant density and spherical.

The liquid drop model of the nucleus means that the volume of the nucleus is directly proportional to the number of nucleons present in that nucleus.

$$V = kA = \frac{4}{3}\pi r^3$$

Where r is the radius of the nucleus with mass number A and volume V.

Using the equation, a different equation can be derived.

$$r = \sqrt[3]{\frac{3kA}{4\pi}}$$

Or

$$r = r_0 A^{1/3}$$

Where r_0 is the radius of the proton.

Mass & Energy

When protons and neutrons combine to make an atom energy is released, this is called binding energy.

The mass of a nucleus is less than the mass of the individual protons and neutrons because of the binding energy released.

Energy and mass are linked with the equation:

$$E = mc^2$$

Where E is energy, m is mass and c is the speed of light.

If the change in mass between the individual particles and the mass of the nucleus is known, we can find the binding energy using this equation.

Fission

Nuclear fission is a reaction in which a nucleus is split (or fissured).

Energy is released when heavy nuclei are split apart. The new nuclei (daughter nuclei) have a larger binding energy per nucleon than the parent. This means that a large amount of energy is released (about 100x the energy of a normal nuclear decay).

Fission occurs when an unstable atom splits, we can force this split by making the atom absorb a neutron.

The fission reaction will produce daughter nuclei but also release energy and some neutrons. These neutron will go on to cause fission reactions themselves, which will produce more neutrons. This is a chain reaction.

Fusion

Nuclear fusion is a reaction in which two nuclei are combined, or fused, to form a larger nucleus.

We know that all nuclei have less mass than the sum of the masses of the nucleons. When an atom is formed it releases binding energy, and the greater the binding energy, the greater the missing mass. The binding energy per nucleon is at a maximum at iron. This means that if two low-mass nuclei can be fused together to form a larger nucleus, energy can be released.

Fusion would release a huge amount of energy but there are many issues which need to be overcome before it will work on earth. The repulsion between positive nuclei is very strong and can only be overcome by very high temperatures or pressures.

If we know the mass of the nuclei before and after fusion, we can find change in energy using $E = mc^2$.