Physics Knowledge Organiser

P7 – Atomic Structure

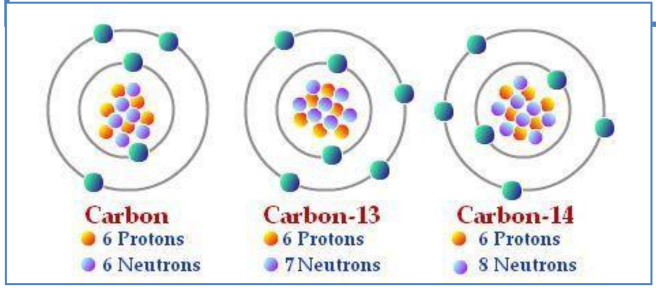
The structure of the atom and isotopes

You've already studied the structure of the atom in the first chemistry topic. Go back and recap that first.

Shells, or energy levels, where electrons are found can *change*:

- Electrons move *up* an energy level with the **absorption** of a specific wavelength of EM radiation
- Electrons move *down* an energy level by **emitting** a specific wavelength of EM radiation.

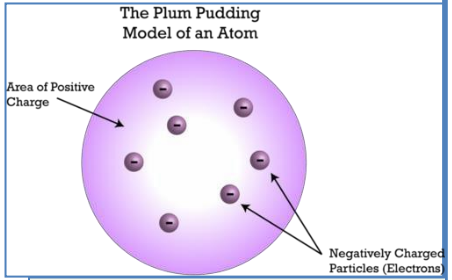
Atoms of a particular element always have the same number of protons (the atomic number in the periodic table). However, they don't all have to have the same number of *neutrons* to be the same element. If the number of neutrons varies between atoms of an element (but number of protons stays the same), we call the atoms **isotopes** of the element. Look at the diagram for the example of three isotopes of carbon.

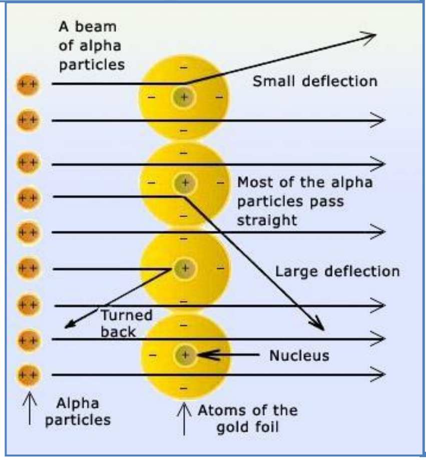


Radioactive decay

Some atomic nuclei are **unstable**. For instance, carbon-14 above is unstable. The nucleus will spontaneously and randomly change to become more stable. When the nucleus does this, it gives out nuclear radiation.

Since it is **a random** process, it is impossible to predict which particular nucleus will decay next. However, with a huge number of them, it is possible to measure the rate at which the whole source of radiation is decaying. This rate is measured in number of decays per second: the unit is the **becquerel (Bq).** One Bq = 1 decay per second. This can be measured with a detector called a Geiger- Muller tube – in this case, 1 Bq = 1 count per second.





Key Terms	Definitions
Isotopes	Isotopes of an element have the same number of protons but different numbers of neutrons in the nucleus.
Energy level	The other name for electron 'shells'. Each energy level is a specific distance from the nucleus and holds a limited number of electrons.
Radioactive decay	The process of an unstable nucleus becoming stable and giving out nuclear radiation in the process.
Nuclear radiation	Types of radiation that come from the nucleus of atoms during decay. Four types: alpha, beta, gamma, and neutrons.

How the modern model of the atom was developed

The model of the atom that you know all about has changed over time. Here's a brief timeline:

1. Before electrons were discovered, atoms were thought of as simply tiny, hard spheres that couldn't be divided into smaller particles.
2. Electrons were discovered (which are smaller than atoms!), so the model was modified. The **plum pudding** model of the atom was described: the atom as a ball of positive charge with negative electrons embedded in it like pieces of fruit in a pudding (see diagram).
3. A famous experiment by the scientists **Rutherford** and **Marsden** showed that the plum pudding model was wrong. Particles named **alpha particles** (more on these later) were fired at a sheet of atoms and some rebounded, some were deflected and others went straight through (see diagram). This showed that atoms have a hard, very small concentration of mass in the centre – which was named the **nucleus**. It also showed that the nucleus was charged, and we now know that is due to the protons in the nucleus. This model, that you use, is sensibly called the **nuclear model** of the atom.
4. The nuclear model was further developed to include the idea that electrons orbit at specific distances from the nucleus: in energy levels. The key scientist presenting this model was **Niels Bohr**.
5. Next, the nucleus was investigated further. It was found that the nucleus can be split up, producing particles with an equally-sized positive charge. These particles are named 'protons' – of course!
6. Then, in 1932, a scientist named **James Chadwick** proved that there were also uncharged particles in the nucleus. He called these particles 'neutrons' as they are neutral: no charge. This was about 20 years after the nucleus had already been accepted as the right idea about atoms.

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Types of nuclear radiation

As you've seen, the rate of decay is measured in Bq, or can be measured as the count rate in Bq. What it actually 'counts' is the amount of radiation hitting the detector each second. The radiation emitted from the nucleus thanks to radioactive decay can be:

- An **alpha particle** (symbol: α). An alpha particle is made of two protons and two neutrons (making it identical to the nucleus of helium atoms). Since there are four subatomic particles in one alpha particle, it has a mass number of 4. Since there are two protons in an alpha particle, it has a proton number of 2.
- A **beta particle** (symbol: β). A beta particle is a high speed electron. Beta particles are emitted during a type of radioactive decay where a neutron turns into a proton. This process also makes an electron, and electrons aren't 'allowed' in nuclei, so it gets fired out.
- A **gamma ray** (symbol: γ). Yes, the same wave as in the electromagnetic spectrum. It has a very high frequency and very short wavelength.
- A **neutron** (symbol: n). An uncharged particle – you know all about them already.

Alpha, beta and gamma

As well as being different in form, alpha, beta and gamma are also different in terms of how they behave after emission from a nucleus.

Type of nuclear radiation	Range in air	Penetrating power	Ionising power
Alpha	A few centimet-res	Not very penetrating at all: absorbed by a thin sheet of paper.	Strongly ionising (as alpha particles are large and have a +2 charge)
Beta	A few metres	Fairly penetrating: completely absorbed by a sheet of aluminium 5mm thick.	Moderately ionising (as not as big as alpha particles and their charge is smaller, -1)
Gamma	Enormous distances	Penetrates most materials. Absorbed only by several metres of concrete or a thick sheet of lead.	Only weakly ionising.

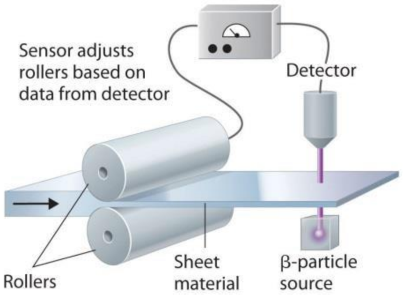
Key Terms	Definitions
Emission	Releasing or giving out. Nuclear radiation is **emitted** during radioactive decay.
Penetration	Passing through a material. Different types of nuclear radiation can penetrate different materials, and are absorbed by certain materials.
Ionisation	The process of making an ion by 'knocking off' electrons. Ionising radiation causes this, and can break up molecules into ions which go on to react with other chemicals. This is very dangerous in living organisms.

Using nuclear radiation

Nuclear radiation can be very useful. Here are some examples: notice that the type of nuclear radiation used depends on exactly what you need it for, so it links to the properties in the table opposite.

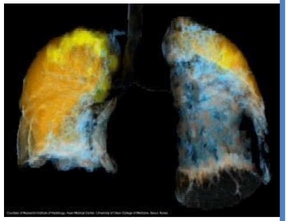
Radiotherapy: this is a treatment for cancer, using gamma rays. Gamma rays easily penetrate body tissues, so they can reach a tumour e.g. in the brain. The gamma rays can kill the cancer cells. However, since gamma rays are dangerous to healthy tissue, they use beams of gamma rays from many angles to the tumour, so healthy cells between source and tumour are not affected too badly.

Monitoring thickness of paper in a factory: As the diagram shows, a beta source is used. This is because beta will pass through materials such as paper. The detector on the other side of the sheet will measure a lower count rate if the sheet gets too thick, and a higher count rate if it gets too thin. The rollers can be automatically adjusted to fix this.



Medical diagnosis: sources of radiation can be taken into the body and the nuclear radiation monitored from the outside to give information about body function.

Obviously, alpha is NOT suitable for this as it won't penetrate body tissues to get to the detector! For example, a radioactive xenon isotope can be inhaled to check lung function. On the image, the left lung isn't getting much air to the bottom parts.



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Nuclear equations

To show what happens to an atom when it radioactively decays, we use nuclear equations. In these equations, we represent alpha and beta particles as shown in the key terms table.

Recalling what an alpha particle actually is (2 protons and 2 neutrons), it is clear that a nucleus going through alpha decay loses 4 subatomic particles (so the mass number has to **decrease** by *four*). Two of those are *protons*, so the *atomic number* must decrease by 2. Here's an example:

$$^{219}_{86}\text{radon} \longrightarrow {}^{215}_{84}\text{polonium} + {}^{4}_{2}\text{He}$$

This shows that a radon nucleus decays to produce a polonium nucleus and an alpha particle.

Beta decay results in a beta particle, and happens because a neutron turns into a proton and an electron. The electron is ejected from the nucleus. Since neutrons and protons have the same mass, the mass number does not change. However, there is an *extra proton*, so the atomic number must increase by one (therefore the charge of the nucleus increases by 1). Here's an example:

$$^{14}_{6}\text{carbon} \longrightarrow {}^{14}_{7}\text{nitrogen} + {}^{0}_{-1}\text{e}$$

This shows that the carbon nucleus decays to produce a nitrogen nucleus and a beta particle.

NB: emission of a gamma ray DOES NOT cause any change to the mass or atomic number.

Radioactive contamination

It is vital to realise that being exposed to nuclear radiation DOES NOT make something radioactive! (Despite what comic books show.) We say the exposed material/object is **irradiated**, and it is dangerous for living cells, as you know.

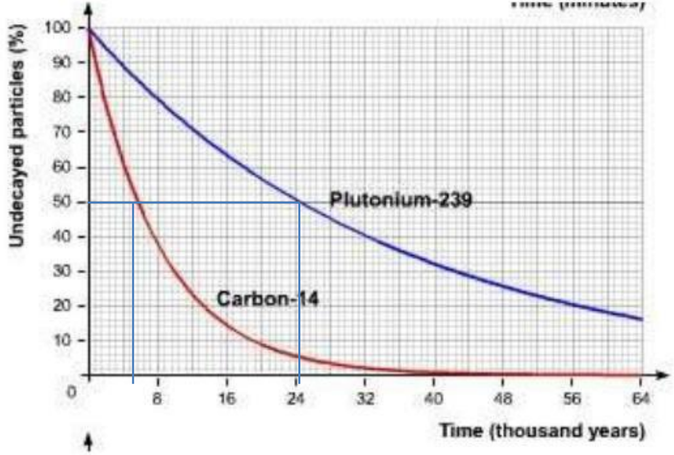
So, **radioactive contamination** is NOT being exposed to nuclear radiation. It means getting unwanted radioactive materials onto other materials. For instance, spilling a powdered radioactive source onto clothes. This is dangerous because the radioactive material keeps on emitting nuclear radiation through nuclear decay, so it can keep on irradiating the thing its on.

The hazards due to irradiation or contamination mean that *precautions* must be taken. For instance, the radioactive materials (e.g. uranium) used in nuclear power plant is only transferred, stored and used in containers that nuclear radiation can't penetrate. There is ongoing research by scientists into the effects of nuclear radiation on human health. Like all scientific findings, this research should be **published** and receive **peer review** – where other scientists check the methods and analysis performed, to make sure it is right!

Key Terms	Definitions
Mass number	The total number of subatomic particles in the nucleus of an atom (protons + neutrons).
Atomic number	The number of protons in the nucleus of an atom. In other words, the number of positive (+1) charges in the nucleus.
Alpha particle	Can be represented with the symbol: $^{4}_{2}\text{He}$
Beta particle	Can be represented with the symbol: $^{0}_{-1}\text{e}$
Half-life	The half-life of a radioactive isotope is the average time it takes for the number of radioactive nuclei to halve. It can be also be measured as the time it takes for the count rate of the sample to decrease to half its starting count rate.

Half life

Radioactive decay is **random** – so you don't know which nucleus will decay next. However, with a large number of radioactive nuclei, the time it takes for HALF of them to decay *is* predicable. This differs depending on the particular isotope involved. This length of time is called a **half-life** (see definitions too). Plotting the number of radioactive nuclei OR the count rate against time makes half-life easy to find. Read off the time it takes for the number on the y-axis to decrease by a half. So, in this example, we can see that the half-life of carbon-14 is 5.5 thousand years, whereas the half-life of plutonium-239 is 24 thousand years.



The y-axis could also show count rate (Bq) – the shape of the graph would be identical

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Nuclear fission

When people say 'splitting the atom', they mean **nuclear fission**. Nuclear fission is the splitting of a large, unstable atomic nucleus. This rarely just happens spontaneously, but we can force it to happen by making a large, unstable atomic nucleus first absorb a **neutron**. Then it will split into two nuclei, but of smaller atoms. During this split, 2 or 3 neutrons will also be released, and gamma rays are emitted. LOTS of energy is released by this process – which is why it is used in nuclear power stations.

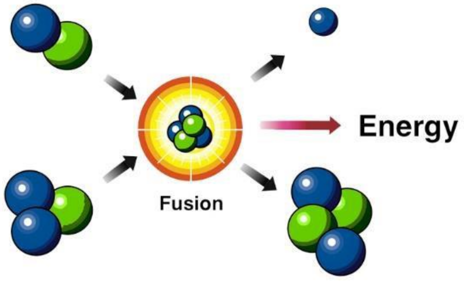
In nuclear power stations, the large, unstable nuclei used is usually uranium (but plutonium can also be split). The neutrons released by the fission of one nucleus can then be absorbed by other large, unstable nuclei. This is a **chain reaction** (shown in diagram). In nuclear power stations, some of the neutrons are absorbed to control the reaction and stop it getting out of control. In nuclear weapons, the chain reaction *does* get out of control, causing the massive explosion.

Nuclear fusion

Nuclear fusion involves small atomic nuclei, like hydrogen isotopes, joining – or *fusing* – together to make a heavier nucleus (such as helium). This occurs in stars. At the moment on Earth, this can be done, but not in a way that is any use for generating electricity, at least not yet. Very extreme conditions are required for nuclear fusion – extreme temperatures and pressures, which is why you only find it occurring naturally in stars.

An example of a fusion reaction is shown below.

Some of the **mass** of the fusing isotopes can be converted into energy, transferred by radiation.



$$^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n$$

Key Terms	**Definitions**
Nuclear fission	Splitting of a large atomic nucleus into smaller nuclei, with release of energy
Chain reaction	A reaction where the first reaction starts another one of the same sort, which then sets off another reaction, and so on.
Uranium	Heaviest naturally occurring element (a metal). It has numerous isotopes, where U-235 can be used for fission in nuclear power stations. So it is nuclear fuel.
Nuclear fusion	Joining to two light atomic nuclei to form a new nucleus with higher mass number (i.e. a heavier element), with the release of energy.