Modern Physics

Particle and Nuclear Physics

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The results of the α-particle scattering experiment & the existence and small size of the nucleus

Rutherford Alpha Particle Scattering Experiment

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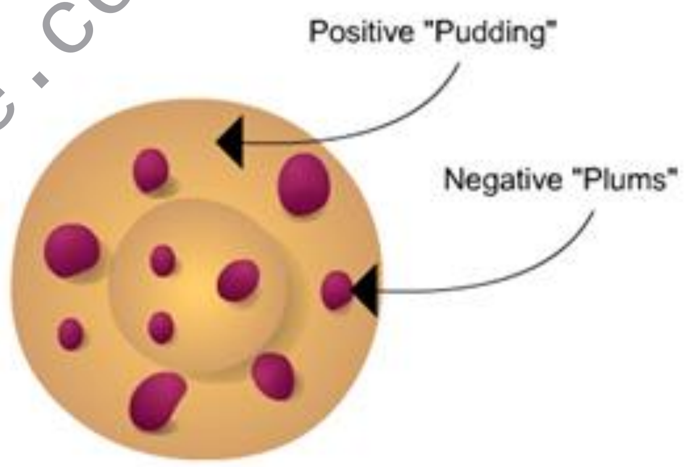
Rutherford Alpha Particle Scattering Experiment

- **Rutherford's** alpha particle scattering experiment changed the way we think of atoms.

- Before the experiment the best model of the atom was known as the Thomson or **"plum pudding"** model. The atom was believed to consist of a positive material "pudding" with negative "plums" distributed throughout.



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Rutherford Alpha Particle Scattering Experiment

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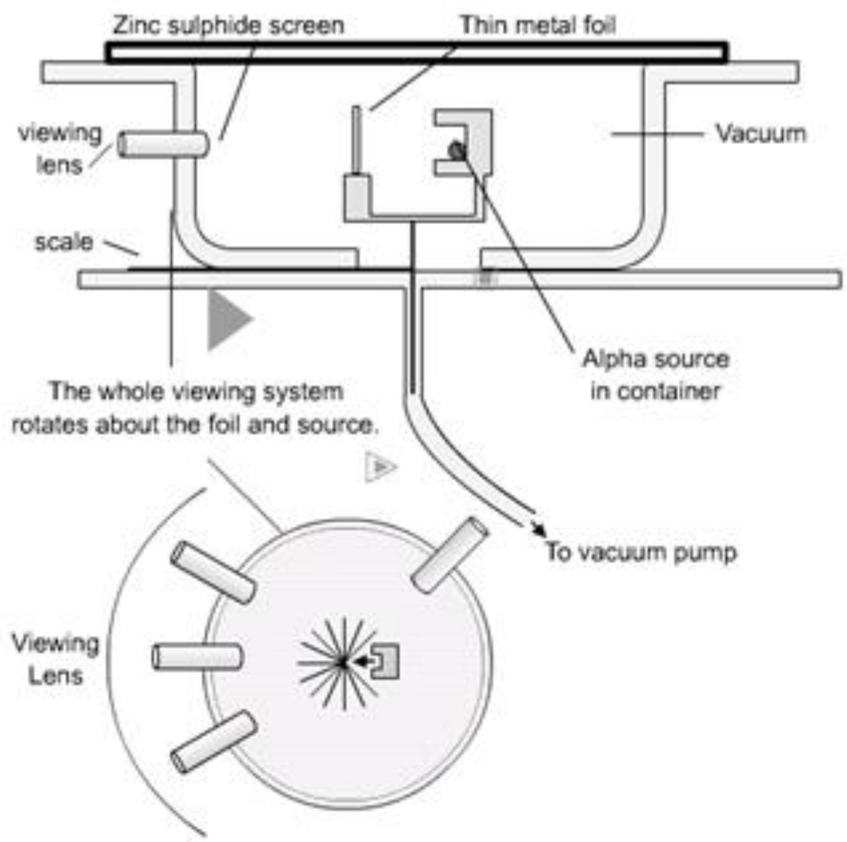

Note : Diagram is only for your reference, its not in syllabus

- Rutherford directed beams of alpha particles (which are the nuclei of helium atoms and hence positively charged) at thin gold foil to test this model and noted how the alpha particles scattered from the foil.

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Rutherford Alpha Particle Scattering Experiment

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- **Rutherford made 3 observations:**

- **Most** of the fast, highly charged alpha particles went whizzing straight through un-deflected. This was the expected result for **all** of the particles if the plum pudding model was correct.
- **Some** of the alpha particles were deflected back through large angles. This was **not** expected.
- A **very small number** of alpha particles were deflected **backwards**! This was definitely not as expected.

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Rutherford Alpha Particle Scattering Experiment

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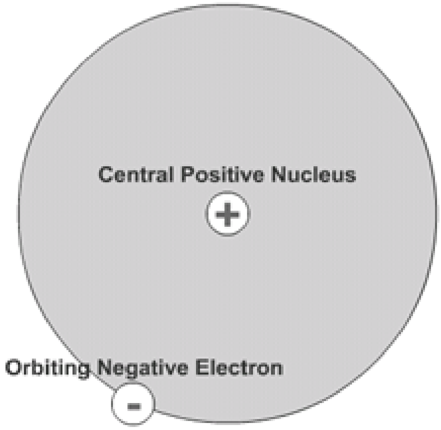
- **To explain these results a new model of the atom was needed.**



- In this model the positive material is concentrated in a small but massive (lot of mass - not size) region called the **nucleus.** The negative particles (electrons) must be around the outside preventing the atom from trespassing on its neighbours space to complete this model.
- The diagram in next slide will help you to understand the results of the experiment.

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Rutherford Alpha Particle Scattering Experiment

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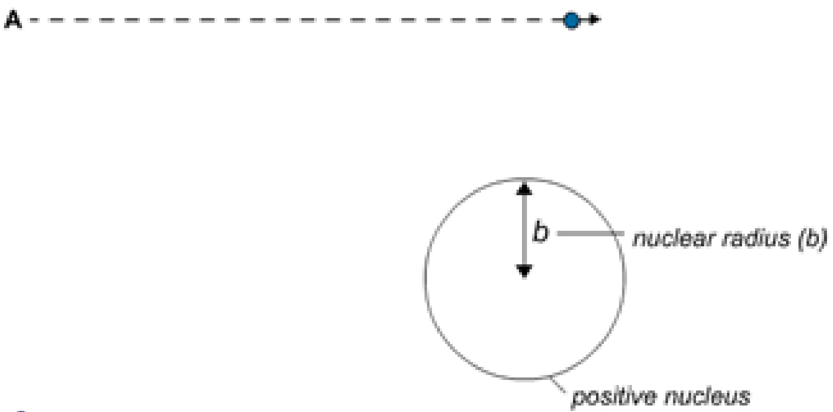
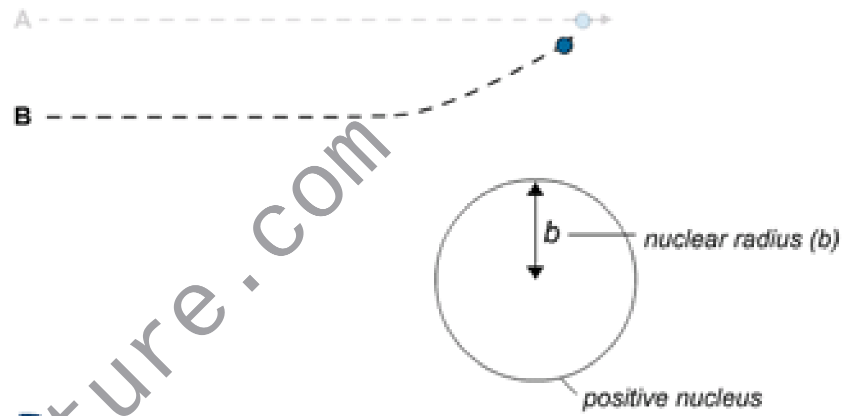
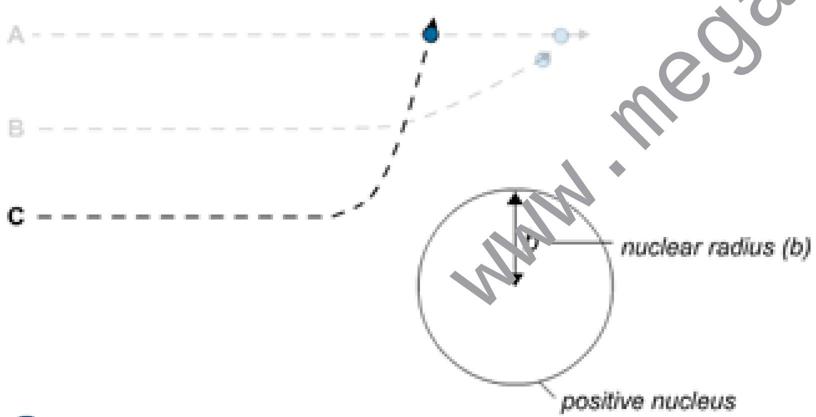


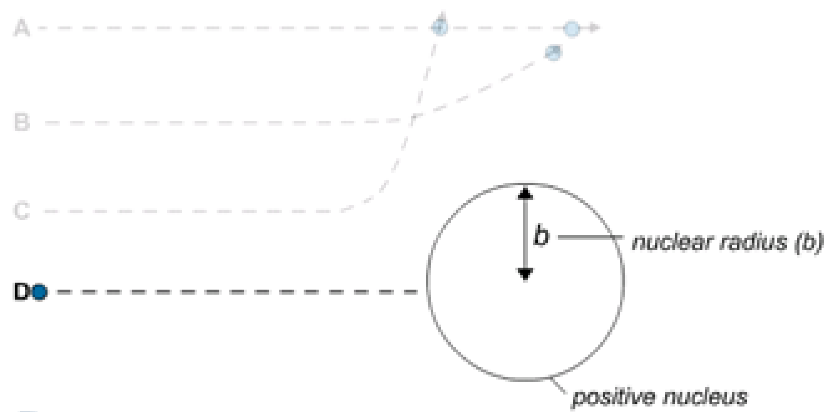
A Alpha particles this far from the nucleus experience little or no deflection as they are not close enough to the small positive nucleus.



B Here, alpha particles will be slightly deflected as they are closer to the nucleus, so you will see some scattering.



C This close to the nucleus, the alpha particles experience a large deflection, so they are scattered through large angles.



D The alpha particle has a head on collision with the nucleus so it bounces straight back

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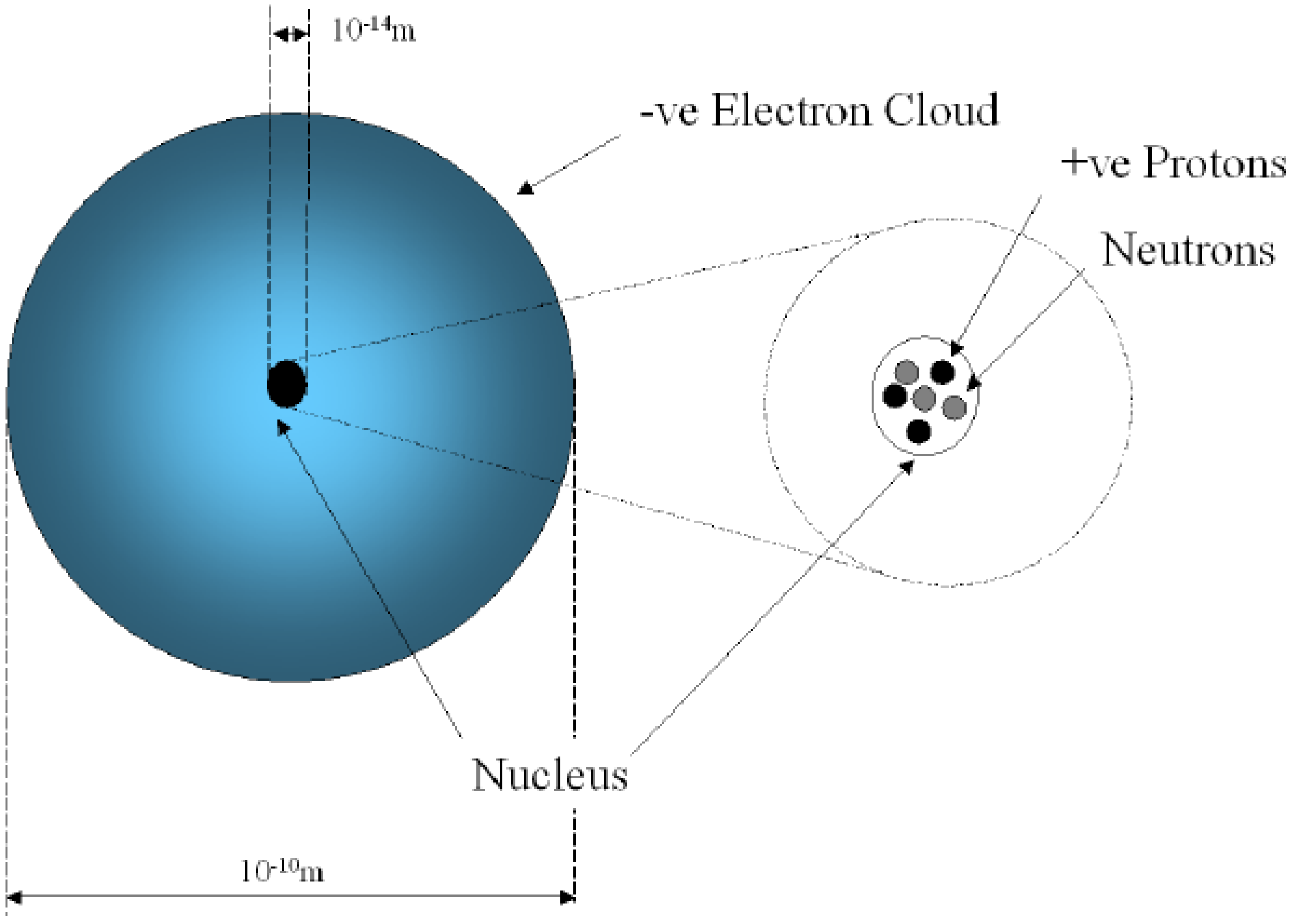
describe a simple model for the nuclear atom to include protons, neutrons and orbital electrons



	Protons	Neutrons	Electrons
Relative Mass	1	1	Negligible
Charge	+1	Neutral	-1

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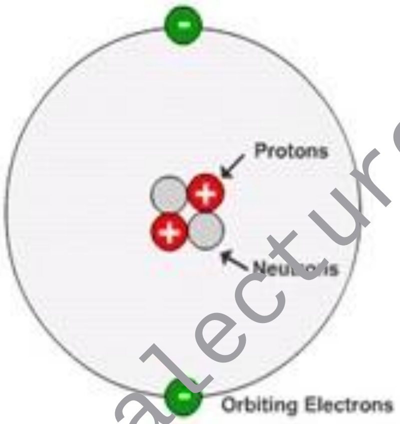
Particles in the Atom

Atoms contain 3 types of particles: protons, neutrons and electrons.



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It is important to understand that the picture above is a **model** of the atom. It conveys an impression of what the atom is like, but is not a completely true representation.

As an example of this consider the relative sizes of the nucleus and whole atom. It can be found that a typical nuclear diameter is 1×10^{-14} m while the typical atomic diameter is 1×10^{-10} m. Thus the nucleus is around 10,000 times smaller than the entire atom. You could build a model of an atom by placing a pea on the centre spot of a football stadium (to represent the nucleus) and then placing the electrons somewhere out in the stands. The picture above certainly does not reflect this fact accurately! Molecules are simply combinations of 1 or more atoms so are slightly larger than atoms themselves.

Each of these particles has a **mass** and a **charge.**

Table of masses and charges

	Mass/Kg	Charge/Coulombs
Proton	1.660×10^{-27}	1.602×10^{-19}
Neutron	1.660×10^{-27}	0
Electron	9.110×10^{-31}	1.602×10^{-19}

It is possible to simplify this information by looking for patterns in the numbers.

Firstly, notice that the electron and proton have **equal** and **opposite** charges. A new unit of charge called the **elementary charge** ($e = 1.602 \times 10^{-19}$ Coulombs) allows us to assign the values of +1e and **-**1e, to the charge of these particles.

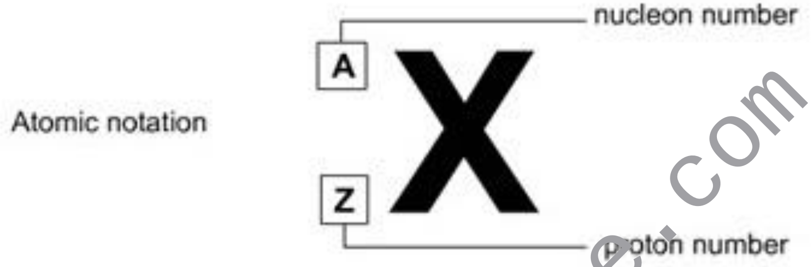
Secondly, as the mass of the proton, neutron and electron are very small a more convenient unit is the atomic mass unit ($u = 1.660 \times 10^{-27}$ kg). Using this new unit we can approximate the masses of the proton, neutron and electron to be 1u, 1u and 0 u respectively. The **relative atomic masses** of the three particles can therefore simply be stated as 1,1,0.

Table of relative masses and charges

	Relative Mass	Relative Charge
Proton	1	+1
Neutron	1	0
Electron	0	-1

Many different atoms can be built using the 3 particles described above. 91 different atoms occur naturally (the chemical elements) and many more can be found in situations where energy levels are high. It is useful to have a concise way of describing these atoms.

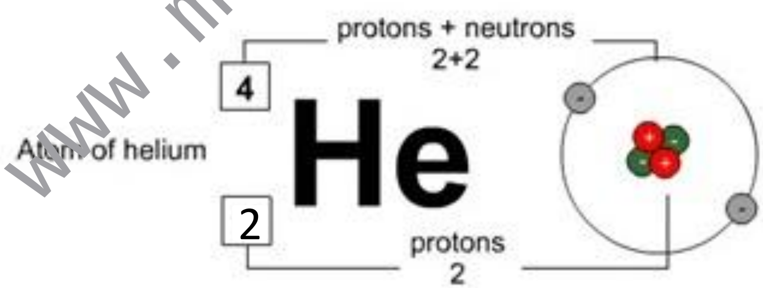
To describe the number of particles in a given atom, we use this notation:



The top number (A) is called the **nucleon number** (as it is the number of things in the nucleus of the atom) or the **mass number** (as it is the mass of the atom.)

The bottom number (Z) is called the **proton number** (as it is the number of protons) or the **atomic number** (as it is the number that tells you which element the atoms belongs to).

The letters give you a clue as to the name of the element. ***For example here is an atom of helium:***.



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How do we know about the protons and neutrons in the nucleus?

It is an established scientific fact that the atom has a small, central nucleus containing protons and neutrons. **But how did physicists gather evidence to support this view?**

The Rutherford scattering experiment proved that the nucleus was small and positive but it took a different experiment to prove the existence of the protons and neutrons within. Very high-energy electrons have enough energy to actually penetrate into the nucleus itself.

Isotopes

The **number of protons in an atom is crucial**. It gives you the charge of the nucleus and therefore it gives you the number of electrons needed for a neutral atom. And the number of electrons governs how an atom behaves and reacts chemically with other atoms. In other words, it gives you its properties. So the number of protons makes the atom belong to a particular element. **Change the number of protons and you change the element.**

The number of neutrons in the nucleus is less crucial. You can change the number of neutrons without changing the chemical properties of the atom. So it behaves in the same way. Atoms with the same proton number but different numbers of neutrons are called isotopes.

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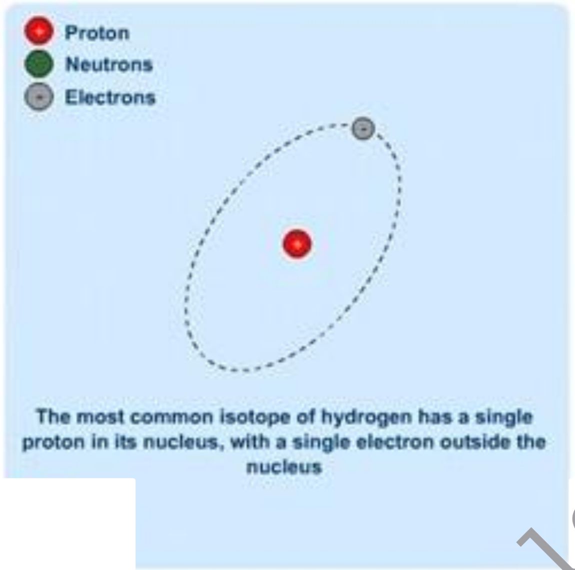
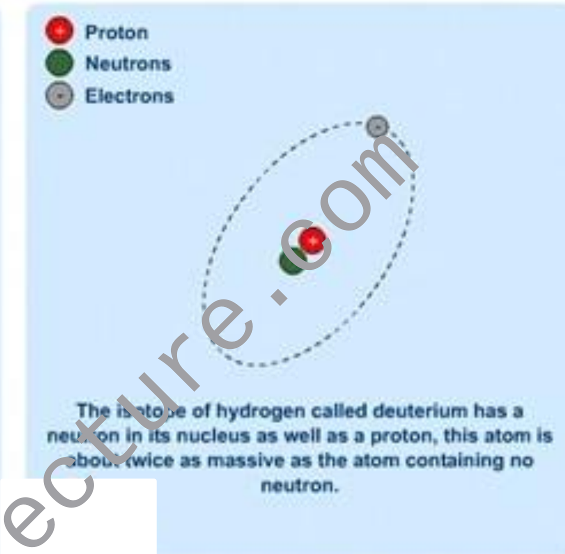
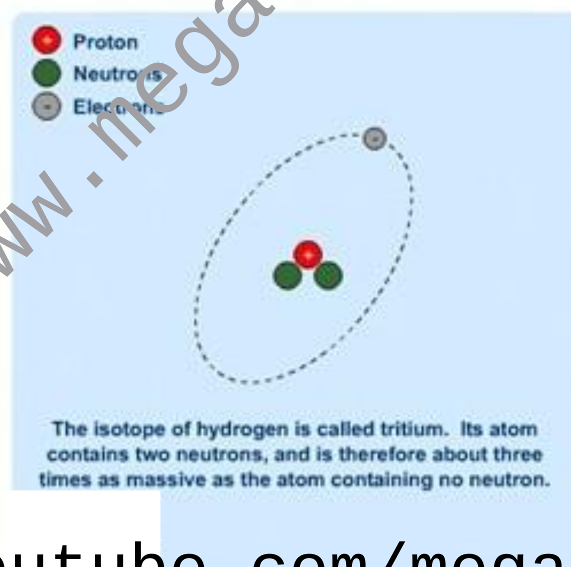
Here are the 3 isotopes of hydrogen.



The most common isotope of hydrogen has a single proton in its nucleus, with a single electron outside the nucleus



The isotope of hydrogen called deuterium has a neutron in its nucleus as well as a proton, this atom is about twice as massive as the atom containing no neutron.



The isotope of hydrogen is called tritium. Its atom contains two neutrons, and is therefore about three times as massive as the atom containing no neutron.

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Recap...

distinguish between nucleon number and proton number

Nucleon number A: The number of nucleons (Protons and Neutrons)
Proton number Z: The number of protons in the nucleus
Neutron number N: The number of neutrons in the nucleus

show an understanding that an element can exist in various isotopic forms, each with a different number of neutrons

Nuclide: An atom with a particular number of protons and neutrons
Isotope: Isotopes are nuclides that contain the same number of protons, but different numbers of neutrons.
Nucleon: Component of the nucleus = Protons and Neutrons

Decay equations

To show what happens before and after a nuclear reaction (reaction involving the nucleus of an atom) we use equations that show both the proton (Z) and nucleon number (A). To balance a nuclear equation (left side and right side) you have to make sure that the sum of the nucleon (top) numbers on the left hand side equals the sum of the nucleon numbers on the right hand side AND the sum of the proton numbers on both sides also balance.

For Example:.

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

Note : This equation is an example for balanced equation. Do not consider it for alpha emission.

Top row = 18 on both the left and right sides.

Bottom row = 9 on both the left and right sides.

This is a balanced equation.

Nuclear equations such as these are useful for explaining what happens in radioactive decay processes.

Unstable nuclei emit **alpha, beta** or **gamma** radiation in order to become more stable.

As a result of emitting this radiation the character of the nucleus remaining is changed. This is **radioactive decay**.

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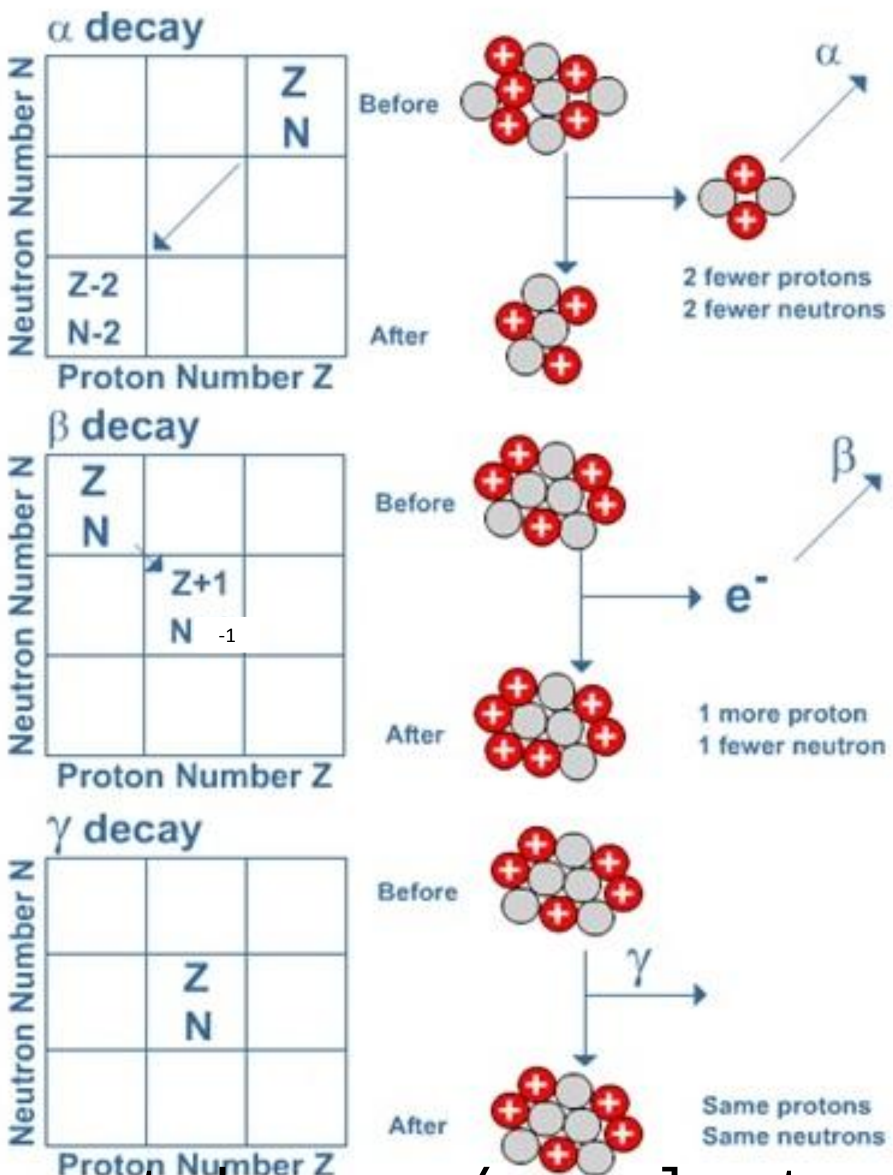
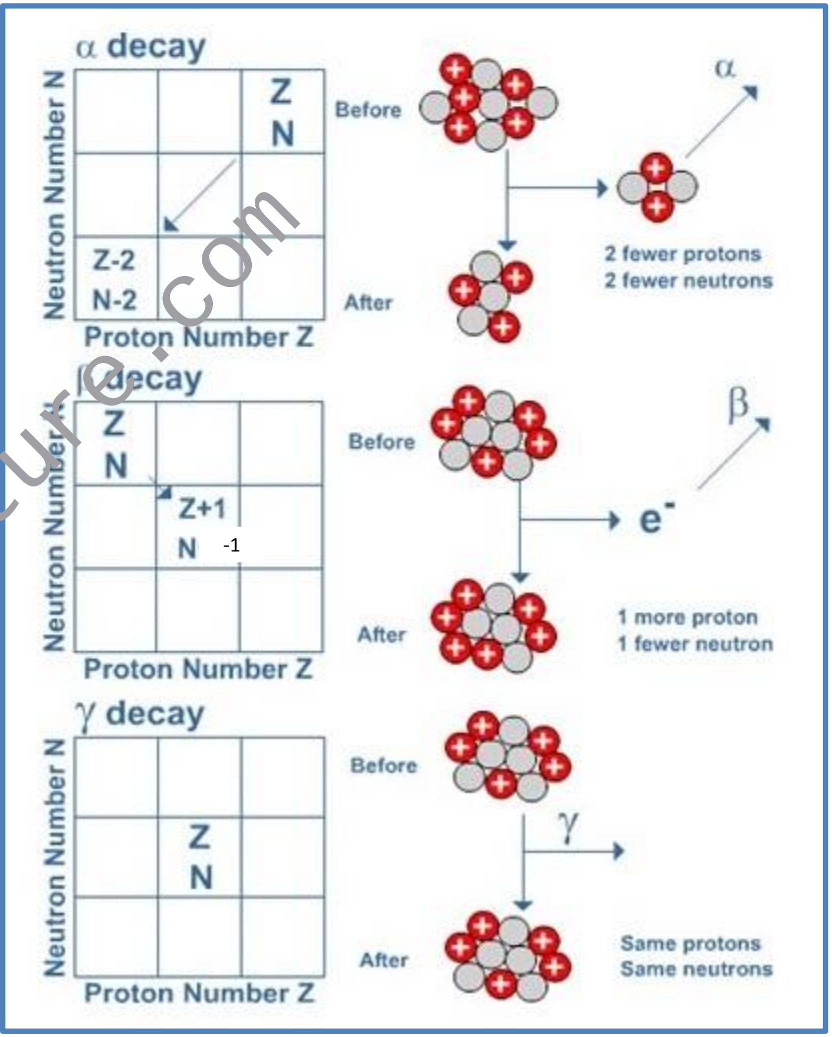
The diagrams below show what happens when a nucleus emits alpha, beta or gamma radiation.



- In alpha decay 2 protons and 2 neutrons are emitted. Notice that this reduces the nucleon number by 4 and the proton number by 2. A new element is thus formed.

- In beta decay a neutron changes into a proton (which remains in the nucleus) and an electron (which is emitted as beta radiation). The net effect is an increase in proton number by 1, while the nucleon number stays the same. Again a new element is formed.

- When a nucleus has undergone alpha or beta decay it is often left in a high-energy (**excited**) state. This energy can be lost in the form of an emitted a gamma ray. Because the composition of the nucleus is unchanged no new element is formed.



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Recap…

represent simple nuclear reactions by nuclear equations of the form

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

Alpha decay….

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

Example….

$$^{241}_{95}Am \rightarrow ^{237}_{93}Np + ^{4}_{2}\alpha$$

Beta decay

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

$$^{90}_{38}Sr \rightarrow ^{90}_{39}Y + ^{0}_{-1}\beta + \overline{\nu}$$

Gamma decay

$$^{A}_{Z}X^{*} \rightarrow ^{A}_{Z}X + ^{0}_{0}\gamma$$

In any nuclear reaction the following must *always* be true:

- The total atomic number before the reaction must be the same as the total atomic number after the reaction.
- The total atomic mass before the reaction must be the same as the total atomic mass after the reaction.

The first requirement above is the statement of the conservation of charge in nuclear reactions.
The second requirement is the statement of the conservation of nucleon number.

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Why are Some Atoms Radioactive?

Instability

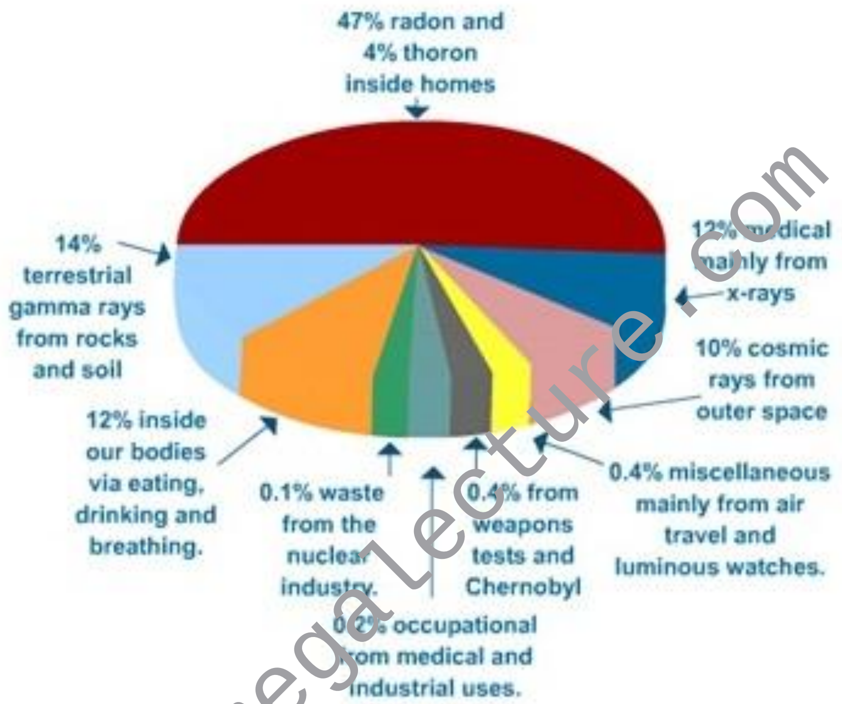
Some atoms are unstable. They have too much energy or the wrong mix of particles in the nucleus. So to make themselves more stable, they breakdown (or decay) and get rid of some matter and/or some energy. This is called radioactive decay and isotopes of atoms that do this are called **radioisotopes.**

The process is spontaneous and random. You can't do anything to speed it up or slow it down and you can't predict when it will happen. The only reason we can do any calculations on radioisotopes is because there are **huge** numbers of atoms in most samples so we can use statistics to accurately predict what's most likely to happen.

Background Radiation

A Geiger counter set up anywhere on Earth will always register a count. This is due to tiny fragments of radioactive elements present in all rocks and soil, the atmosphere and even living material. The Earth is also continuously bombarded by high-speed particles from outer space and the Sun called cosmic rays. In addition the nuclear and health industries produce small amounts of radiation each year. Collectively this radiation around us from natural and unnatural sources is called **background radiation.**

The chart shows the main sources of background radiation.



When carrying out practical work involving count-rates from radioactive sources, allowance should be made for this background radiation. This can usually be done effectively by measuring the background count in the laboratory for several minutes, and subtracting the appropriate amount from subsequent readings taken with the source.

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What is ionising radiation?

Alpha, beta and gamma

Ionising radiation comes in three varieties:

α (alpha) particles

β (beta) particles

γ (gamma) rays.

All of these forms of radiation are energetic enough to pull electrons away from atoms. The atoms that have had electrons removed in this way are now charged particles, or **ions**, and hence the name **ionising radiation.**

The fact that these radiations are ionising allows them to be detected and discriminated from other forms of radiation (such as infra-red or radiowaves). Detectors such as ionisation chambers, Geiger-Muller tubes and cloud chambers all rely on the ionising properties of these radiations to produce measurable effects.

Properties of alpha, beta and gamma radiation

Alpha Particles.

Alpha particles are strongly ionising but can be stopped by paper or skin. They have a strong positive charge (+2) and a mass of 4 (i.e. 4 times the mass of a proton)

An alpha particle is in fact the same as a helium nucleus - 2 protons and 2 neutrons.

Beta particles.

Beta particles are electrons - but they are called beta particles to identify that they came from the nucleus of the atom.

How do you get an electron from the nucleus? A neutron splits up and becomes a proton and an electron. The proton remains behind in the nucleus, the electron is emitted.

Beta particles are also strongly ionising (perhaps 1 beta particle will cause 100 ionisations).

Gamma Rays.

Gamma rays are very poor at ionising (about 1 to 1) but they are very difficult to stop (they are very penetrating). As they are not good ionisers, they are less dangerous to life.

They are in fact pure energy (at the shortest wavelength end of the E-M spectrum) and gamma emission accompanies most emissions of beta or alpha particles.

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Recap….

show an understanding of the nature and properties of α-, β- and γ- radiations (β+ is not included: β- radiation will be taken to refer to β–)

Property	Alpha	Beta	Gamma
Description	Helium nuclei	Electron from the nucleus	Electromagnetic radiation
~Ionising power	High	Medium	Low
Penetration (absorbed by)	Low (paper)	Medium (5mm Al)	High (Thick lead)
Charge	+ve	-ve	None

Fundamental particles?

Chemistry is very complicated because there are literally billions of different molecules that can exist. The discovery of the Periodic Table simplified things because it suggested that there were roughly 92 different elements whose atoms could be arranged to make these various molecules. The idea that atoms are made up of just three types of particle (protons, neutrons and electrons) seemed to simplify things still more, and scientists were very happy with it because it seemed to provide a very simple explanation of a complex world. Protons, neutrons and electrons were thought of as fundamental particles, which could not be subdivided further.

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However, in the middle decades of the 20th century, physicists discovered many other particles that did not fit this pattern. They gave them names such as pions, kaons, muons, etc., using up most of the letters of the Greek alphabet.

These new particles were found in two ways:

- by looking at cosmic rays, which are particles that arrive at the Earth from outer space
- by looking at the particles produced by high-energy collisions in particle accelerators (Figure 16.9).

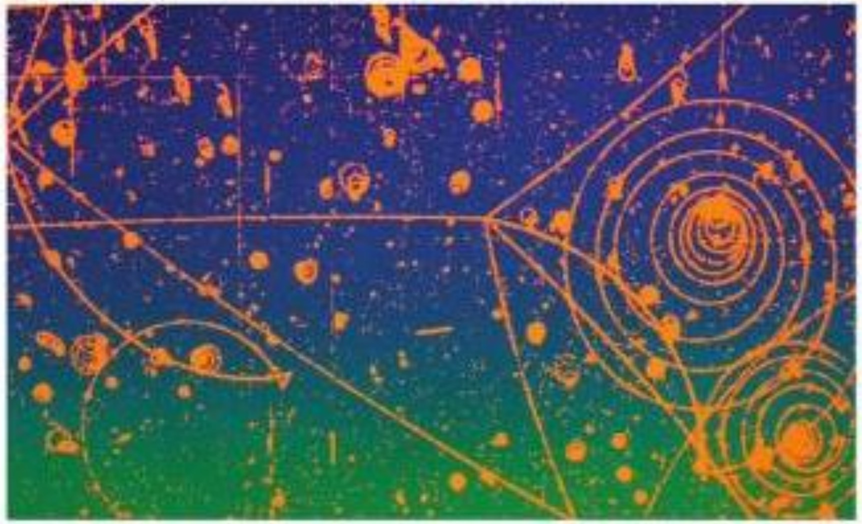

Figure 16.9 Particle tracks in a bubble chamber detector. A particle has entered from the left and then struck another particle just to the right of the centre. Four new particles fly out from the point of impact.

The discovery of new particles with masses different from those of protons, neutrons and electrons suggested that these were not fundamental particles. Various attempts were made to tidy up this very confusing picture.

In principle, we can never know for certain whether a particle such as the electron is truly fundamental; the possibility will always remain that a physicist will discover some deeper underlying structure.

Families of particles

Today, sub-atomic particles are divided into two families:

- **Hadrons** such as protons and neutrons. These are all particles that are affected by the strong nuclear force.
- **Leptons** such as electrons. These are particles that are unaffected by the strong nuclear force.

The word 'hadron' comes from a Greek word meaning 'bulky', while 'lepton' means 'light' (in mass). It is certainly true that protons and neutrons are bulky compared to electrons.

At the Large Hadron Collider (Figure 16.10) at the CERN laboratory in Geneva, physicists are experimenting with hadrons in the hope of finding answers to some

Figure 16.10 Particle accelerators have become bigger and bigger as scientists have sought to look further and further into the fundamental nature of matter. This is one of the particle detectors of the Large Hadron Collider (LHC) as it was about to be installed. The entire collider is 27 km in circumference.

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fundamental questions about this family of particles. In 2013, they announced the discovery of the Higgs boson, a particle which was predicted 50 years earlier and which is required to explain why matter has mass.

Inside hadrons

To sort out the complicated picture of the hadron family of particles, Murray Gell-Mann in 1964 proposed a new model. He suggested that they were made up of just a few different particles, which he called quarks.

Figure 16.11 shows icons used to represent three quarks, together with the corresponding antiquarks. These are called the up (u), down (d) and strange (s) quarks. Gell-Mann's idea was that there are two types of hadron: baryons, made up of three quarks, and mesons, made up of two quarks. In either case, the quarks are held together by the strong nuclear force. For example:

- A proton is made up of two up quarks and a down quark; proton = (uud).
- A neutron is made up of one up quark and two down quarks; neutron = (udd).
- A pi^+ meson is made up of an up quark and a down antiquark; pi^+ meson = $(u\bar{d})$.
- A phi meson is made up of a strange quark and an antistrange quark; phi meson = $(s\bar{s})$.

Antiquarks are shown with a 'bar' on top of the letter for the quark. Antiquarks are needed to account for the existence of antimatter. This is matter that is made of antiparticles; when a particle meets its antiparticle, they annihilate each other, leaving only photons of energy.

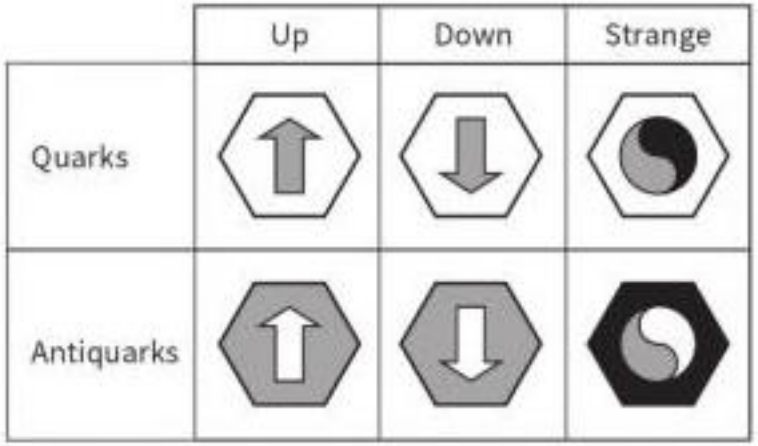

Figure 16.11 Icons representing three 'flavours' of quark, up, down and strange, and their antiquarks.

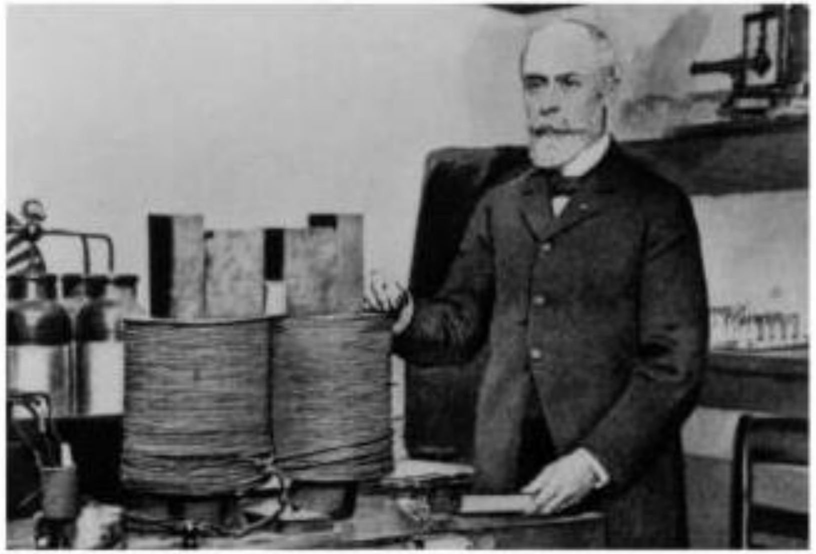

Figure 16.12 Henri Becquerel, the discoverer of radioactivity, in his laboratory. His father and grandfather had been professors of physics in Paris before him.

Discovering radioactivity

The French physicist Henri Becquerel (Figure 16.12) is credited with the discovery of radioactivity in 1896. He had been looking at the properties of uranium compounds when he noticed that they affected photographic film – he realised that they were giving out radiation all the time and he performed several ingenious experiments to shed light on the phenomenon.

Radiation from radioactive substances

There are three types of radiation which are emitted by radioactive substances: alpha (α), beta (β) and gamma (γ) radiations come from the unstable nuclei of atoms. Nuclei consist of protons and neutrons, and if the balance between these two types of particles is too far to one side, the nucleus may emit α- or β-radiation as a way of achieving greater stability. Gamma-radiation is usually emitted after α or β decay, to release excess energy from the nuclei.

In fact, there are two types of β-radiation. The more familiar is beta-minus (β^-) radiation, which is simply an electron, with negative charge of $-e$. However, there are also many unstable nuclei that emit beta-plus (β^+) radiation. This radiation is in the form of positrons, similar to electrons in terms of mass but with positive charge of $+e$. Positrons are a form of **antimatter**. When a positron collides with an electron, they annihilate each other. Their mass is converted into electromagnetic energy in the form of two gamma photons (Figure 16.13).

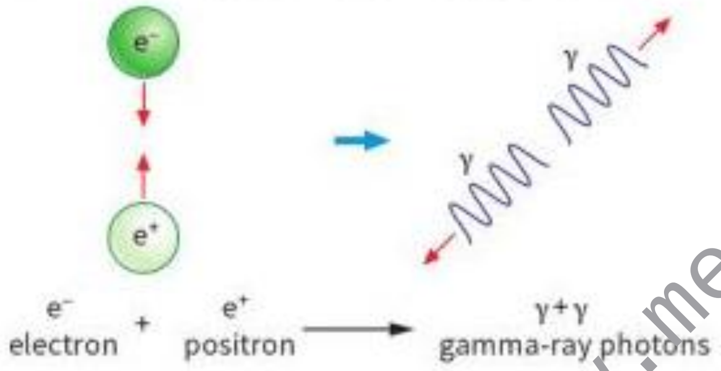

Figure 16.13 Energy is released in the annihilation of matter and antimatter.

Table 16.4 shows the basic characteristics of the different types of radiation. The masses are given relative to the mass of a proton; charge is measured in units of e, the elementary charge.

Radiation	Symbol	Mass (relative to proton)	Charge	Typical speed
α-particle	α, ^4_2He	4	+2e	'slow' ($10^6\ m\ s^{-1}$)
β^--particle	β, β^-, e, $^{0}_{-1}e$	$\frac{1}{1840}$	−e	'fast' ($10^8\ m\ s^{-1}$)
β^+-particle	β, β^+, e^+, $^{0}_{+1}e$	$\frac{1}{1840}$	+e	'fast' ($10^8\ m\ s^{-1}$)
γ-ray	γ	0	0	speed of light ($3 \times 10^8\ m\ s^{-1}$)

Table 16.4 The basic characteristics of ionising radiations.

Note the following points:

- α- and β-radiation are particles of matter. A γ-ray is a photon of electromagnetic radiation, similar to an X-ray. (X-rays are produced when electrons are decelerated; γ-rays are produced in nuclear reactions.)
- An α-particle consists of two protons and two neutrons; it is a nucleus of helium-4. A β^--particle is simply an electron and a β^+-particle is a positron.
- The mass of an α-particle is nearly 10 000 times that of an electron and it travels at roughly one-hundredth of the speed of an electron.

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Discovering neutrinos

There is a further type of particle which we need to consider. These are the neutrinos. When β decay was first studied, it was realised that β-particles were electrons coming from the **nucleus** of an atom. There are no electrons in the nucleus (they 'orbit' outside the nucleus), so the process was pictured as the decay of a neutron to give a proton and an electron.

It was noticed that β-particles were emitted with a **range** of speeds – some travelled more slowly than others. It was deduced that some other particle must be carrying off some of the energy and momentum released in the decay. This particle is now known as the **antineutrino** (or, more correctly, the electron antineutrino), with symbol $\bar{\nu}$. The decay equation for β^- decay is written as:

beta-minus (β^-) decay: $^1_0\text{n} \rightarrow {}^1_1\text{p} + {}^{\ 0}_{-1}\text{e} + \bar{\nu}$

Neutrinos are bizarre particles. They have very little mass (much less than an electron) and no electric charge, which makes them very difficult to detect. The Austrian physicist Wolfgang Pauli predicted their existence in 1930, long before they were first detected in 1956.

In β^+ decay, a proton decays to become a neutron and an **electron neutrino** (symbol ν) is released:

beta-plus (β^+) decay: $^1_1\text{p} \rightarrow {}^1_0\text{n} + {}^{\ 0}_{+1}\text{e} + \nu$

The two equations highlighted above show two important features of radioactive decay. Firstly, nucleon number *A* is conserved; that is, there are as many nucleons after the decay as there were before. In β^- decay, a neutron has become a proton so that the total number of nucleons is unchanged. In β^+ decay, a proton becomes a neutron, so again *A* is conserved.

Secondly, proton number *Z* is also conserved. In β^- decay, we start with a neutron ($Z = 0$). After the decay, we have a proton ($Z = +1$) and a β^- particle ($Z = -1$). Together these have $Z = 1 - 1 = 0$. Since *Z* tells us about the charge of each particle, we would be surprised if we had a different amount of charge after the decay than before the decay. A similar analysis shows that *Z* is conserved in β^+ decay.

Do these conservation laws apply to α decay? Here is an equation that represents a typical α decay:

$$^{222}_{86}\text{Rn} \rightarrow {}^{218}_{84}\text{Po} + {}^4_2\text{He}$$

In α decay, an alpha particle (two protons and two neutrons) is emitted by a nucleus. Although these nucleons are now outside the nucleus, the equation shows that there is the same number of nucleons after the decay (218 + 4) as before the decay (222). So nucleon number A is conserved. Similarly, proton number Z is conserved (84 + 2 = 86).

The conservation of nucleon number and proton number are important laws in nuclear physics. They apply to all nuclear changes, not just to α and β decay.

There is a third quantity that is conserved. You might expect mass to be conserved, but this is not so. For example, in the α decay equation given above, the combined mass of the polonium nucleus and the alpha particle is slightly less than that of the original radon nucleus. The 'lost' mass has become energy – this is where the fast-moving alpha particle gets its kinetic energy. The relationship between mass m and energy E is given by Einstein's equation $E = mc^2$, where c is the speed of light in free space. So, instead of saying that mass is conserved in nuclear processes, we have to say that mass–energy is conserved.

Fundamental families

Electrons and neutrinos both belong to the family of fundamental particles called **leptons**. These are particles that do not feel the strong nuclear force. Recall that particles that experience the strong force are hadrons, and that these are made up of fundamental particles called quarks.

So we have two families of fundamental particles, quarks and leptons. How can we understand β decay in terms of these particles?

Consider first β^- decay, in which a neutron decays. A neutron consists of three quarks (up, down, down or u d d). It decays to become a proton (u u d). Comparing these shows that one of the down quarks has become an up quark. In the process, it emits a β-particle and an antineutrino:

$$d \rightarrow u + {}^{0}_{-1}e + \bar{\nu}$$

In β^+ decay, a proton decays to become a neutron. In this case, an up quark becomes a down quark:

$$u \rightarrow d + {}^{0}_{+1}e + \nu$$

Fundamental forces

The nucleus is held together by the strong nuclear force, acting against the repulsive electrostatic or Coulomb force between protons. This force explains α decay, when a positively charged α-particle flies out of the nucleus, leaving it with less positive charge.

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However, the strong force cannot explain β decay. Instead, we have to take account of a further force within the nucleus, the weak interaction, also known as the weak nuclear force. This is a force that acts on both quarks and leptons. The weak interaction is responsible for β decay.

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