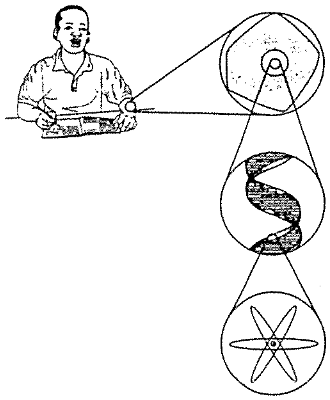
Atomic structure 1

INTRODUCTION

All matter that surrounds us, living or otherwise, is made up of different combinations of atoms. There are only a hundred, or so, different types of atoms present in nature. Atoms of a single type form an element. Each of these elements has a name and a chemical symbol e.g. hydrogen, the simplest of all the elements, has the chemical symbol H. Oxygen has the chemical symbol O. The combination of two hydrogen atoms with one oxygen atom is called a water molecule – H_2O. The full list of elements is shown in a periodic table. Atoms consist of a combination of three things: protons, neutrons and electrons.

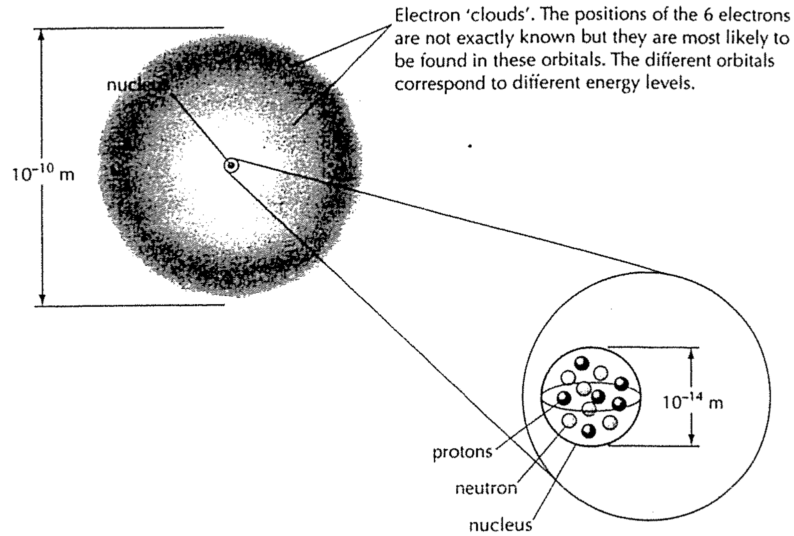


In the basic atomic model, we are made up of protons, neutrons, and electrons – nothing more.

ATOMIC MODEL

The basic atomic model, known as the nuclear model, was developed during the last century and describes a very small central nucleus surrounded by electrons arranged in different energy levels. The nucleus itself contains protons and neutrons (collectively called **nucleons**). All of the positive charge and almost all the mass of the atom is in the nucleus. The electrons provide only a tiny bit of the mass but all of the negative charge. Overall an atom is neutral. The vast majority of the volume is nothing at all – a vacuum. The nuclear model of the atom seems so strange that there must be good evidence to support it.

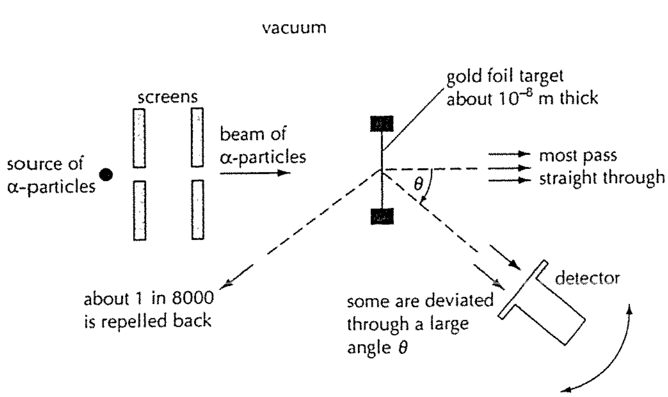
	Protons	Neutrons	Electrons
Relative mass	1	1	Negligible
Charge	+ 1	Neutral	– 1



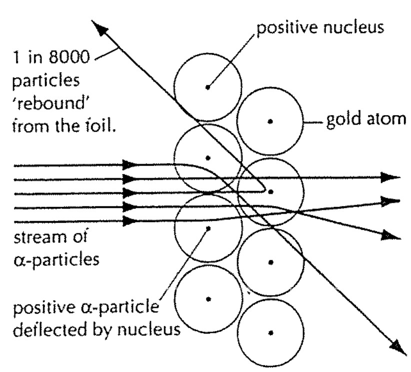
Atomic model of carbon

EVIDENCE

One of the most convincing pieces of evidence for the nuclear model of the atom comes from the Geiger-Marsden experiment. Positive alpha particles were "fired" at a thin gold leaf. The relative size and velocity of the alpha particles meant that most of them were expected to travel straight through the gold leaf. The idea behind this experiment was to see if there was any detectable structure within the gold atoms. The amazing discovery was that some of the alpha particles were deflected through huge angles. The mathematics of the experiment showed that numbers being deflected at any given angle agreed with an inverse square law of repulsion from the nucleus. Evidence for electron energy levels comes from emission and absorption spectra. The existence of isotopes provides evidence for neutrons.



Geiger and Marsden's experiment

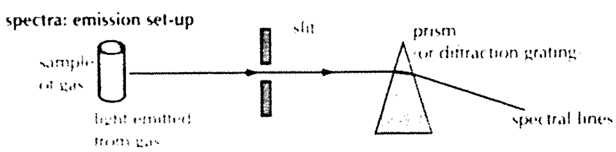


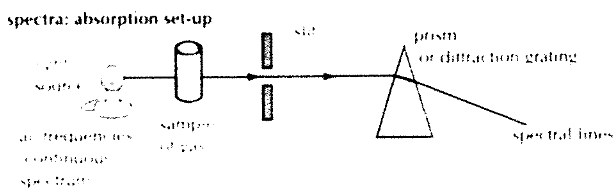
Atomic explanation of Geiger and Marsden's experiment

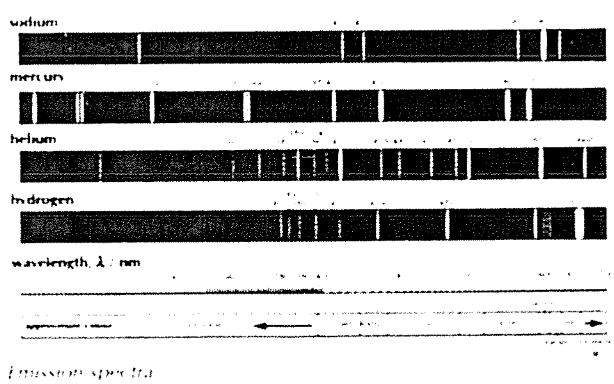
Atomic structure 2 – Emission and absorption spectra

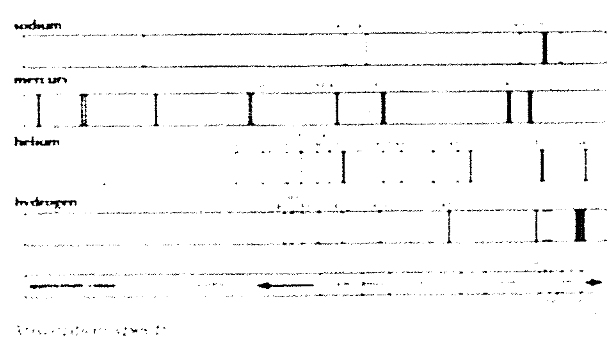
EMISSION SPECTRA AND ABSORPTION SPECTRA

When an element is given enough energy it emits light. This light can be analysed by splitting it into its various colours (or frequencies) using a prism or a diffraction grating. If all possible frequencies of light were present, this would be called a **continuous spectrum** (see optics section – option H). The light an element emits, its **emission spectrum**, is not continuous, but contains only a few characteristic colours. The frequencies emitted are particular to the element in question. For example, the yellow-orange light from a street lamp is often a sign that the element sodium is present in the lamp. Exactly the same particular frequencies are **absent** if a continuous spectrum of light is shone through an element when it is in gaseous form. This is called an **absorption** spectrum.





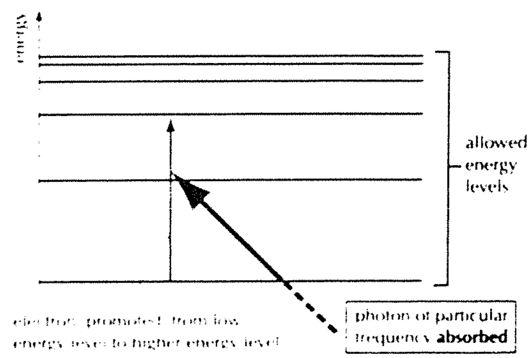


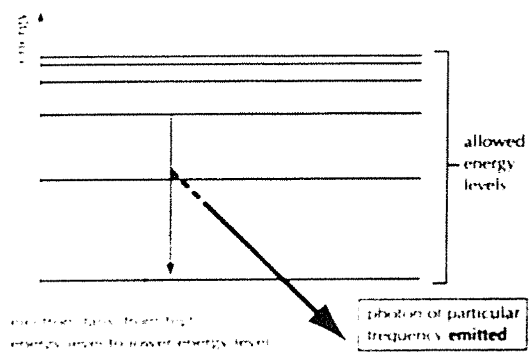


EXPLANATION OF ATOMIC SPECTRA

In an atom, electrons are bound to the nucleus. This means that they cannot "escape" without the input of energy. If enough energy is put in, an electron can leave the atom. If this happens, the atom is now positive overall and is said to be ionised. Electrons can only occupy given energy levels – the energy of the electron is said to be **quantized**. These energy levels are fixed for particular elements and correspond to "allowed" obitals. The reason why only these energies are "allowed" forms a significant part of quantum theory (see HL topic 12).

When an electron moves between energy levels it must emit or absorb energy. The energy emitted or absorbed corresponds to the difference between the two allowed energy levels. This energy is emitted or absorbed as "packets" of light called photons (for more information, see option H). A higher energy photon corresponds to a higher frequency (shorter wavelength) of light. Thus the frequency of the light, emitted or absorbed, is fixed by the energy difference between the levels. Since the energy levels are unique to a given element, this means that the emission (and the absorption) spectrum will also be unique.



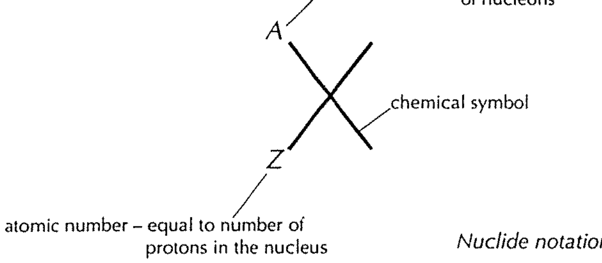


Nuclear structure

ISOTOPES

When a chemical reaction takes place, it involves the outer electrons of the atoms concerned. Different elements have different chemical properties because the arrangement of outer electrons varies from element to element. The chemical properties of a particular element are fixed by the amount of positive charge that exists in the nucleus – in other words, the number of protons. In general, different nuclear structures will imply different chemical properties. A **nuclide** is the name given to a particular species of atom (one whose nucleus contains a specified number of protons and a specified number of neutrons). Some nuclides are the same element – they have the same chemical properties and contain the same number of protons. These nuclides are called **isotopes** – they contain the same number of protons but different numbers of neutrons.

NOTATION



Nuclide notation

EXAMPLES

	Notation	Description	Comment
1	$^{12}_{6}C$	carbon-12	isotope of **2**
2	$^{13}_{6}C$	carbon-13	isotope of **1**
3	$^{238}_{92}U$	uranium-238	
4	$^{198}_{78}Pt$	platinum-198	same mass number as **5**
5	$^{198}_{80}Hg$	mercury-198	same mass number as **4**

Each element has a unique chemical symbol and its own atomic number. *No.1* and *No.2* are examples of two isotopes, whereas *No.4* and *No.5* are not.

In general, when physicists use this notation they are concerned with the nucleus rather than the whole atom. Chemists use the same notation but tend to include the overall charge on the atom. Thus $^{12}_{6}C$ can represent the carbon nucleus to a physicist or the carbon atom to a chemist depending on the context. If the charge is present the situation becomes unambiguous. $^{35}_{17}Cl^{-}$ must refer to a chlorine ion – an atom that has gained one extra electron.

STRONG NUCLEAR FORCE

The protons in a nucleus are all positive. Since like charges repel, they must be repelling one another all the time. This means there must be another force keeping the nucleus together. Without it the nucleus would "fly apart". We know a few things about this force.

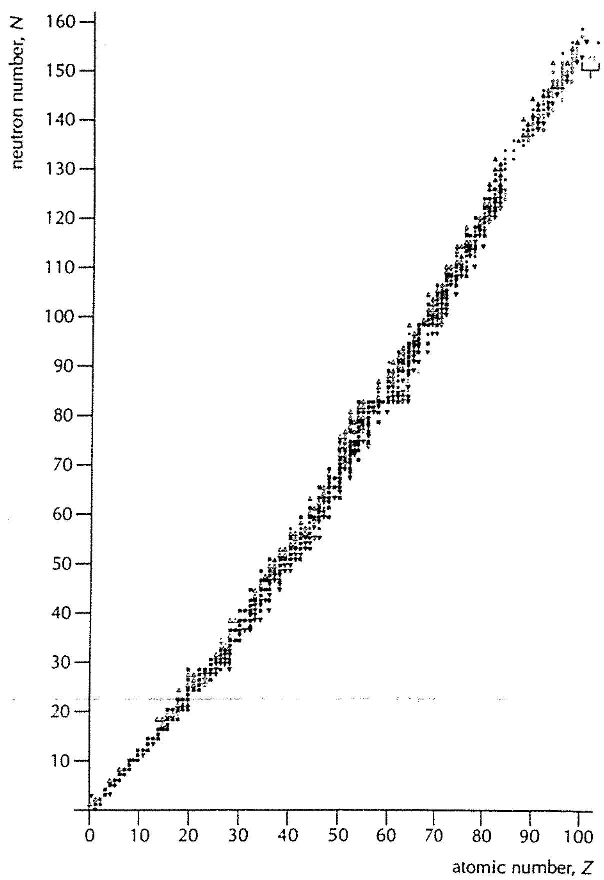
- It must be strong. If the proton repulsions are calculated it is clear that the gravitational attraction between the nucleons is far too small to be able to keep the nucleus together.
- It must be very short-ranged as we do not observe this force anywhere other than inside the nucleus.
- It is likely to involve the neutrons as well. Small nuclei tend to have equal numbers of protons and neutrons. Large nuclei need proportionately more neutrons in order to keep the nucleus together.

The name given to this force is the **strong nuclear force**.

NUCLEAR STABILITY

Many atomic nuclei are unstable. The stability of a particular nuclide depends greatly on the numbers of neutrons present. The graph below shows the stable nuclides that exist.

- For small nuclei, the number of neutrons tends to equal the number of protons.
- For large nuclei there are more neutrons than protons.
- Nuclides above the band of stability have "too many neutrons" and will tend to decay with either alpha or beta decay. (see page 51)
- Nuclides below the band of stability have "too few neutrons" and will tend to emit positrons. (see page 54)



Key

N number of neutrons

Z number of protons

■ naturally occurring stable nuclide

● naturally occurring α-emitting nuclide

○ artificially produced α-emitting nuclide

▲ naturally occurring β^{-}-emitting nuclide

△ artificially produced β^{+}-emitting nuclide

▽ artificially produced β^{-}-emitting nuclide

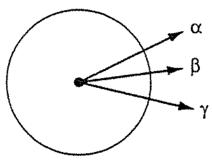
▼ artificially produced electron-capturing nuclide

▼ artificial nuclide decaying by spontaneous fission

Radioactivity

IONISING PROPERTIES

Many atomic nuclei are unstable. The process by which they decay is called **radioactive decay**. Every decay involves the emission of one of three different possible radiations from the nucleus: alpha (α), beta (β) or gamma. (γ). (see also page 54)



Alpha, beta and gamma all come from the nucleus

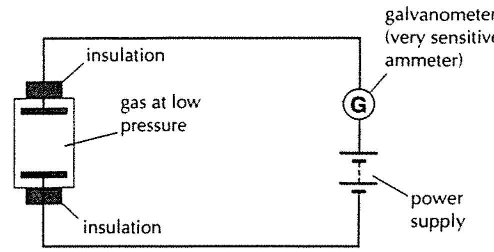
All three radiations are ionising. This means that as they go through a substance, collisions occur which cause electrons to be removed from atoms. Atoms that have lost or gained electrons are called ions. This ionising property allows the radiations to be detected. It also explains their dangerous nature. When ionisations occur in biologically important molecules, such as DNA, mutations can occur.

DETECTION

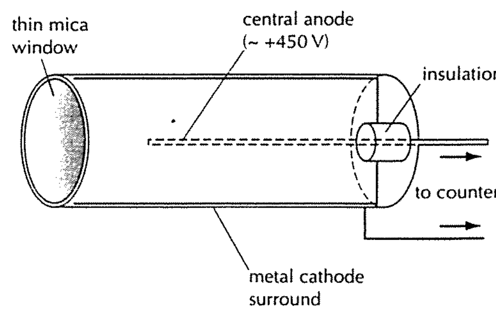
The ionisation chamber and the Geiger-Muller tube ("Geiger counter") can be used to count the number of ionising radiations that enter these detection devices.

They are similar in principle. When radiation enters the chamber it ionises gas molecules. The voltage causes the ions to accelerate towards the electrodes and an electrical pulse passes through the circuit. The number of pulses that arrive per second is a measure of the rate at which ionising radiation is entering the chamber.

ionization chamber



Geiger–Müller tube



Detection devices

PROPERTIES OF ALPHA, BETA, GAMMA

Property	Alpha, α	Beta, β	Gamma, γ
Effect on photographic film	Yes	Yes	Yes
Approximate number of ion-pairs produced in air	10^4 per mm	10^2 per mm	1 per mm
Typical material needed to absorbed it	10^{-2} mm Aluminium piece of paper	A few mm Aluminium	10 cm lead
Penetration ability	Low	Medium	High
Typical path length in air	A few cm	Less than one m	Effectively infinite
Deflection by magnetic and electric fields	Behaves like a positive charge	Behaves like a negative charge	Not deflected
Speed	About 10^7 m s^{-1}	About 10^8 m s^{-1}, very variable	3×10^8 m s^{-1}

NATURE OF ALPHA, BETA AND GAMMA DECAY

When a nucleus decays the mass numbers and the atomic numbers must balance on each side of the nuclear equation.

- Alpha particles are helium nuclei, ${}^{4}_{2}\alpha$ or ${}^{4}_{2}He^{2+}$. In alpha decay, a "chunk" of the nucleus is emitted. The portion that remains will be a different nuclide.

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

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

The atomic numbers and the mass numbers balance on each side of the equation.

(95 = 93 + 2 and 241 = 237 +4)

- Beta particles are electrons, ${}^{0}_{-1}\beta$ or ${}^{0}_{-1}e^{-}$, emitted **from the nucleus**. The explanation is that the electron is formed when a neutron decays. At the same time, another particle is emitted called an antineutrino.

$$ {}^{1}_{0}n \rightarrow {}^{1}_{1}P + {}^{0}_{-1}\beta + \bar{\nu} $$

Since an antineutrino has no charge and virtually no mass it does not affect the equation and so is sometimes ignored. See page 86 for more details.

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

$$ \text{e.g. } {}^{90}_{38}Sr \rightarrow {}^{90}_{90}Y + {}^{0}_{-1}\beta + \bar{\nu} $$

- Gamma rays are unlike the other two radiations in that they are part of the electromagnetic spectrum. After their emission, the nucleus has less energy but its mass number and its atomic number have not changed. It is said to have changed from an **excited state** to a lower energy state.

$$ \underbrace{{}^{A}_{Z}X^{*}}_{\text{Excited state}} \rightarrow \underbrace{{}^{A}_{Z}X}_{\text{Lower energy state}} + {}^{0}_{0}\gamma $$

Half-life

RANDOM DECAY

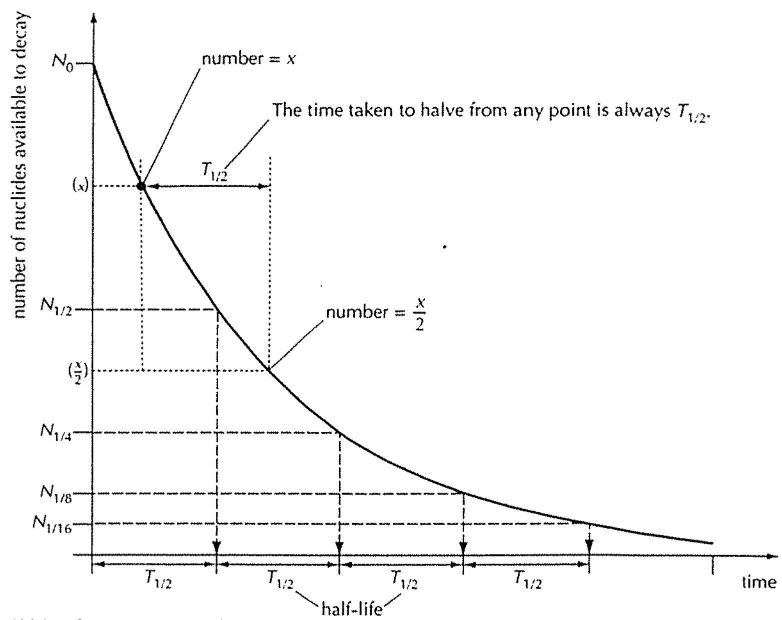
Radioactive decay is a **random** process and is not affected by external conditions. For example, increasing the temperature of a sample of radioactive material does not affect the rate of decay. This means that is there no way of knowing whether or not a particular nucleus is going to decay within a certain period of time. All we know is the *chances* of a decay happening in that time.

Although the process is random, the large numbers of atoms involved allows us to make some accurate predictions. If we start with a given number of atoms then we can expect a certain number to decay in the next minute. If there were more atoms in the sample, we would expect the number decaying to be larger. On average the rate of decay of a sample is proportional to the number of atoms in the sample. This proportionality means that radioactive decay is an **exponential** process. The number of atoms of a certain element, N, decreases exponentially over time. Mathematically this is expressed as:

$$\frac{dN}{dt} \propto -N$$

HALF-LIFE

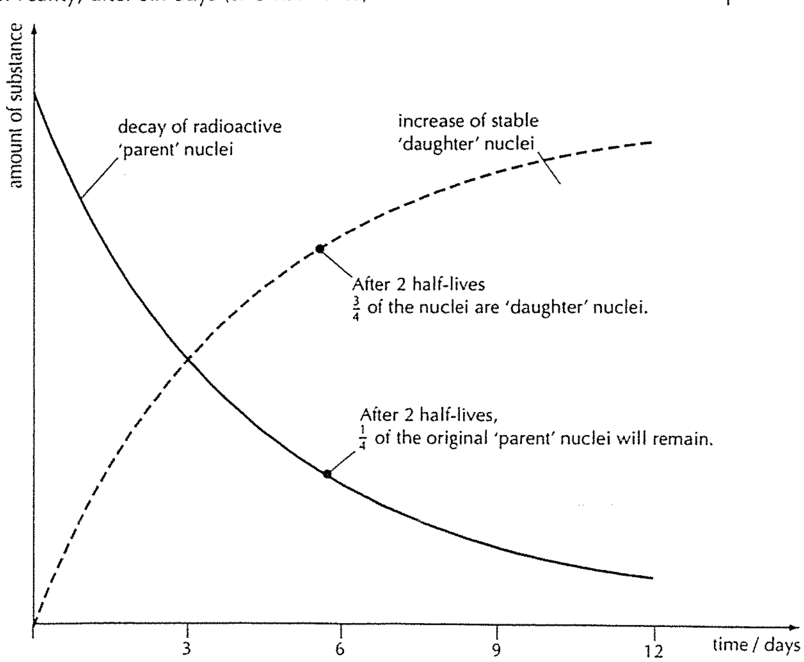
There is a temptation to think that every quantity that decreases with time is an exponential decrease, but exponential curves have a particular mathematical property. In the graph shown below, the time taken for half the number of nuclides to decay is always the same, whatever starting value we choose. This allows us to express the chances of decay happening in a property called the **half-life,** $T_{1/2}$. The half-life of a nuclide is the time taken for half the number of nuclides present in a sample to decay. An equivalent statement is that the half-life is the time taken for the rate of decay of a particular sample of nuclides to halve. A substance with a large half-life takes a long time to decay. A substance with a short half-life will decay quickly. Half-lives can vary from fractions of a second to millions of years.



Half-life of an exponential decay

EXAMPLE

In simple situations, working out how much radioactive material remains is a matter of applying the half-life property several times. A common mistake is to think that if the half-life of a radioactive material is 3 days then it will all decay in six days. In reality, after six days (two half-lives) a "half of a half" will remain i.e. a quarter.



The decay of parent into daughter

e.g. The half-life of $^{14}_{6}C$ is 5570 years. Approximately how long is needed before less than 1% of a sample of $^{14}_{6}C$ remains?

Time	**Fraction left**
$T_{1/2}$	50%
$2T_{1/2}$	25%
$3T_{1/2}$	12.5%
$4T_{1/2}$	~ 6.3%
$5T_{1/2}$	~ 3.1%
$6T_{1/2}$	~ 1.5%
$7T_{1/2}$	~ 0.8%

6 half lives = 33420 years

7 half lives = 38990 years

$\therefore$ approximately 37000 years needed

Nuclear reactions

ARTIFICIAL TRANSMUTATIONS

There is nothing that we can do to change the likelihood of a certain radioactive decay happening, but under certain conditions we can make nuclear reactions happen. This can be done by bombarding a nucleus with a nucleon, an alpha particle or another small nucleus. Such reactions are called **artificial transmutations**. In general, the target nucleus first "captures" the incoming object and then an emission takes place. The first ever artificial transmutation was carried out by Rutherford in 1919. Nitrogen was bombarded by alpha particles and the presence of oxygen was detected spectroscopically.

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

The mass numbers (4 + 14 = 17 +1) and the atomic numbers (2 + 7 = 8 +1) on both sides of the equation must balance.

UNIFIED MASS UNITS

The individual masses involved in nuclear reactions are tiny. In order to compare atomic masses physicists often use unified mass units, u. These are defined in terms of the most common isotope of carbon, carbon-12. There are 12 nucleons in the carbon-12 atom (6 protons and 6 neutons) and one unified mass unit is defined as exactly one twelfth the mass of a carbon-12 atom. Essentially, the mass of a proton and the mass of a neutron are both 1 u as shown in the table below.

$$1 \text{ u} = \frac{1}{12} \text{ mass of a (carbon-12) atom} = 1.66 \times 10^{-27} \text{ kg}$$

mass* of 1 proton = 1.007 276 u

mass* of 1 neutron = 1.008665 u

mass* of 1 electron = 0.000549 u

* = *Technically these are all "rest masses" – see Relativity option*

MASS DEFECT AND BINDING ENERGY

The table above shows the masses of neutrons and protons. It should be obvious that if we add together the masses of 6 protons, 6 neutrons and 6 electrons we will get a number bigger than 12 u, the mass of a carbon-12 atom. What has gone wrong? The answer becomes clear when we investigate what keeps the nucleus bound together.

The difference between the mass of a nucleus and the masses of its component nucleons is called the **mass defect**. If one imagined assembling a nucleus, the protons and neutrons would initially need to be brought together. Doing this takes work because the protons repel one another. The energy needed to do this work must come from somewhere. The answer lies in Einstein's famous mass-energy equivalence relationship.

$$E = mc^2$$

energy in joules   mass in kg   speed of light in m s^{-1}

In Einstein's equation, mass is another form of energy and it is possible to convert mass directly into energy and vice versa. The **binding energy** is the amount of energy that is released when a nucleus is assembled from its component nucleons. It comes from a decrease in mass. The binding energy would also be the energy that needs to be added in order to separate a nucleus into its individual nucleons. The mass defect is thus a measure of the binding energy.

UNITS

Using Einstein's equation, 1 kg of mass is equivalent to 9×10^{16} J of energy. This is a huge amount of energy. At the atomic scale other units of energy tend to be more useful. The electronvolt (see topic 5), or more usually, the megaelectronvolt are often used.

$1 \text{ eV} = 1.6 \times 10^{-19}$ J

$1 \text{ M eV} = 1.6 \times 10^{-13}$ J

1 u of mass converts into 935.5 M eV

Since mass and energy are equivalent it is sometimes useful to work in units that avoid having to do repeated multiplications by the (speed of light)^2. A new possible unit for mass is thus M eV c^{-2}. It works like this:

If 1 M eV c^{-2} worth of mass is converted you get 1 M eV worth of energy.

WORKED EXAMPLES

Question:

How much energy would be released if 14 g of carbon-14 decayed as shown in the equation below?

$$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}\beta$$

Answer:

Information given

atomic mass of carbon-14 = 14.003242 u;

atomic mass of nitrogen-14 = 14.003074 u;

mass of electron = 0.000549 u

$$\begin{aligned}
\text{mass of left-hand side} &= \text{nuclear mass of } ^{14}_{6}C \\
&= 14.003242 - 6(0.000549) \text{ u} \\
&= 13.999948 \text{ u} \\
\text{nuclear mass of } ^{14}_{7}N &= 14.003074 - 7(0.000549) \text{ u} \\
&= 13.999231 \text{ u} \\
\text{mass of right-hand side} &= 13.999231 + 0.000549 \text{ u} \\
&= 13.999780 \text{ u} \\
\text{mass difference} &= \text{LHS} - \text{RHS} \\
&= 0.000168 \text{ u} \\
\text{energy released per decay} &= 0.000168 \times 935.5 \text{ MeV} \\
&= 0.157164 \text{ MeV}
\end{aligned}$$

14g of C-14 is 1 mol

$\therefore$ Total number of decays = $N_A = 6.22 \times 10^{23}$

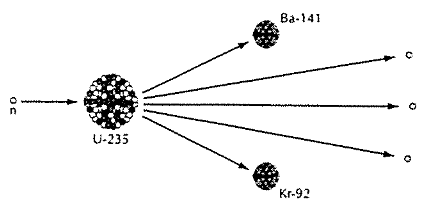
$$\begin{aligned}
\therefore \text{ Total energy release} &= 6.022 \times 10^{23} \times 0.157164 \text{ MeV} \\
&= 9.464 \times 10^{22} \text{ MeV} \\
&= 15143 \text{ J} \\
&\approx 15 \text{ kJ}
\end{aligned}$$

Fission, fusion and antimatter

FISSION

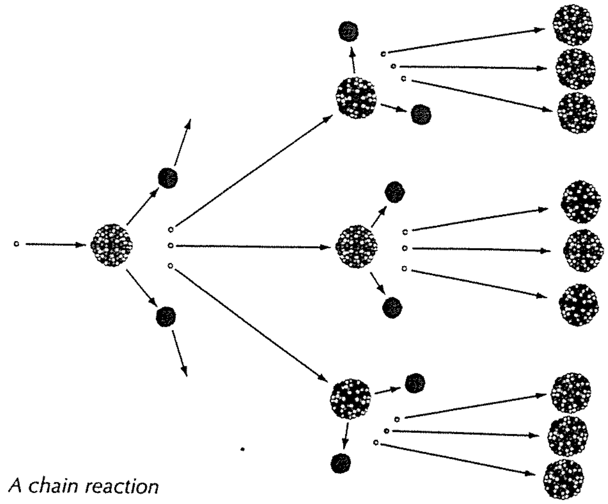
Fission is the name given to the nuclear reaction whereby large nuclei are induced to break up into smaller nuclei and release energy in the process. It is the reaction that is used in nuclear reactors and atomic bombs. A typical single reaction might involve bombarding a uranium nucleus with a neutron. This can cause the uranium nucleus to break up into two smaller nuclei. A typical reaction might be:

$${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n + \text{energy}$$



A fission reaction

Since the one original neutron causing the reaction has resulted in the production of three neutrons, there is the possibility of a **chain reaction** occurring. It is technically quite difficult to get the neutrons to lose enough energy to go on and initiate further reactions, but it is achievable.

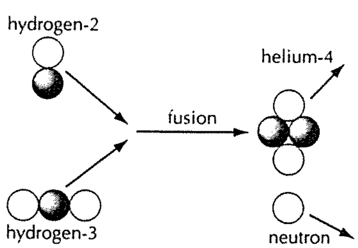


A chain reaction

FUSION

Fusion is the name given to the nuclear reaction whereby small nuclei are induced to join together into larger nuclei and release energy in the process. It is the reaction that "fuels" all stars including the Sun. A typical reaction that is taking place in the Sun is the fusion of two different isotopes of hydrogen to produce helium.

$${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + \text{energy}$$

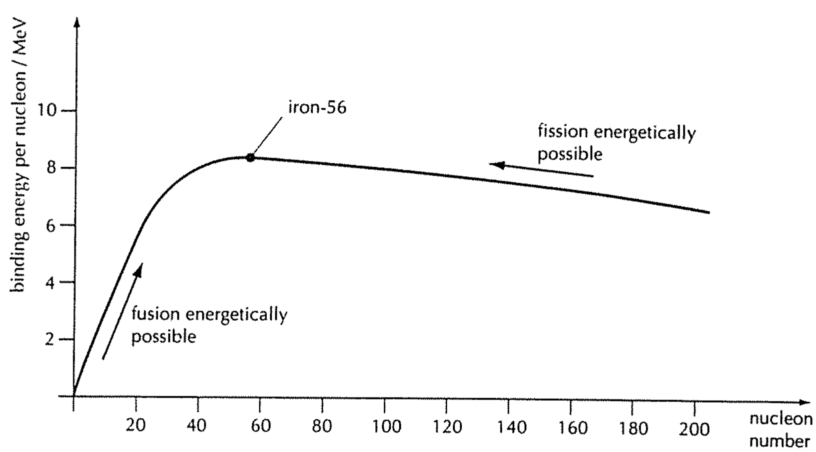


One of the fusion reactions happening in the Sun

BINDING ENERGY PER NUCLEON

Whenever a nuclear reaction (fission or fusion) releases energy, the products of the reaction are in a lower energy state than the reactants. Mass loss must be the source of this energy. In order to compare the energy states of different nuclei, physicists calculate the binding energy per nucleon. This is the total binding energy for the nucleus divided by the total number of nucleons. The nucleus with the largest binding energy per nucleon is iron-56, ${}^{56}_{26}Fe$.

A reaction is energetically feasible if the products of the reaction have a greater binding energy per nucleon when compared with the reactants.



Graph of binding energy per nucleon number

ANTIMATTER

The nuclear model given in the previous pages is somewhat simplified but is all that is required for the IB Standard level examination. One important thing that has not been mentioned is the existence of antimatter. Every form of matter has its equivalent form of antimatter. If matter and antimatter came together they would annihilate each other. Not surprisingly, antimatter is rare but it does exist. For example, another form of radioactive decay that can take place is beta plus or positron decay. In this decay a proton decays into a neutron, and the antimatter version of an electron, a positron, is emitted.

$${}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}\beta^{+} + \upsilon$$

The positron, β^+, emission is accompanied by a neutrino.

The antineutrino is the antimatter form of the neutrino.

$${}^{19}_{10}Ne \rightarrow {}^{19}_{9}F + {}^{0}_{+1}\beta^{+} + \bar{\upsilon}$$

For more details see the Higher level material in section 12.