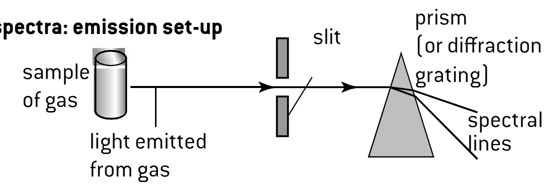
Emission and absorp ion spec ra

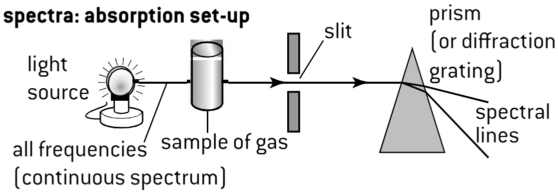
EMISSION SPECTRA AND ABSORPTION SPECTRA

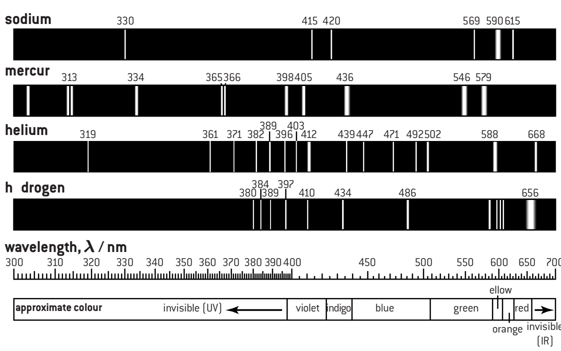
When an element is given enough energy it emits light. This light can be analysed by splitting it into its various colours (or frequencies) using a prism or a diffraction grating. If all possible frequencies of light were present, this would be called a **continuous spectrum**. The light an element emits, 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.

spectra: emission set-up

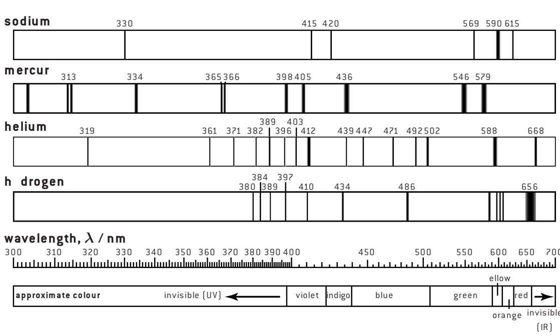


spectra: absorption set-up





Emission spectra



Absorption spectra

EXPLANATION OF ATOMIC SPECTRA

In an atom, electrons are bound to the nucleus. See page 77, the atomic model. 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 ionized. 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. A higher energy photon corresponds to a higher frequency (shorter wavelength) of light.

The energy of a photon is given by

$$E = f$$

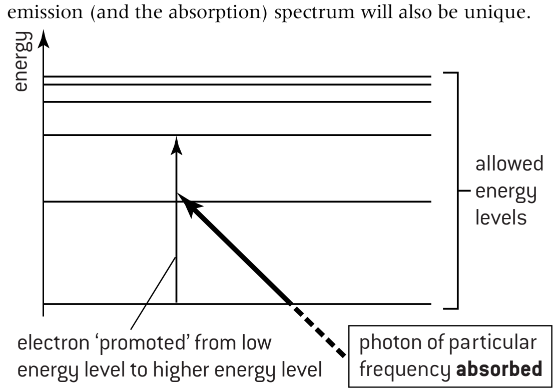
energy in joules (E); frequency of light in Hz (f); Planck's constant 6.63×10^{-34} J s

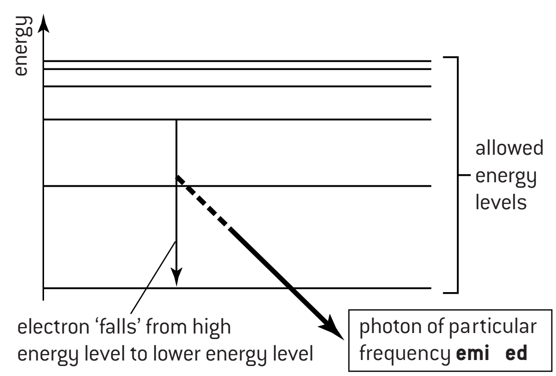
Since $c = f\lambda$ (Speed of light in m s^{-1})

$$\lambda = \frac{c}{E}$$

Wavelength in m

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.



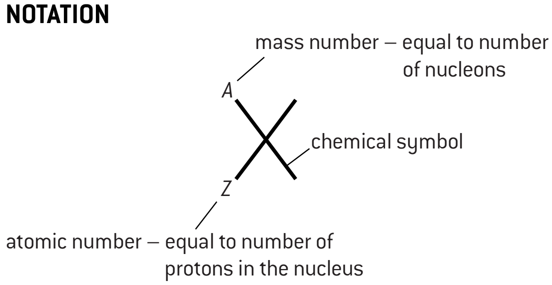


Nuclear stabilit

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**

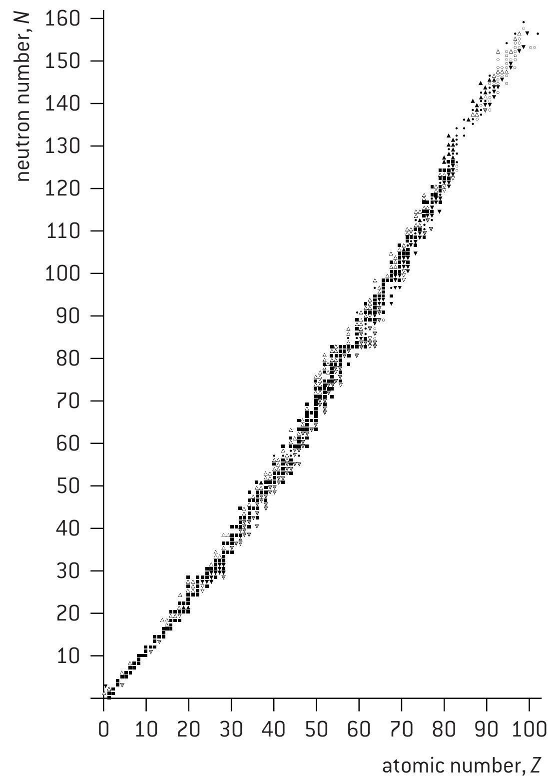
Each element has a unique chemical symbol and its own atomic number. *No.1* and *No.2* are examples of two isotopes, whereas *No.4* and *No.5* are not.

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.

NUCLEAR STABILITY

Many atomic nuclei are unstable. The process by which they decay is called radioactive decay (see page 72). It involves emission of alpha (α), beta (β) or gamma (γ) radiation.
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 72).
- Nuclides below the band of stability have 'too few neutrons' and will tend to emit positrons (see page 73).



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

Fundamental forces

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**.

WEAK NUCLEAR FORCE

The strong nuclear force (see box left) explains why nuclei do not fly apart and thus why they are stable. Most nuclei, however, are unstable. Mechanisms to explain alpha and gamma emission (see page 72) can be identified but another nuclear force must be involved if we wish to be able to explain all aspects of the nucleus including beta emission. We know a few things about this force:

- It must be weak. Many nuclei are stable and beta emission does not always occur.
- It must be very short-ranged as we do not observe this force anywhere other than inside the nucleus.
- Unlike the strong nuclear force, it involves the lighter particles (e.g. electrons, positrons and neutrinos) as well as the heavier ones (e.g. protons and neutrons).

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

OTHER FUNDAMENTAL FORCES/INTERACTIONS

The standard model of particle physics is based around the forces that we observe on a daily basis along with the two 'new' forces that have been identified as being involved in nuclear stability (above). As a result in the standard model, there are only four fundament forces (or **interactions**) that are known to exist. These are Gravity, Electromagnetic, Strong and Weak. More detail about all these forces is discussed on page 78. Outline information about two 'everyday' interactions is listed below:

Gravity

- Gravity is the force of attraction between all objects that have mass.
- Gravity is always attractive – masses are pulled together.
- The range of the gravity force is infinite.
- Despite the above, the gravity force is relatively quite weak. At least one of the masses involved needs to be large for the effects to be noticeable. For example, the gravitational force of attraction between you and this book is negligible, but the force between this book and the Earth is easily demonstrable (drop it).
- Newton's law of gravitation describes the mathematics governing this force.

Electromagnetic

- This single force includes all the forces that we normally categorize as either electrostatic or magnetic.
- Electromagnetic forces involve charged matter.
- Electromagnetic forces can be attractive or repulsive.
- The range of the electromagnetic force is infinite.
- The electromagnetic force is relatively strong – tiny imbalances of charges on an atomic level give rise to significant forces on the laboratory scale.
- At the end of the 19th century, Maxwell showed that the electrostatic force and the magnetic force were just two different aspects of the more fundamental electromagnetic force.
- The mathematics of the electromagnetic force is described by Maxwell's equations.
- Friction (and many other 'everyday' forces) is simply the result of the force between atoms and this is governed by the electromagnetic interaction.

The electromagnetic force and the weak nuclear force are now considered to be aspects of the single electroweak force.

PARTICLES THAT EXPERIENCE AND MEDIATE THE FUNDAMENTAL FORCES.

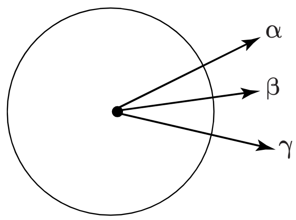
See page 78 onwards for more details about the standard model for the fundamental structure of matter. The following table summarizes which particles experience these forces and how they are mediated.

	Gravitational	Weak	Electromagnetic	Strong
Particles experience	All	Quark, Gluon	Charged	Quark, Gluon
Particles mediate	Graviton	W^+, W^-, Z^0	γ	Gluon

Radioactivit 1

IONIZING PROPERTIES

Many atomic nuclei are unstable. The process by which they decay is called **radioactive decay**. Every decay involves the emission o one o three di erent possible radiations rom the nucleus: alpha (α), beta (β) or gamma (γ).



Alpha, beta and gamma all come rom the nucleus

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

EFFECTS OF RADIATION

At the molecular level, an ionization could cause damage directly to a biologically important molecule such as DNA or RNA. This could cause it to cease unctioning. Alternatively, an ionization in the surrounding medium is enough to inter ere with the complex chemical reactions (called **metabolic pathways**) taking place.

Molecular damage can result in a disruption to the unctions that are taking place within the cells that make up the organism. As well as potentially causing the cell to die, this could just prevent cells rom dividing and multiplying. On top o this, it could be the cause o the trans ormation o the cell into a malignant orm.

As all body tissues are built up o cells, damage to these can result in damage to the body systems that have been a ected. The non- unctioning o these systems can result in death or the animal. I malignant cells continue to grow then this is called **cancer**.

RADIATION SAFETY

There is no such thing as a sa e dose o ionizing radiation. Any hospital procedures that result in a patient receiving an extra dose (or example having an X-ray scan) should be justifiable in terms o the in ormation received or the benefit it gives.

There are three main ways o protecting onesel rom too large a dose. These can be summarized as ollows:

- **Run away!**
  The simplest method o reducing the dose received is to increase the distance between you and the source. Only electromagnetic radiation can travel large distances and this ollows an inverse square relationship with distance.
- **Don't waste time!**
  I you have to receive a dose, then it is important to keep the time o this exposure to a minimum.
- **I you can't run away, hide behind something!**
  Shielding can always be used to reduce the dose received. Lead-lined aprons can also be used to limit the exposure or both patient and operator.

PROPERTIES OF ALPHA, BETA AND GAMMA RADIATIONS

Property	**Alpha**, α	**Beta**, β	**Gamma**,
E ect on photographic film	Yes	Yes	Yes
Approximate number o ion pairs produced in air	10^4 per mm travelled	10^2 per mm travelled	1 per mm travelled
Typical material needed to absorb it	10^{-2} mm aluminium; piece o paper	A ew mm aluminium	10 cm lead
Penetration ability	Low	Medium	High
Typical path length in air	A ew cm	Less than one m	E ectively infinite
Deflection by E and B 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 o the nuclear equation.

- Alpha particles are helium nuclei, ${}^{4}_{2}\alpha$ or ${}^{4}_{2}He^{2+}$. In alpha decay, a 'chunk' o the nucleus is emitted. The portion that remains will be a di erent 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 o the equation.

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

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

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

Since an antineutrino has no charge and virtually no mass it does not a ect the equation.

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

$$\text{e.g. } {}^{90}_{38}Sr \rightarrow {}^{90}_{39}Y + {}^{0}_{-1}\beta + \bar{\nu}$$

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

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

Excited state → Lower energy state

Radioactivit 2

ANTIMATTER

The nuclear model given on page 77 is somewhat simplified. One important thing that is not mentioned there 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.

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

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

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

The antineutrino is the antimatter form of the neutrino.

For more details see page 78.

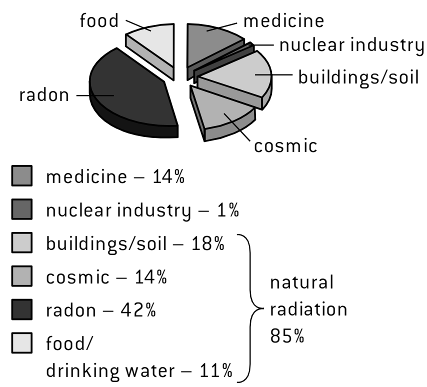
BACKGROUND RADIATION

Radioactive decay is a natural phenomenon and is going on around you all the time. The activity of any given source is measured in terms of the number of individual nuclear decays that take place in a unit of time. This information is quoted in **becquerels** (Bq) with 1 Bq = 1 nuclear decay per second.

Experimentally this would be measured using a **Geiger counter**, which detects and counts the number of ionizations taking place inside the **GM tube**. A working Geiger counter will always detect some radioactive ionizations taking place even when there is no identified radioactive source: there is a **background count** as a result of the **background radiation**. A reading of 30 counts per minute, which corresponds to the detector registering 30 ionizing events, would not be unusual.

To analyse the activity of a given radioactive source, it is necessary to correct for the background radiation taking place. It would be necessary to record the background count without the radioactive source present and this value can then be subtracted from all readings with the source present.

Some cosmic gamma rays will be responsible, but there will also be α, β and γ radiation received as a result of radioactive decays that are taking place in the surrounding materials. The pie chart below identifies typical sources of background radiation, but the actual value varies from country to country and from place to place.



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.

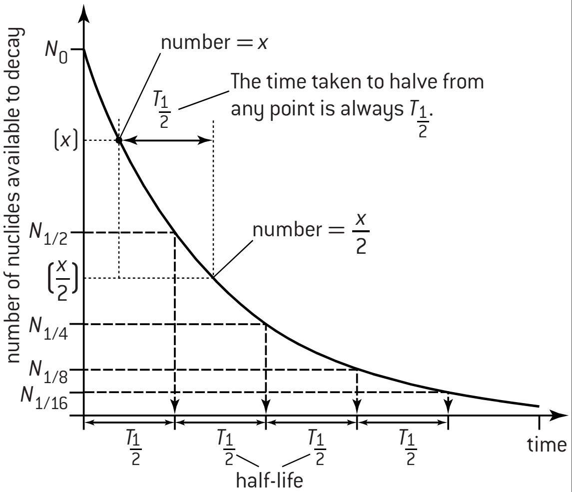
Although the process is random, the large numbers of atoms involved allows us to make some accurate predictions. If we start with a given number of atoms then we can expect a certain number to decay in the next minute. If there were more atoms in the sample, we would expect the number decaying to be 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:

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

Ha f- ife

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 or hal the number o nuclides to decay is always the same, whatever starting value we choose. This allows us to express the chances o decay happening in a property called the **half-life,** $T_{\frac{1}{2}}$. The hal -li e o a nuclide is the time taken or hal the number o nuclides present in a sample to decay. An equivalent statement is that the hal -li e is the time taken or the rate o decay (or activity) o a particular sample o nuclides to halve. A substance with a large hal -li e takes a long time to decay. A substance with a short hal -li e will decay quickly. Hal -lives can vary rom ractions o a second to millions o years.



Hal -li e o an exponential decay

INVESTIGATING HALF-LIFE EXPERIMENTALLY

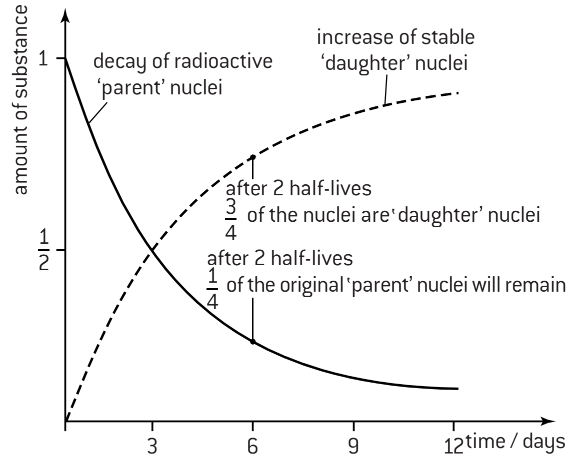
When measuring the activity o a source, the background rate should be subtracted.

- I the hal -li e is short, then readings can be taken o activity against time.
  - → A simple graph o activity against time would produce the normal exponential shape. Several values o hal -li e could be read rom the graph and then averaged. This method is simple and quick but not the most accurate.
  - → A graph o ln (activity) against time could be produced. This should give a straight line and the decay constant can be calculated rom the gradient. See page 217.
- I the hal -li e is long, then the activity will e ectively be constant over a period o time. In this case one needs to find a way to calculate the number o nuclei present, N, and then use

$$\frac{dN}{dt} = -\lambda N.$$

EXAMPLE

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



The decay o parent into daughter

e.g. The hal -li e o ${}^{14}_{6}C$ is 5570 years.

Approximately how long is needed be ore less than 1% o a sample o ${}^{14}_{6}C$ remains?

Time	**Fraction left**
$T_{\frac{1}{2}}$	50%
$2T_{\frac{1}{2}}$	25%
$3T_{\frac{1}{2}}$	12.5%
$4T_{\frac{1}{2}}$	~ 6.3%
$5T_{\frac{1}{2}}$	~ 3.1%
$6T_{\frac{1}{2}}$	~ 1.6%
$7T_{\frac{1}{2}}$	~ 0.8%
6 hal lives	= 33420 years
7 hal lives	= 38990 years

approximately 37000 years needed

SIMULATION

The result o the throw o a die is a random process and can be used to simulate radioactive decay. The dice represent nuclei available to decay. Each throw represents a unit o time. Every six represents a nucleus decaying meaning this die is no longer available.

Nuclear reactions

ARTIFICIAL TRANSMUTATIONS

There is nothing that we can do to change the likelihood o 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 Ruther ord in 1919. Nitrogen was bombarded by alpha particles and the presence o 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 o the equation must balance.

UNIFIED MASS UNITS

The individual masses involved in nuclear reactions are tiny. In order to compare atomic masses physicists o ten use unified mass units, u. These are defined in terms o the most common isotope o 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 twel th the mass o a carbon-12 atom. Essentially, the mass o a proton and the mass o a neutron are both 1 u as shown in the table below.

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

mass* o 1 proton = 1.007 276 u

mass* o 1 neutron = 1.008 665 u

mass* o 1 electron = 0.000 549 u

** = Technically these are all 'rest masses' – see option A*

MASS DEFECT AND BINDING ENERGY

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

The di erence between the mass o a nucleus and the masses o its component nucleons is called the **mass de ect**. I 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. Creating the bonds between the protons and neutrons releases a greater amount o energy than the work done in bringing them together. This energy released must come rom somewhere. The answer lies in Einstein's amous mass–energy equivalence relationship.

$$\Delta E = \Delta mc^2$$

energy in joules — mass in kg — speed o light in $m\ s^{-1}$

In Einstein's equation, mass is another orm o energy and it is possible to convert mass directly into energy and vice versa. The **binding energy** is the amount o energy that is released when a nucleus is assembled rom its component nucleons. It comes rom 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 de ect is thus a measure o the binding energy.

UNITS

Using Einstein's equation, 1 kg o mass is equivalent to 9×10^{16} J o energy. This is a huge amount o energy. At the atomic scale other units o energy tend to be more use ul. The electronvolt (see page 53), or more usually, the megaelectronvolt are o ten used.

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

$1\ MeV = 1.6 \times 10^{-13}$ J

1 u o mass converts into 931.5 MeV

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

I 1 MeV c^{-2} worth o mass is converted you get 1 MeV worth o energy.

WORKED EXAMPLES

Question:

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

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

Answer:

In ormation given

atomic mass o carbon-14 = 14.003242 u;
atomic mass o nitrogen-14 = 14.003074 u;
mass o electron = 0.000549 u

mass o le t-hand side = nuclear mass o $^{14}_{6}C$
= 14.003242 − 6(0.000549) u
= 13.999948 u

nuclear mass o $^{14}_{7}N$ = 14.003074 − 7(0.000549) u
= 13.999231 u

mass o right-hand side = 13.999231 + 0.000549 u
= 13.999780 u

mass di erence = LHS − RHS
= 0.000168 u

energy released per decay = 0.000168 × 931.5 MeV
= 0.156492 MeV

14g o C-14 is 1 mol

∴ Total number o decays = $N_A = 6.022 \times 10^{23}$

∴ Total energy release = $6.022 \times 10^{23} \times 0.156492$ MeV
$= 9.424 \times 10^{22}$ MeV
$= 9.424 \times 10^{22} \times 1.6 \times 10^{-13}$ J
$= 1.51 \times 10^{10}$ J
≈ 15 GJ

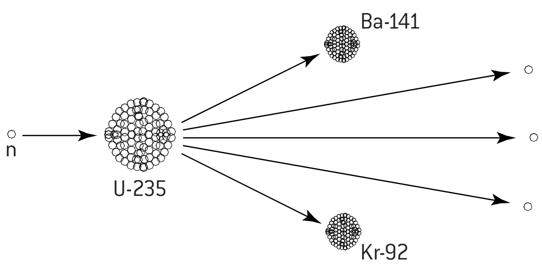
NB Many examination calculations avoid the need to consider the masses o the electrons by providing you with the *nuclear mass* as opposed to the *atomic mass*.

Fission and fusion

FISSION

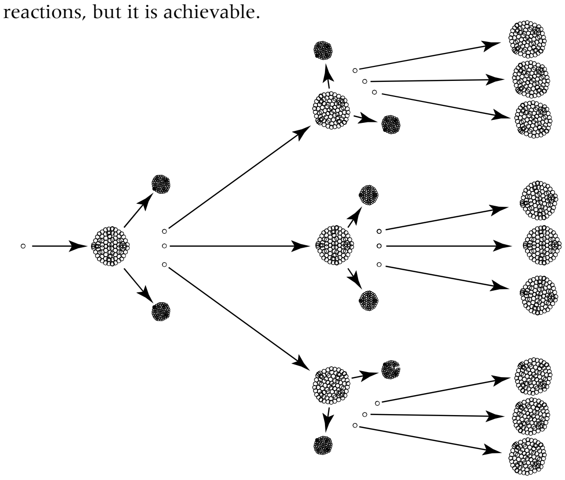
Fission is the name given to the nuclear reaction whereby large nuclei are induced to break up into smaller nuclei and release energy in the process. It is the reaction that is used in nuclear reactors and atomic bombs. A typical single reaction might involve bombarding a uranium nucleus with a neutron.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

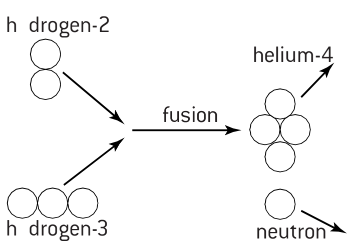


A chain reaction

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.

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

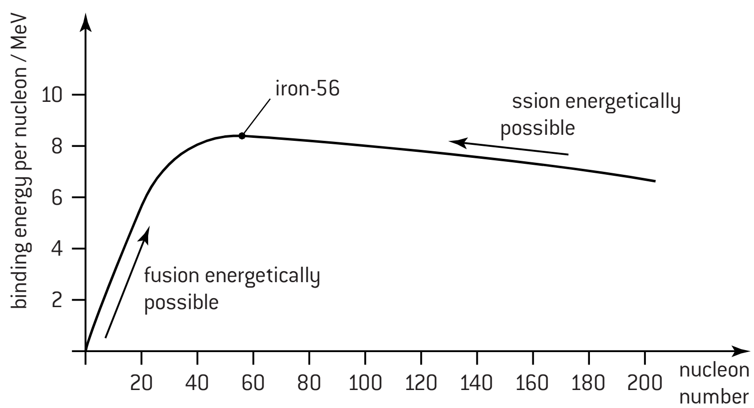


One of the fusion reactions happening in the Sun

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. One of the nuclei 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.

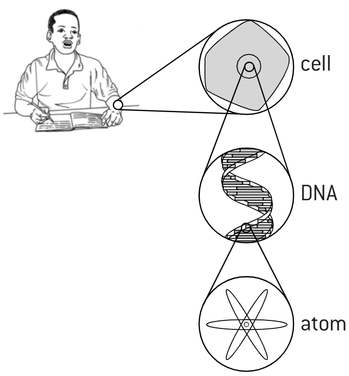


Graph of binding energy per nucleon

Structure of matter

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.

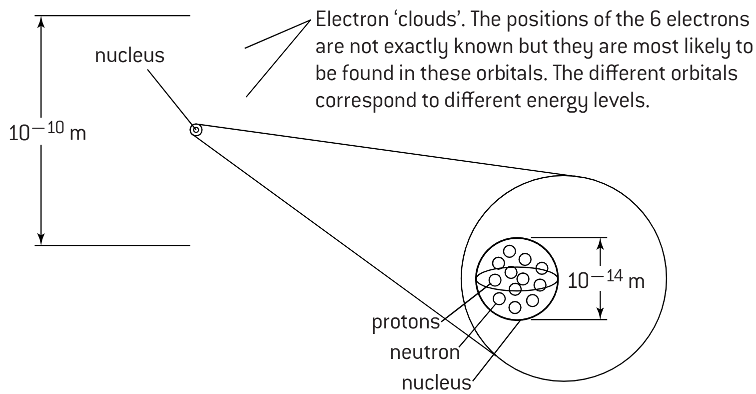


In the basic atomic model, we are made up of protons, neutrons, and electrons nothing more.

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

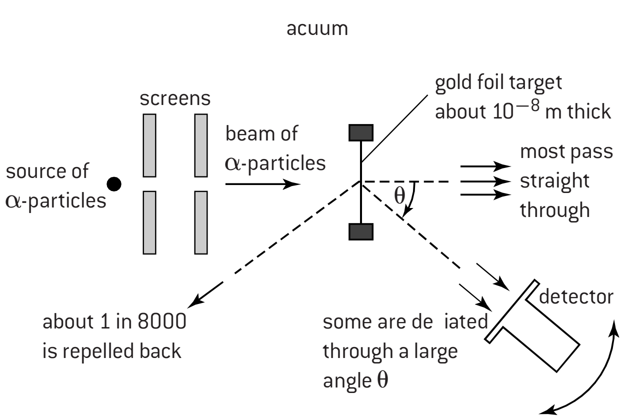


Atomic model of carbon

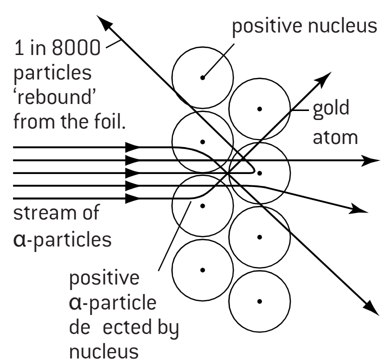
This simple model has limitations. Accelerated charges are known to radiate energy so orbital electrons should constantly lose energy (the changing direction means the electrons are accelerating).

EVIDENCE

One of the most convincing pieces of evidence for the nuclear model of the atom comes from the Rutherford–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.



Rutherford–Geiger–Marsden experiment



NB not to scale. Only a minute percentage of α-particles are scattered or rebound.

Atomic explanation of Rutherford–Geiger–Marsden experiment

Descrip ion and classifica ion of par icles

CLASSIFICATION OF PARTICLES

Particle accelerator experiments identify many, many 'new' particles. Two original classes of particles were identified – the **leptons** (= 'light') and the **hadrons** (= 'heavy'). Protons and neutrons are hadrons whereas electrons are leptons. The hadrons were subdivided into **mesons** and **baryons**. Protons and neutrons are baryons. Another class of particles is involved in the mediation of the interactions between the particles. These were called **gauge bosons** or 'exchange bosons'.

Particles are called **elementary** if they have no internal structure, that is, they are not made out of smaller constituents. The classes of elementary particles are **quarks**, **leptons** and the **exchange particles**. Another particle, the Higgs boson, is also an elementry particle. Combinations of elementary particles are called **composite** particles. All hadrons are composed of combinations of quarks. Inside all baryons there are three quarks (or three antiquarks); inside all mesons there is one quark and one antiquark.

CONSERVATION LAWS

Not all reactions between particles are possible. The study of the reactions that did take place gave rise to some experimental conservation laws that applied to particle physics. Some of these laws were simply confirmation of conservation laws that were already known to physicists – charge, momentum (linear and angular) and mass-energy. On top of these fundamental laws there appeared to be other rules that were never broken e.g. the law of conservation of baryon number. If all baryons were assigned a 'baryon number' of 1 (and all antibaryons were assigned a baryon number of −1) then the total number of baryons before and after a collision was always the same. A similar law of conservation of lepton number applies.

Other reactions suggested new and different particle properties that were often, but not always, conserved in reactions. 'Strangeness' and 'charm' are examples of two such properties. Strangeness is conserved in all electromagnetic and strong interactions, but not always in weak interactions.

All particles, whether they are elementary or composite, can be specified in terms of their mass and the various quantum numbers that are related to the conservation laws that have been discovered. The quantum numbers that are used to identify particles include:

- electric charge, strangeness, charm, lepton number, baryon number and colour (this property is not the same as an object's actual colour – see page 79).

Every particle has its own **antiparticle**. An antiparticle has the same mass as its particle but all its quantum numbers (including charge, etc.) are opposite. There are some particles (e.g. the photon) that are their own antiparticle.

THE STANDARD MODEL – LEPTONS

There are six different leptons and six different antileptons. The six leptons are considered to be in three different generations or families in exactly the same way that there are considered to be three different generations of quarks (see page 79).

The electron and the electron neutrino have a lepton (electron family) number of +1. The antielectron and the antielectron neutrino have a lepton (electron family) number of −1.

Similar principles are used to assign lepton numbers of +1 or −1 to the muon and the tau family members.

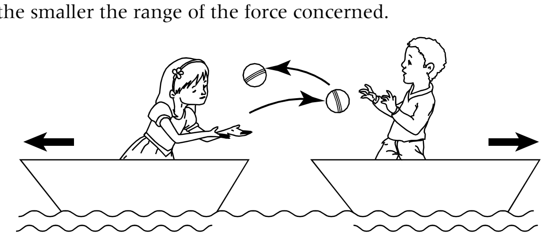
Lepton family number is also conserved in all reactions. For example, whenever a muon is created, an antimuon or an antimuon neutrino must also be created so that the total number of leptons in the muon family is always conserved.

	Electric charge	**'Generation'** 1	2	3
Lepton	0	ν_e (electron-neutrino) $M = 0$ or almost 0	ν_μ (muon-neutrino) $M = 0$ or almost 0	ν_τ (tau-neutrino) $M = 0$ or almost 0
	−1	e (electron) $M = 0.511$ MeV c^{-2}	μ (muon) $M = 105$ MeV c^{-2}	τ (tau) $M = 1784$ MeV c^{-2}

EXCHANGE PARTICLES

There are only four fundamental interactions that exist: Gravity, Electromagnetic, Strong and Weak.

All four interactions can be thought of as being mediated by an exchange of particles. Each interaction has its own exchange particle or particles. The bigger the mass of the exchange boson, the smaller the range of the force concerned.



The exchange results in repulsion between the two particles

From the point of view of quantum mechanics, the energy needed to create these virtual particles, E is available so long as the energy of the particle does not exist for a longer time t than is proscribed by the uncertainty principle (see page 126).

The greater the mass of the exchange particle, the smaller the time for which it can exist. The range of the weak interaction is small as the masses of its exchange particles (W^+, W^- and Z^0) are large.

In particle physics, all real particles can be thought of as being surrounded by a cloud of virtual particles that appear and disappear out of the surrounding vacuum. The lifetime of these particles is inversely proportional to their mass. The interaction between two particles takes place when one or more of the virtual particles in one cloud is absorbed by the other particle.

Interaction	**Relative strength**	**Range (m)**	**Exchange particle**	**Particles experience**
Strong	1	$\sim 10^{-15}$	8 different gluons	Quarks, gluons
Electromagnetic	10^{-2}	infinite	photon	Charged
Weak	10^{-13}	$\sim 10^{-18}$	W^+, W^-, Z^0	Quarks, lepton
Gravity	10^{-39}	infinite	graviton	All

Leptons and bosons are unaffected by the strong force.

Quarks

STANDARD MODEL – QUARKS

The **standard model** of particle physics is the theory that says that all matter is considered to be composed of combinations of six types of quark and six types of lepton. This is the currently accepted theory. Each of these particles is considered to be fundamental, which means they do not have any deeper structure. Gravity is not explained by the standard model.

All hadrons are made up from different combinations of fundamental particles called **quarks**. There are six different types of quark and six types of antiquark. This very neatly matches the six leptons that are also known to exist. Quarks are affected by the strong force (see below), whereas leptons are not. **The weak interaction can change one type o quark into another.**

	Electric charge	'Generation' 1	2	3
Quarks	$+\frac{2}{3}e$	u (up) $M = 5$ MeV c^{-2}	c (charm) $M = 1500$ MeV c^{-2}	t (top) $M = 174$ MeV c^{-2}
	$-\frac{1}{3}e$	d (down) $M = 10$ MeV c^{-2}	s (strange) $M = 200$ MeV c^{-2}	b (bottom) $M = 4700$ MeV c^{-2}

All quarks have a baryon number of $+\frac{1}{3}$,

All antiquarks have a baryon number of $-\frac{1}{3}$

All quarks have a strangeness number of 0 except the s quark that has a strangeness number of -1.

The c quark is the only quark with a charm number $= +1$, all other quarks have charm number of 0.

Isolated quarks cannot exist. They can exist only in twos or threes. Mesons are made from two quarks (a quark and an antiquark) whereas baryons are made up of a combination of three quarks (either all quarks or all antiquarks).

	Name o particle	Quark structure
Baryons	proton (p)	u u d
	neutron (n)	u d d
	lambda Λ	u d s
	antiproton ($\bar{p}$)	$\bar{u}$ $\bar{u}$ $\bar{d}$
Mesons	π^- (pi-minus)	d $\bar{u}$
	π^+ (pi-plus)	u $\bar{d}$
	K^0 (K_{zero})	d $\bar{s}$

The force between quarks is still the strong interaction but the full description of this interaction is termed QCD theory – quantum chromodynamics. The quantum difference between the quarks is a property called colour. All quarks can be red (r), green (g) or blue (b). Antiquarks can be antired ($\bar{r}$), antigreen ($\bar{g}$) or antiblue ($\bar{b}$). The two up quarks in a proton are not identical because they have different colours.

Only white (**colour neutral**) combinations are possible. Baryons must contain r, g and b quarks (or $\bar{r}$, $\bar{g}$, $\bar{b}$) whereas mesons contain a colour and the anticolour (e.g. r and $\bar{r}$ or b and $\bar{b}$, etc.) The force between quarks is sometimes called the colour force. Eight different types of gluon mediate it.

The details of QCD do not need to be recalled.

QUANTUM CHROMODYNAMICS (QCD)

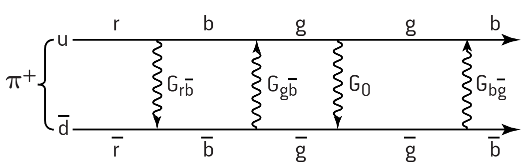
The interaction between objects with colour is called the colour interaction and is explained by a theory called quantum chromodynamics. The force-carrying particle is called the gluon. There are eight different types of gluon each with zero mass. Each gluon carries a combination of colour and anticolour and their emission and absorption by different quarks causes the colour force.

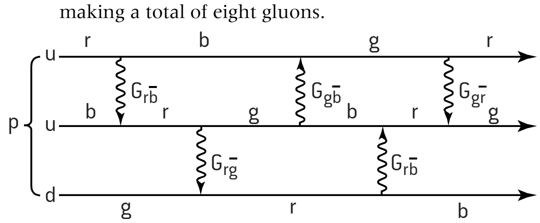
As the gluons themselves are coloured, there will be a colour interaction between gluons themselves as well as between quarks. The overall effect is that they bind quarks together. The force between quarks increases as the separation between quarks increases. **Isolated quarks and gluons cannot be observed.** If sufficient energy is supplied to a hadron in order to attempt to isolate a quark, then more hadrons or mesons will be produced rather than isolated quarks. This is known as **quark confinement**.

The six colour-changing gluons are: $G_{r\bar{b}}$, $G_{r\bar{g}}$, $G_{b\bar{g}}$, $G_{b\bar{r}}$, $G_{g\bar{b}}$, $G_{g\bar{r}}$.

For example when a blue up quark emits the gluon $G_{b\bar{r}}$ it loses its blue colour and becomes a red up quark (the gluon contains antired, so red colour must be left behind). A red down quark absorbing this gluon will become a blue down quark.

There are two additional colour-neutral gluons: G_0 and G_0', making a total of eight gluons.





STRONG INTERACTION

The colour interaction and the strong interaction are essentially the same thing. Properly, the colour interaction is the fundamental force that binds quarks together into baryons and mesons. It is mediated by gluons. The **residual strong interaction** is the force that binds colour-neutral particles (such as the proton and neutron) together in a nucleus. The overall effect of the interactions between all the quarks in the nucleons is a short-range interaction between colour-neutral nucleons.

The particles mediating the strong interaction can be considered to involve the exchange of composite particles (π mesons: π^+, π^- or π^0) whereas the fundamental colour interaction is always seen as the exchange of gluons.

HIGGS BOSON

In addition to the three generations of leptons and quarks in the standard model there are the four classes of gauge boson and an additional highly massive boson, the Higgs boson. This was proposed in 1964 to explain the process by which particles can acquire mass. In 2013 scientists working with the Large Hadron Collider announced the experimental detection of a particle that that matched the standard model's predictions for the Higgs boson.

Fe nman diagrams

RULES FOR DRAWING FEYNMAN DIAGRAMS

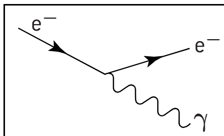
Feynman diagrams can be used to represent possible particle interactions. The diagrams are used to calculate the overall probability o an interaction taking place. In quantum mechanics, in order to find out the overall probability o an interaction, it is necessary to add together all the possible ways in which an interaction can take place. Used properly they are a mathematical tool or calculations but, at this level, they can be seen as a simple pictorial model o possible interactions.

In the Feynman diagrams below the *x*-axis represents time going rom le t to right and the *y*-axis represents space (some books reverse these two axes). To view them in the alternative way, turn the page anti-clockwise by 90°.

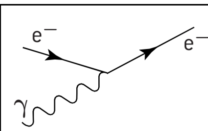
Some simple rules help in the construction o correct diagrams:

- Each junction in the diagram (vertex) has an arrow going in and one going out. These will represent a lepton–lepton transition or a quark–quark transition.
- Quarks or leptons are solid straight lines.
- Exchange particles are either wavy or broken (photons, $W^{\pm}$ or Z^{0}) or curly (gluons).
- Time flows rom le t to right. Arrows rom le t to right represent particles travelling orward in time. Arrows rom right to le t represent antiparticles travelling orward in time.
- The labels or the di erent particles are shown at the end o the line.
- The junctions will be linked by a line representing the exchange particle involved.

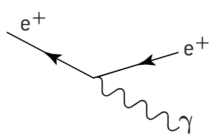
EXAMPLES



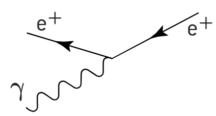
An electron emits a photon.



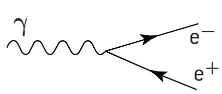
An electron absorbs a photon.



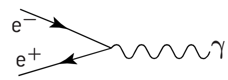
A positron emits a photon.



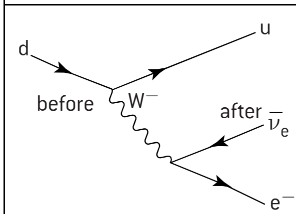
A positron absorbs a photon.



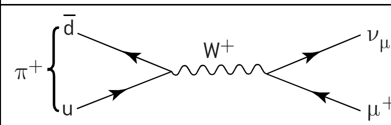
A photon produces an electron and a positron (an electron–positron pair).



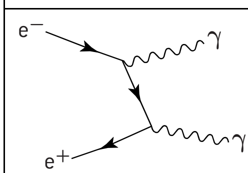
An electron and a positron meet and annihilate (disappear), producing a photon.



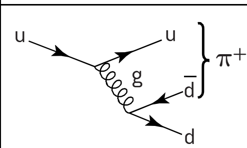
Beta decay. A down quark changes into an up quark with the emission o a W^- particle. This decays into an electron and an antineutrino. The top vertex involves quarks, the bottom vertex involves leptons.



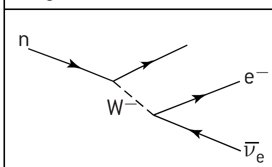
Pion decay. The quark and antiquark annihilate to produce a W^+ particle. This decays into an antimuon and a muon neutrino.



An electron and positron annihilate to produce two photons.

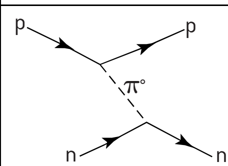


An up quark (in a proton) emits a gluon which in turn trans orms into a down/antidown quark pair. This reaction could take place as a result o a proton–proton collision: $p + p \rightarrow p + n + \pi^+$.



Simple diagrams can also be drawn with exchanges between hadrons.

Beta decay (hadron version)



A π^0 mediates the strong nuclear orce between a proton and a neutron in a nucleus.

USES OF FEYNMAN DIAGRAMS

Once a possible interaction has been identified with a Feynman diagram, it is possible to use it to calculate the probabilities or certain undamental processes to take place. Each line and vertex corresponds to a mathematical term. By adding together all the terms, the probability o the interaction can be calculated using the diagram.

More complicated diagrams with the same overall outcome need to be considered in order to calculate the overall probability o a chosen outcome. The more diagrams that are included in the calculation, the more accurate the answer.

In a Feynman diagram, lines entering or leaving the diagram represent real particles and must obey mass, energy and momentum relationships. Lines in intermediate stages in the diagram represent virtual particles and do not have to obey energy conservation providing they exist or a short enough time or the uncertainty relationship to apply. Such virtual particles cannot be detected.

IB Quest ons – atom c, nuclear and part cle phys cs

1. A sample of radioactive material contains the element Ra 226. The half-life of Ra 226 can be defined as the time it takes for
   A. the mass of the sample to fall to half its original value.
   B. half the number of atoms of Ra 226 in the sample to decay.
   C. half the number of atoms in the sample to decay.
   D. the volume of the sample to fall to half its original value.
2. Oxygen-15 decays to nitrogen-15 with a half-life of approximately 2 minutes. A pure sample of oxygen-15, with a mass of 100 g, is placed in an airtight container. After 4 minutes, the masses of oxygen and nitrogen in the container will be

	Mass of oxygen	Mass of nitrogen
A.	0 g	100 g
B.	25 g	25 g
C.	50 g	50 g
D.	25 g	75 g

3. A radioactive nuclide $_{Z}X$ undergoes a sequence of radioactive decays to form a new nuclide $_{Z+2}Y$. The sequence of emitted radiations could be
   A. β, β B. α, β, β
   C. α, α D. α, β, γ
4. In the Rutherford scattering experiment, a stream of α particles is fired at a thin gold foil. Most of the α particles
   A. are scattered randomly.
   B. rebound.
   C. are scattered uniformly.
   D. go through the foil.
5. A piece of radioactive material now has about 1/16 of its previous activity. If the half-life is 4 hours the difference in time between measurements is approximately
   A. 8 hours.
   B. 16 hours.
   C. 32 hours.
   D. 60 hours.
6. a) Use the standard model to describe, in terms of fundamental particles, the internal structure of:
   (i) A proton
   (ii) An electron
   (iii) Baryons
   (iv) Mesons
   b) Draw Feynman diagram for β^+ decay.
7. A proton undergoes a strong interaction with a ϕ^- particle (quark content: $\overline{u}d$) to produce a neutron and another particle. Use conservation laws to deduce the structure of the particle produced in this reaction.
8. a) Two properties of the isotope of uranium, $^{238}_{92}U$ are:
   (i) it decays radioactively (to $^{234}_{90}Th$)
   (ii) it reacts chemically (e.g. with fluorine to form UF_6).
   What features of the structure of uranium atoms are responsible for these two widely different properties? [2]
   b) A beam of deuterons (deuterium nuclei, $^{2}_{1}H$) are accelerated through a potential difference and are then incident on a magnesium target ($^{26}_{12}Mg$). A nuclear reaction occurs resulting in the production of a sodium nucleus and an alpha particle.
   (i) Write a balanced nuclear equation for this reaction. [2]
   (ii) Explain why it is necessary to give the deuterons a certain minimum kinetic energy before they can react with the magnesium nuclei. [2]
9. *Radioactive carbon dating*
   The carbon in trees is mostly carbon-12, which is stable, but there is also a small proportion of carbon-14, which is radioactive. When a tree is cut down, the carbon-14 present in the wood at that time decays with a half-life of 5,800 years.
   a) Carbon-14 decays by beta-minus emission to nitrogen-14. Write the equation for this decay. [2]
   b) For an old wooden bowl from an archaeological site, the average count-rate of beta particles detected per kg of carbon is 13 counts per minute. The corresponding count rate from newly cut wood is 52 counts per minute.
   (i) Explain why the beta activity from the bowl diminishes with time, even though the probability of decay of any individual carbon-14 nucleus is constant. [3]
   (ii) Calculate the approximate age of the wooden bowl. [3]
10. This question is about a nuclear fission reactor for providing electrical power.
    In a nuclear reactor, power is to be generated by the fission of uranium-235. The absorption of a neutron by ^{235}U results in the splitting of the nucleus into two smaller nuclei plus a number of neutrons and the release of energy. The splitting can occur in many ways; for example
    n + $^{235}_{92}U \rightarrow {}^{90}_{38}Sr + {}^{143}_{54}Xe$ + neutrons + energy
    a) *The nuclear fission reaction*
    (i) How many neutrons are produced in this reaction? [1]
    (ii) Explain why the release of several neutrons in each reaction is crucial for the operation of a fission reactor. [2]
    (iii) The sum of the rest masses of the uranium plus neutron before the reaction is 0.22 u greater than the sum of the rest masses of the fission products. What becomes of this 'missing mass'? [1]
    (iv) Show that the energy released in the above fission reaction is about 200 MeV. [2]
    b) *A nuclear fission power station*
    (i) Suppose a nuclear fission power station generates electrical power at 550 MW. Estimate the minimum number of fission reactions occurring each second in the reactor, stating any assumption you have made about efficiency. [4]
11. Which of the following is a correct list of particles upon which the strong nuclear force may act?
    A. protons and neutrons B. protons and electrons
    C. neutrons and electrons D. protons, neutrons and electrons