Section Four: Atoms and Nuclei
Topic One: The Structure of the Atom

Most of what we know about “the atom” depends on previous study of the light and various other radiations that can be emitted, and/or absorbed, by atoms. **Atomic spectra** analysis requires the study of the spectra (ie. light wavelengths) emitted or absorbed by atoms of a single, pure element. These spectra are made visible by using spectrosopes. A **line emission spectrum** is emitted when the atoms of a gas are excited either by intense heat or by applying a high voltage across a sample of the gas in question, placed at relatively low pressure in a discharge tube.

There is a strong electric field between the anode and the cathode that causes electrons to be emitted by the gas atoms. The part of the atom left is called a **positive ion** and the process is called **ionisation**. The **emission spectrum** of a particular element has discrete photon energies (and hence discrete frequencies and wavelengths) because if \( f \) is the frequency of the light, photon energy \( E = hf \), where emitted wavelength \( \lambda = \frac{hc}{E} \).

\[ f = \text{frequency of light} \quad h = \text{Planck’s constant} = 6.63 \times 10^{-34} \text{Js} \]
\[ c = \text{speed of light in a vacuum} = 3.0 \times 10^8 \text{ms}^{-1}. \]

The energy \( E = hf \) is measured in Joules (J). The energy in electron volts (eV) is the energy in J divided by e.

The presence of discrete frequencies in the emission spectrum of an atom, can be interpreted as providing evidence for the existence of **discrete atomic energy levels** which can be shown on an energy level diagram.

In general the energy levels get closer as the least strongly bound electron in an atom gains energy.

Since single atoms only emit discrete frequencies, this implies that the atoms themselves can only have discrete energy levels. When such an atom raised to an energy level with \( n > 1 \) it is said to be **excited** and it can return to a lower energy level in the process of the atom emitting one or more different frequency photons.

The ionisation energy (or binding energy) of an atom is defined as the minimum energy that must be absorbed by an atom in its ground state to cause ionisation. It is the energy necessary to remove the most loosely bound electron. eg. ionisation energy for H is 13.56eV

The concept of an atom as being the fundamental part of any element had been accepted in the eighteenth century (before 1900). In the 1890’s physicists found that small negative particles (electrons) existed in all atoms. The positive parts of ionised atoms were found to have different masses, depending on the element.

Several models of the atom were devised – each better than its predecessor. When Rutherford had interpreted the results of various experiments he deduced that most of the mass of any atom was concentrated in a small region (diameter about \( 10^{-14} \text{m} \)) and this was called the **nucleus**. The electrons (negative particles with fixed charge, e and mass \( m_e \)) existed outside of the nucleus. The total atomic diameter was found to be about \( 10^{-10} \text{m} \) from which it seems that most of any atom is empty space.

The charge on any atomic nucleus is \( +Z \ e \) (\( e = \) magnitude of electron charge) and where \( Z = \) atomic number = number of electrons in a neutral atom = position of atom (element) in periodic table.

The diagram shows some of the possible energy level transitions that enable photons to be emitted from atomic hydrogen. Note that when the transitions occur to the ground state (\( n = 1 \)) the minimum energy of a photon emitted:

\[ 13.6 - 3.4 = 10.2 \text{eV} = 10.2 \times 1.60 \times 10^{-19} \text{J} \]

Since \( E = hf = \frac{hc}{\lambda} \) so \( \lambda = \frac{hc}{E} = \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{10.2 \times 1.60 \times 10^{-19}} = 1.2 \times 10^{-7} \text{m} = 120 \text{nm} \)

This wavelength is in the ultraviolet (UV) region of the electromagnetic spectrum and is therefore not visible to the human eye.
The same applies to all transitions to the ground state as all have wavelengths < 120 nm. The wavelengths are discrete and form a set of lines all in the UV called the Lyman series for atomic hydrogen. When transitions occur to the n = 2 state, the minimum energy is 1.9eV. The wavelength of this line can be shown to be 650nm that is a visible line in the H spectrum. Other lines occur to the state n = 2 and these form the Balmer series.

Problem: Given that the visible range is from 400 to 800nm, prove that all Balmer lines are not visible.

It follows that the lines in the atomic hydrogen spectrum can be split up into groups:
The **Lyman series** consists of all lines involving a transition to state n = 1 from a state n > 1. These are UV lines.
The **Balmer series** consists of all lines from n > 2 to n = 2 (the first excited state). Some of these are visible but the series limit is in the UV.
The **Paschen series** consists of all lines from n >3 to n= 3. These are less energetic photons and the lines are in the infrared.

Note the increasing closeness of lines towards the short wavelength end of each series, i.e. the series limit.

The **ionisation energy** of an atom is the minimum energy required to remove a single electron from an atom in its most stable (or ground) state. The ionisation energy for hydrogen is therefore 13.6eV or $13.6 \times 1.6 \times 10^{-19} = 2.2 \times 10^{-18} \text{J}$.

A continuous spectrum consists of a continuous range of frequencies that can extend into the UV and IR. All bodies emit electromagnetic radiation but, as the temperature of a body increases, the average photon energy increases, i.e. more higher frequency (lower wavelength) radiation is produced.

An ordinary electric filament lamp contains a tungsten filament that can be heated in an inert gas by the passage of electricity through the filament wire. When turned on the wire heats up very quickly – first “red hot” and then it becomes “white hot” as a larger proportion of the shorter wavelengths are emitted.

“Spectrum of frequencies emitted by a hot body at two different temperatures.” Note that 6000K is approximately the temperature of the sun’s surface and the maximum is greenish in colour.

Notice that as the temperature increases, more of all wavelengths present increases and, in addition, the peak of the curve which shows the radiation wavelength most commonly emitted, moves towards the shorter wavelengths. As the temperature of the filament in an electric lamp increases, it first glows dull red (when the current through it is low) then as the current increases it becomes orange, then yellowish and finally appears to us as effectively white light.

In general, a continuous spectrum is emitted by solids, liquids and high-pressure gases that have been heated – the materials become visible as the temperature rises.

**Line Absorption Spectrum**

When light with a continuous spectrum, i.e. all wavelengths are present, is incident on a gas of an element, discrete frequencies of the lines are absorbed resulting in dark lines appearing in the otherwise continuous spectrum thus producing a line absorption spectrum.

In the laboratory, an absorption spectrum of a gas at room temperatures may be produced as shown in the diagram below.

Atomic Hydrogen gas at room temperature has most of its atoms in the lowest (most highly bound) state. When frequencies in the visible range fall on atomic hydrogen none of these has sufficient energy to lift an electron from n=1 to n=2 state. This energy is a minimum of 13.6 - 3.4= 10.2eV to excite the atom from the ground state. A 10.2eV photon is in the ultraviolet (its $\lambda = 1.2 \times 10^{-7} \text{m}$) and hence no absorption spectrum can be observed, in the laboratory, for atomic hydrogen at room temperatures.

Note that only photons of energy exactly equal to the energy difference between two energy states of an atom can be absorbed. This is why the absorption spectrum of atomic hydrogen gas is a line spectrum in the ultraviolet region when the gas is at room temperature.

Lines in absorption spectra are not quite completely ‘dark’ because when incident radiation is absorbed it excites the atom but this frequency is almost instantly re-emitted in all directions, not simply in the direction of the incident radiation. Thus there is a reduction in the intensity of particular frequencies but the lines are only relatively dark in comparison with the rest of the bright spectrum.

It is worth noting that from the above argument, we can see that the frequencies (and hence wavelengths) of the absorption lines for any element will only be a subset of those in the line emission spectrum of the same element.
Absorption Spectrum of the Sun-Fraunhofer lines

The core of the Sun is at a very high temperature (hundreds of millions of °C or K – it doesn’t matter which) while the outer corona has its surface layer at about 6000K. This means that lines in the very high frequencies in the continuous spectrum from the Sun’s core can be absorbed by atoms of gas which are at very higher temperatures than in the laboratory.

The dark absorption lines appearing in the spectrum of the Sun are called Fraunhofer lines. An analysis of the wavelengths of these lines, using spectrometers, where the instruments often use reflection gratings as dispersion elements, show us that the Sun itself contains at least 2/3 of the elements present on the Earth.

Fluorescence

“When an atom absorbs high-energy photons, it is elevated to ‘excited states’ (energy states above the ground state). Excited states are usually short-lived and the atom quickly returns to its ground state, often by emitting a series of lower energy photons. This process of converting high-energy photons into a larger number of lower-energy photons is called ‘fluorescence’.” Consider the energy level diagram for atomic hydrogen.

Process of Ordinary and Stimulated Emission from Atoms

To date we have only talked about the ordinary or spontaneous emission of photons from atoms which have been excited either in an electric discharge (by collision with electrons) or by absorption of photons of light from a source of electromagnetic radiation, which emits some photons with energies exactly equal to the energy differences between lower and higher atomic energy levels of the atom concerned.

When, however, a photon with energy corresponding to a transition from a higher energy state to a lower state is incident on an atom already in that higher energy state it can stimulate a transition to the lower state. When this occurs the photon emitted is identical in energy, direction and phase, to the original ‘stimulating’ photon.

Normally in a group of atoms, the population of atoms in the lowest state will be greater than that of the first excited state. The population of this first excited state will then in general, be greater than that of the second excited state and so on.

This can be illustrated below where the horizontal lines represent the proportion of atoms, in a sample, in each energy state.

If the temperature rises to $T_2$, where $T_2>T_1$, the proportion of atoms in each excited state increases, while that in the ground state decreases. The general shape of this distribution remains as shown.

A population inversion is produced in a set of atoms whenever there are more atoms in a higher energy state than in a lower-energy state.

When a population inversion occurs within a set of atoms and these atoms are stimulated by bombardment with photons of energy exactly equal to the difference in energy between the ground and excited state, there will be more stimulated emissions that absorptions. It is under such conditions that laser action is possible.

LASER is an acronym – LIGHT AMPLIFICATION by the STIMULATED EMISSION of RADIATION.

Population inversion will, in general, only occur when the average lifetime of atoms in an excited state is very much greater than is usually the case (eg $10^{-15}$s rather than $10^{-18}$s). These relatively long-lived states are called METASTABLE and in a gas laser the existence of an appropriate metastable state is a requirement for laser action to occur. For laser action to occur more than 50% of the atoms in a sample must be in an excited state.

Application LASERS

The Helium-Neon (He-Ne) gas laser is common in most schools. The gas is a mixture of about 15% He and 85% Ne. A high voltage is applied to this, causing an electric discharge within the gas. The energy changes occurring are illustrated below.

Note: 20.61 eV in He is almost exactly to 20.66eV in Ne.

Energy levels for Helium and Neon. Helium is excited in the electric discharge to state $E_1$. This energy is transferred to $E'_3$ level of the Neon by collision. $E'_2$, is metastable and decays to $E'_1$ by stimulated emission.
An actual He-Ne gas laser would look something like this.

Evacuated tube containing He-Ne gas

A highly reflecting mirror

A highly reflective end mirror which will transmit some light, although it reflects most of it.

Absorber
The small portion of light incident on the right hand reflecting mirror, which is transmitted, forms the laser beam. Most of the light travels backwards and forwards between the two reflecting surfaces and these photons stimulate other atoms causing them to emit radiation leading to an energy build-up. Because only the light waves normal to the mirrors (which must be accurately aligned) is reinforced, the laser beam which is emitted does not diverge ie it is a plane wave.

Note that the laser is a device that can produce a very narrow, intense beam of monochromatic and coherent light. The Human eye has its own convex lens and a narrow laser beam directed into a persons eye would focus onto an even narrower beam on the retina of the eye. This high concentration of energy, across a very small area can, and does, burn the retina therefore destroying its capability to provide "sight" in this region. School lasers are low in power but despite this they can cause serious damage to eyes.

SAFETY RULES WHEN HANDLING LASERS

- Never look directly into (ie along) a laser beam either directly or after reflection from a smooth surface such as a mirror or a shiny piece of paper.
- Never play with lasers. They are not toys.
- When handling lasers one should always wear safety goggles - this is very important indeed with high-energy lasers.

Lasers can, in practice, be designed to operate continuously or emit short pulses of high intensity radiation as described in the LADS application.

Laser applications use the properties of the light as being monochromatic, coherent and having a very high intensity. They are used in:

- CD players or scanners for reading bar-codes in shops where the bar-code reader is finely tuned to be the laser frequency so it is not confused with other light.
- Surveying or "flattening" paddocks for agriculture where the light can be detected after travelling very long distances in a very straight line.
- Medicine: narrow high intensity beams can "weld" detached retinas or be used in surgery with optical fibre transmission or for breaking up gall and kidney stones.
- Industry: welding metals with high energy laser beams or using narrow beams for "drilling" (really evaporating) little holes in metals!
- Holography ie 3D image production.

Problem set example

1. (a) How do the emission spectra of elements provide evidence that (outer) electrons may only possess certain energies characteristic of each element. Chararcteristic energy transitions

(b) Two lines in the sodium spectrum have wavelengths \(5.890 \times 10^{-7}\) metres and \(5.896 \times 10^{-7}\) metres.

An experimental physicist wishes to produce a sodium spectrum containing one of the two lines constituting the "sodium doublet". Suggest the energies of electrons with which they will bombard sodium vapour in order to attempt to provide such a spectrum.

\[
E = \frac{hc}{\lambda} = \frac{6.625 \times 10^{-34} \times 3 \times 10^8}{5.89 \times 10^{-7}}
\]

\[
= 3.36 \times 10^{-19}\text{ Joules} = 2.108 \text{ eV.}
\]

\[
E = \frac{hc}{\lambda} = \frac{6.625 \times 10^{-34} \times 3 \times 10^8}{5.896 \times 10^{-7}}
\]

\[
= 3.32 \times 10^{-19}\text{ Joules} = 2.106 \text{ eV.}
\]

Energies less than 2.108 eV and greater than or equal to 2.106 eV.

2. (a) Suggest experiments to show which of the Fraunhofer lines in the spectrum of sunlight are due to absorption in the Sun's atmosphere rather than to absorptions in the Earth's atmosphere.

To answer this question you would need to go outside the Earth's atmosphere.

(b) How might one decide from spectroscopic observations whether the moon and the planets shine by their own light or by light reflected from the Sun?

You would see if the Solar emission lines exist in the "reflected" spectrum.

3. Theoretically, how many series of lines are there in the emission spectrum of hydrogen?

In all these spectra how many are in the visible spectrum?

Theoretically infinite and there are 4 frequencies in the visible spectrum
**Topic Two: The Structure of the Nucleus**

All **neutral atoms** contain a small (radius about \(10^{-14}\) m), positively charged **nucleus** surrounded by electrons in an ordered arrangement so that the total positive charge on the nucleus is equal to the total negative charge of all the "attached" electrons.

Nuclei consist of **protons** (positively charged) and, other than for the simplest atom of hydrogen, one or more neutral **neutrons**. The mass of a proton is about \(1836\times\text{mass of an electron}\).

The mass of a neutron is about \(1838 \times \text{mass of an electron}\). This means that neutrons and protons have approximately the same mass. It also means that by far the most massive part of any atom is its nucleus.

A **nucleon** is a collective term meaning protons and neutrons.

The number of protons + number of neutrons in a nucleus = number of nucleons in that nucleus. The total number of nucleons in a nucleus (or atom) is called the **mass number** of that nucleus (or atom) and has the symbol \(A\).

The number of protons in a nucleus (or atom) is called the **atomic number** of that nucleus (or atom). The number of neutrons in a nucleus (or atom) = \(A - Z\). i.e. \(A = N + Z\)

A nucleus is specified in the form \(\frac{A}{Z}X\) or \((X^A)\) where \(X\) represents the chemical symbol for the element involved.

Example: hydrogen \(\frac{1}{1}H\) contains 1 proton only (\(Z=1, A=1, N=0\)). Heavy hydrogen \(\frac{2}{1}H\) has \(Z=1, A=2, N=1\). This form of hydrogen is often called heavy hydrogen or deuterium and its nucleus is called the **deuteron**.

Carbon \(\frac{12}{6}C\) (\(Z=6, A=12, N=6\)) is only one of the possible forms of carbon, \(\frac{13}{6}C\), \(\frac{14}{6}C\), \(\frac{11}{6}C\) etc all exist and are called **isotopes** of carbon. They have the same number of protons but differing numbers of neutrons. Isotopes of any given atom are chemically the same but differ in mass. The charge on a proton is numerically equal to the electron charge. However a proton is positively charged whilst an electron has a negative charge.

The isotopes of a given element are chemically identical because each has the same pattern of surrounding electrons and it is these that are involved in chemical reactions.

**Nuclear Forces**

These are the forces that are strongly attractive in order to hold the nucleons in nucleus tightly together.

Nuclear forces are very strong compared with electrical forces but they are **very short range forces**.

Nuclear forces become negligible at more than a few nucleon diameters from another nucleon. They are also repulsive when the nucleon separation is very small indeed – this implies that no two nucleons can, at any instant, occupy the same bit of space.

Attractive nucleon forces are independent of the nature of the nucleon. i.e. The force between 2 protons = the force between 2 neutrons = the force between a proton and a neutron, provided that the separation is the same for each pair of nucleons specified.

Although the positive protons in a nucleus repel each other with Coulomb electrostatic forces, stable nuclei containing up to 83 protons can exist provided that each one contains a number of neutrons (usually greater than the number of protons). These neutrons separate the protons and dilute the repulsive forces so that the very strong nuclear attractive forces take over.

**Binding Energy and Mass Defect**

When two or more nucleons combine to form a nucleus the total mass of the nucleus is always less than the sum of the masses of the individual nucleons. i.e. it would appear that mass has been destroyed.

The mass lost has been converted into energy according to Einstein’s well known relationship: \(E = \Delta mc^2\) where \(c\) is the speed of light. The mass that “disappears” when a nucleus is formed is called the mass defect, \(\Delta m\).

The binding energy \(BE\) of a nucleus is the minimum amount of energy that needs to be given to a nucleus in order to split it into its separate nucleons. \(BE = \Delta mc^2\)

If \(\Delta m\) is in KE, using \(c = 3\times10^8\text{ms}^{-1}\) gives a BE in joules (J).

The BE in eV is calculated by dividing the BE in J by the charge on an electron \(e = 1.6\times10^{-19}\text{C}\).

Note: When a nucleus is separated into its constituent nucleons, energy must be supplied and its mass increases by an amount \(\Delta m\). When the constituent nucleons combine to form a nucleus energy is given out.

**Problem**

Consider the situation when a neutron combines with a proton to produce a nucleus \(\frac{2}{1}H\) (a deuteron).

What is the BE of \(\frac{2}{1}H\)? The relevant nuclear equation is: \(\frac{1}{1}H + \frac{1}{0}n \rightarrow \frac{2}{1}H\)

\[
\text{mass } \frac{1}{1}H (\text{a proton}) = 1.67349 \times 10^{-27} \text{kg} \\
\text{mass } \frac{1}{0}n (\text{a neutron}) = 1.67489 \times 10^{-27} \text{kg} \\
\text{mass } \frac{2}{1}H (\text{a deuteron}) = 3.34442 \times 10^{-27} \text{kg}
\]

Here \(\Delta m = [(1.67349 + 1.67489) - 3.34442] \times 10^{-27}\)

\[= 3.96 \times 10^{-30} \text{kg}\]

\[\text{BE} = 3.96 \times 10^{-30} \times (3 \times 10^9)^2 \]

\[= 3.56 \times 10^{-13} \text{J} = 2.22 \times 10^9 \text{eV} = 2.22\text{MeV}\]

The deuteron plays an important part in nuclear physics because just as the hydrogen atom with 1 proton and 1 electron is the simplest atom, so is the deuteron with 1 proton and 1 neutron the simplest nucleus.
Conservation Laws in Nuclear Reactions

In nuclear reactions the following quantities are conserved:

- Number of nucleons
- Total charge
- Momentum
- Mass/energy ie. the total energy is conserved where mass is regarded as a form of energy.

Nuclear reactions can be written in the form of equations: e.g. \( ^{226}_{86}\text{Ra} \rightarrow ^{222}_{86}\text{Rn} + ^4_2\text{He} + Q \)

Note: ie. the number of nucleons is the same on both sides of equation. \{ 226=222+4 \}

ie. the charge is the same on both sides of the equation. \{88=86+2 \}

Q represents the energy given off in the reaction which is the decay (natural) of radium to produce radon plus a He nucleus. It can be calculated because: \( Q = (\text{mass Ra} - \text{mass Rn} - \text{mass He}) \times c^2 \)

**APPLICATION The Production of radio-isotopes**

**Transmutation of Nuclei:** When a particles such as a neutron \(^1_n\), proton \(^1_H\), deuteron \(^2_H\) or \(^\alpha\)-particle \(^4_2\text{He}\) is incident on the nucleus \(^A_Z\text{X}\) of an atom, it is possible to produce a nuclear reaction in which a new element Y (with differing values of Z, A or both, from element X) will be produced.

Very often in a nuclear reaction the sum of the masses of the product particles are greater than the sum of the masses of the original particles – in this case the extra mass must be produced from the kinetic energy of the incident particle. If \( A + B \rightarrow C + D \) and \( \{m_A + m_B\} c^2 > \{m_C + m_D\} c^2 \) i.e \( m_A + m_B > m_C + m_D \) the particles C and D will move off, the excess mass appearing as kinetic energies of particles C and D – an exothermic or exoergic reaction, whereas \( (2) m_A + m_B < m_C + m_D \) 

It follows that the minimum energy required for an incident particle to produce a reaction is

\[ E_{\text{min}} = \{\text{mass}_C + \text{mass}_D - \text{mass}_A - \text{mass}_B\} c^2 \]

An example of such a reaction is \( ^{13}_6\text{C} + ^1_1\text{H} \rightarrow ^{13}_7\text{N} + ^0_1\text{n} \)

Using mass \( ^{13}_6\text{C} = 2.159207 \times 10^{-26} \) kg.

mass \( ^1_1\text{H} = 0.167349 \times 10^{-26} \) kg.

Total mass \( = 2.326556 \times 10^{-26} \) kg.

and mass \( ^{13}_7\text{N} = 2.159603 \times 10^{-26} \) kg.

mass \( ^0_1\text{n} = 0.167488 \times 10^{-26} \) kg.

Total mass \( = 2.327091 \times 10^{-26} \) kg. It is apparent that the mass has been created!

The minimum energy required for this reaction to proceed is therefore

\[ = \{(2.327091 - 2.326556) \times 10^{-26} \} \times c^2 \text{ Joules.} = 4.82 \times 10^{-13} \text{ J} = 4.82 \times 10^{-13} / 1.6 \times 10^{-19} = 3.0 \times 10^6 \text{ eV or 3.0 MeV} \]

This means if \( ^{13}_6\text{C} \) is bombarded with protons that have been accelerated (eg in a cyclotron) then the proton energy must be at least 3.0 MeV if this reaction is to occur the creation of the \( ^{13}_7\text{N} \) isotope of N.

Now this isotope of nitrogen is of use medically. When plotted on a neutron number versus proton number graph for stable nuclei \( ^{13}_7\text{N} \) falls below the curve. It has too many protons for stability and hence will decay by beta plus (\( \beta^+ \)) emission \( ^{13}_7\text{N} \rightarrow ^0_1\text{e} + ^{13}_6\text{C} + \nu \) [half-life of about ten minutes]

When an \( ^0_1\text{e} \) is produced in a body then it immediately interacts with a negative electron and annihilation radiation giving photons of energy 0.51 MeV which can be detected outside the human body. The short half-life is useful – it prevents the patient being “radioactive” for too long a period.

Other reactions can be used to produce \( ^{13}_7\text{N} \) eg by bombarding \( ^{12}_6\text{C} \) with deuterons when \( ^{12}_6\text{C} + ^2_1\text{H} \rightarrow ^{13}_7\text{N} + ^0_1\text{n} \)

A cyclotron also can produce the deuterons.

Nuclear reactors, dealt with later in the course, can be used to produce neutron beams and such beams are also useful for producing radioisotopes for use in medicine, industry and agricultural sciences.

\( ^{60}_{27}\text{Co} \) is used in industrial radiography and radiotherapy and produced by bombarding stable \( ^{59}_{27}\text{Co} \) with neutrons when \( ^{59}_{27}\text{Co} + ^0_1\text{n} \rightarrow ^{60}_{27}\text{Co} \) which is \( \beta^1 \) active, has half-life about 5 years, and the excited Ni nucleus which is produced when \( ^{60}_{27}\text{Co} \) decays will emit two \( \gamma \)-rays of energy 1.17 MeV and 1.33 MeV respectively.

Reactors such as those at Lucas Heights are used for producing isotopes like this.
**Topic Three: Radioactivity**

**Particles**

- **Electron**
  
e, small mass $m_e$, unit negative charge, symbol $^0_e$।

- **Positron**
  
e$, small mass $m_e$, unit positive charge, symbol $^0_+e$।

- **Neutron**
  
neutral particle, mass $\approx 1838 \times m_e$, symbol $^1_0n$।

- **Proton**
  
positive particle, mass $\approx 1836 \times m_e$, symbol $^1_0p$ or $^1_1H$।

- **Neutrino**
  
zero charge and mass, symbol $\nu$।

- **Antineutrino**
  
zero charge and mass, symbol $\bar{\nu}$।

- **Nucleons**
  
either protons or neutrons।

**For an atom**

- atomic number $Z$ = position of atom in periodic table, ।
- = number of protons in nucleus, ।
- = number of electron in neutral atom. ।
- mass number $A$ = number of nucleons in nucleus।

The isotopes of a given atom have nuclei with the same number of protons but differing numbers of neutrons. ie the same $Z$ but different $A$. All isotopes of a given element behave chemically in the same way - they simply differ in mass.

A nuclide is a particular nucleus with specified values of both $Z$ and $A$।

- $^1_1H$ hydrogen (light) contains 1 proton. ।
- $^2_1H$ hydrogen (heavy) or deuteron contains 1 proton and 1 neutron।
- $^3_1H$ hydrogen (heavier) or tritium, contains 1 proton and 2 neutrons।

are all different nuclides of hydrogen।

Nuclei can be either stable or unstable।

A stable nucleus does not disintegrate in any way unless given extra energy।

An unstable nucleus will disintegrate of its own accord either by emitting ।

- $\alpha$-particles ($^4_2He$ nuclei) or ।
- $\beta$-particles (negative electrons) or $\beta^+$ particles (positrons)।

**Stable and Unstable Nuclei**

Naturally occurring isotopes may be either unstable or stable।

For low atomic number nuclei, stable nuclei usually have approximately the same number of protons ($Z$) as they have of neutrons।

ie $N = A - Z = \text{number of neutrons in the nucleus} = \frac{1}{2}X$ (X represents any element)।

Nuclei like this are: ।

- $^2_1H$ the deuteron।
- $^4_2He$ the nucleus of helium, often called an $\alpha$-particle।
- $^{12}_6C$ the nucleus of the most common carbon isotope।
- $^{16}_8O$ the nucleus of the most common oxygen isotope।

This holds until about $Z=20$.।

As the atomic number of a nucleus increases, the repulsive forces between protons increases (protons are positively charged and therefore repel each other). To overcome this for elements with $Z>20$, stable nuclei have more neutrons than they have protons।

The nuclei occupy space, separate the protons somewhat and hence dilute (decrease) the repulsive Coulomb force between protons।

For lead (Pb) we have $Z=82$ and this element has several stable nuclei।

eg $^{206}_{82}Pb$ with the neutron proton ratio $N/Z=1.51$ or $^{208}_{82}Pb$ with $N/Z=1.54$।

All elements with $Z>83$ are inherently unstable and such unstable elements are said to be radioactive।

Graph of neutron number ($N$) plotted against proton number ($Z$) for stable nuclei।
The graph shows that stable nuclei are represented by points lying within a small range about the line of stability.

**Decay of Unstable Nuclei**

There are four possible ways in which unstable nuclei can decay:

1. **Alpha (α) decay** in which α particles (ie He nuclei) are emitted from the unstable nucleus. Occurs when Z>83.
2. **Beta minus (β^-) decay** in which electrons e^- are emitted. Occurs when nucleus N/Z plot lies above the line of stability.
3. **Beta plus (β^+) decay** in which positrons e^+ are emitted, occurs when N/Z plot lies below the line of stability.
4. Spontaneous fission in which the nucleus splits into two parts.

We shall consider each of these processes in turn.

**Alpha Decay**

Since an α-particle is a helium nucleus, \(^4\text{He}\), it has a positive charge of 2 units each of magnitude e and a mass approximately 4×the mass of a proton or a neutron.

The general α-decay equation is: \(\frac{A}{Z}X \xrightarrow{\alpha\text{-decay}} \frac{A-4}{Z-2}Y + \frac{4}{2}\text{He} + \text{energy}\)

X is called the parent nucleus. Y is called the daughter nucleus.

A typical α-decay process is: \(\frac{238}{92}\text{U} \rightarrow \frac{234}{90}\text{Th} + \frac{4}{2}\text{He} + \text{energy}\)

Note: Both U and Th have atomic numbers > 83 and both of these elements are radioactive.

The α-decay process causes a rise in the neutron/proton ratio, ie N/Z increases:

\[
\text{for } ^{238}_{92}\text{U, } \frac{N}{Z} = \frac{238 - 92}{92} = 1.5870 \quad \text{for } ^{234}_{90}\text{Th, } \frac{N}{Z} = \frac{234 - 90}{90} = 1.60
\]

Thus if Th-234 also decayed by α emission an even less stable isotope would be formed as N/Z would increase further. Another type of decay process is needed to reduce N/Z and this is a β^- decay.

When an α-particle is emitted it is often followed almost immediately by the emission of one or more high energy photons (usually energy > 0.5MeV) which are called gamma γ-rays. A γ-ray photon is indistinguishable from an X-ray photon of the same energy.

Nuclei have discrete energy levels, just like atoms. When an α-particle is emitted the daughter nucleus is often excited, ie it is in an energy state above the lowest (ground) state.

The He nucleus is a very tightly bound group of particles, ie its mass is significantly less than the total mass of the 4 nucleons it contains. Because both parent and daughter nuclei are in discrete energy states it follows that the α-particles have discrete energy values as also have associated γ photons.

A diagram showing α-emission followed by γ-ray emission is as follows:

\[E_3\]

\[E_2\]

\[E_1\]

Parent energy levels

\(\alpha_2\)

\(\alpha_1\)

\(\gamma\)

Daughter \(\frac{A-4}{Z-2}Y\) energy levels

\(E_1'\)

\(E_2'\)
If the parent X is in the ground state it could decay to the excited state E′₂ or the ground state E₁′ of the daughter Y - thus 2 discrete energy α's would appear (labelled α₂ and α₁). If Y is in the excited state E₂′ it decays to the ground state by the emission of the γ ray shown. If the daughter has 2 or 3 excited states, not just one, then 3 or 4 α's with differing energies can appear as well as several γ's. The reason why γ rays have higher energy than light from excited atoms (usually visible or ultraviolet photons) so that the separation of nuclear energy levels is much greater than the separation of atomic levels.

Note that the energies of γ rays produced after α-decay are equal to the energy differences between levels in the daughter nucleus.

**Beta Minus Decay** This process occurs only when a nucleus has an excess of neutrons.

The process is

\[ _0^1n \xrightarrow{\beta^- \text{decay}} _0^1H + _1^0e + \overline{\nu} \]

You will notice that a new particle: \( \overline{\nu} \) the antineutrino

\( \overline{\nu} \) is a particle with mass zero (or near zero) and therefore it travels with about the speed of light and only interacts with matter with a very weak force. Hence the neutrino is very difficult to detect - its existence is necessary because the β electron has a range of energies from → zero to → E_{max} and energy would not be conserved unless a third particle was produced. Pauli postulated this in 1930 and called it a neutrino. ie a "little neutral one" . ie no mass, no charge. Neutrinos have however been detected experimentally.

In addition, if momentum is conserved a neutrino also is needed to ensure its conservation.

A general β⁻ decay equation is

\[ \overset{A}{Z}X \xrightarrow{\beta^- \text{decay}} \overset{A}{Z+1}Y + _1^0e + \overline{\nu} \]

ie the mass number of daughter = that of its parent but it has a greater atomic number. ie the neutron proton ratio is decreased.

After β⁻ decay occurs the daughter nucleus may be left in an excited state so that the β⁻ emission is followed quickly by the emission of a γ-ray photon.

An example is

\[ \overset{60}{27}\text{Co} \xrightarrow{\beta^-} \overset{60}{28}\text{Ni} + _{-1}^0e + \overline{\nu} \]

**Beta Plus Decay**

This occurs when the parent nucleus has too many protons. A proton is converted into a neutron plus a positron and a neutrino.

\[ _0^1H \xrightarrow{\beta^+ \text{decay}} _0^1n + _1^0e + \nu \]

The general equation is therefore:

\[ \overset{A}{Z}X \xrightarrow{\beta^+ \text{decay}} A^0e + \nu \]

An example is

\[ \overset{19}{10}\text{Ne} \xrightarrow{\beta^+} \overset{19}{9}\text{F} + _1^0e + \nu \]

The positrons (β⁺ particles) emitted have a range of energies as do β⁻ particles and again, the daughter may be left excited and can decay by γ-ray emission to the ground state.

When a positron appears it disappears fast! There are many free electrons in the environment and when e⁺ meets e⁻ they annihilate and produce 2 γ-rays.

The energy destroyed = \( 2m_e c^2 = 2 \times 9.1 \times 10^{-31} \times (3 \times 10^8)^2 \) J = 1.02 MeV

ie. Each emitted γ has 0.51 MeV of energy. These γ rays are called "annihilation radiation".

**Half-Life and Radioactivity**

A radioactive substance is one in which the nucleus is inherently unstable and decays by α or β emission.

Many unstable isotopes occur in nature eg \(^{235}\text{U},^{238}\text{U},^{40}\text{K}\) and \(^{14}\text{C}\). They are called naturally radioactive. It is possible to produce radioactive isotopes in the laboratory either by bombardment of materials with high-energy particles (eg protons accelerated in a cyclotron) or by nuclear fission and fusion, which will be discussed later.

The number of radioactive nuclei in a sample of given isotope varies exponentially with time.

ie if \( N_0 \) = the original number of radioactive nuclei at time 0. and \( N_t \) = the number left after time t then the activity of the sample at any instant will be decreasing with time.

The unit of activity of a radioactive substance is the bequerel (Bq) where: 1 Bq = 1 decay per second

Note: Activity = the number of decays per second. ie. activity at time t is proportional to \( N_t \) where the constant of proportionality depends on the particular isotope being considered.
(a) The number N of parent nuclei in a given sample of $^{14}\text{C}$ decreases exponentially.

(b) The number of decays per second also decreases exponentially. The half-life of $^{14}\text{C}$ is 5730 yr, which means that the number of parent nuclei, N, and the activity, $\Delta N/\Delta t$, decrease by half every 5730 yr. The half-life, $T_{1/2}$ of a radio-isotope is the time for half of the radioactive nuclei in a given pure sample of isotope to decay.

Example: A sample of $^{13}\text{N}$ in the laboratory having a half-life of 600 seconds contains $7.0 \times 10^{16}$ nuclei. How many nuclei will be left after 2400 seconds have elapsed?

Note: $2400 = 4 \times 600$ ie four half-lives have elapsed.

<table>
<thead>
<tr>
<th>Time</th>
<th>Atoms</th>
<th>No of Half lives</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$7.0 \times 10^{16}$</td>
<td>0</td>
</tr>
<tr>
<td>600</td>
<td>$3.5 \times 10^{16}$</td>
<td>1</td>
</tr>
<tr>
<td>1200</td>
<td>$1.75 \times 10^{16}$</td>
<td>2</td>
</tr>
<tr>
<td>1800</td>
<td>$8.8 \times 10^{15}$</td>
<td>3</td>
</tr>
<tr>
<td>2400</td>
<td>$4.4 \times 10^{15}$</td>
<td>4</td>
</tr>
</tbody>
</table>

ie $4.4 \times 10^{15}$ atoms are left or $1/2^4 = 1/16$ of the number in the original sample.

Note that RADIOACTIVITY IS A RANDOM PROCESS and has a constant probability for any particular radioactive nucleus.

The half-life is greater for smaller decay probabilities. ie long lived isotopes such as $^{238}\text{U}$ where $T_{1/2} = 4.5 \times 10^9$ years have low decay probabilities while short lived isotopes $^{131}\text{I}$ have high decay probabilities the half life being only 8.0 days. All the I-131 in the world is produced artificially. The U-238 is naturally occurring in fact its half-life is about the age of Earth so that there is now only about 1/2 of the original U-238 present.

Some Properties of Radioactive Emissions

Alpha, beta and gamma radiations are all called ionising radiations because they all produce ionisation in any material through which they may pass. Alpha and beta (both $\beta^+$ and $\beta^-$) particles are all charged particles so that on passing through matter, the Coulomb electrical forces can attract and or repel electrons in the matter so strongly that ionisation of both atoms and molecules can occur.

In general it takes up to no more than about 50, at the most, electron volts of energy to ionise an atom or a molecule and since the energy of an $\alpha$ or $\beta$ particle is up to several million electron volts it follows that a single charged particle can produce many thousands of ionisations.

Gamma rays (and X-rays) although not electrically charged can cause ionisation because they can knock electrons out of matter by either the photoelectric effect or Compton scattering process. In addition if gamma or X-ray energy is $>1.02\text{MeV}$ then pair production of high energy electrons occurs. These electrons produce ionisation as do $\beta$ particles.

Neutrons are neutral and collide with nuclei – often a new nucleus is formed which may be radioactive or the incident neutron can split a nucleus into two or more fragments causing more ionisation.
Penetration of Ionising Radiations

Heavy particles (e.g., α particles) are much more likely to lose energy and create ions as they pass through matter than are either β⁻ particles or gamma rays. If follows that when passing through any particular medium the range of gamma ray photons will be greater than that of β⁻ particles which will, in turn, have a greater range than α particles.

range γ > range β⁻ > range α. This means that γ rays penetrate matter more than do β⁻ and β⁻ penetrates more than α.

<table>
<thead>
<tr>
<th>Type of Particle</th>
<th>Electric Field</th>
<th>Magnetic Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ ray photons</td>
<td>No effect</td>
<td>No effect</td>
</tr>
<tr>
<td>β⁻ particles</td>
<td>Accelerate in direction opposite to E and hence travel in straight lines if the direction is parallel to E or a parabolic path if the direction is not parallel to E.</td>
<td>Move in circle if direction is perpendicular to B. Travel in straight line if direction is parallel to B.</td>
</tr>
<tr>
<td>β⁺ particles</td>
<td>As above but accelerate at 180° to above.</td>
<td>As above but accelerate at 180° to above. The speed in all of these cases is constant.</td>
</tr>
<tr>
<td>α particles</td>
<td>Force is 2eE parallel to E. So acceleration is ( a = \frac{2eE}{M} ), where ( M ) = mass of α</td>
<td>Since charge = 2e, ( B(2e)v = Mv^2/r ) and ( r = \frac{Mv}{2eB} ) if ( v ) is perpendicular to B.</td>
</tr>
</tbody>
</table>

The Effects of Ionising Radiation on Living Matter

When ionising radiation passes through living matter – e.g., human skin, flesh, bones and organs, several different processes occur basically because of the ions produced. The ions (ionised atoms) or radicals (ionised parts of molecules which are inclined to hang together as a group, free of other parts of the molecule) produced are often highly reactive and can behave chemically so that they interfere with normal processes within a cell.

These free radicals can sometimes be repaired since if one molecule is destroyed, given time, a replica can be produced. When DNA is damaged, a gene is affected and the cell may die. If many cells die the organism may not recover. If it survives in a damaged state then it may go on dividing and produce many similar damaged cells – a cancer can thus occur.

Radiation damage is classified as either somatic (affects the particular organism under consideration) or genetic (affects reproductive cells and hence the offspring of an individual). Mutations are produced when genetic cells are damaged and the vast majority of these are harmful.

Radiation damage depends, in general, on both the absorbed dose (i.e., the energy absorbed by the material per unit mass) and a quality factor (QF) determined by the type of radiation considered. The unit of absorbed dose is the gray (Gy) where: \( 1 \text{Gy} = 1 \text{Jkg}^{-1} \) (1 joule per kilogram).

The equivalent dose (often called the effective dose) used for measuring the amount of damage is the sievert (Sv). dose in Sv = dose in Gy × QF. By this definition 1 Sv of any type of ionising radiation will produce about the same amount of biological damage in a given tissue.

Radioisotopes are used not only medically but also in other industrial occupations. Again, modern dosage limits and regular monitoring of exposed individuals, ensure that dosages received by operators are not very much greater than those received by members of the general public. Only in cases of accident (e.g., Chernobyl) or personal carelessness of operators is there likely to be a problem.

Minimisation of radiation dosages is best achieved by:

Increasing your distance away from any radioactive source. The radiation from a point source has an intensity which falls off with an inverse square relationship, even in a vacuum. In air there is further reduction due to absorption by air molecules.

Limiting your time of exposure to radiation from a source. Placing shielding materials between yourself and a source.

High energy γ rays or X-rays are best absorbed by high atomic number, dense materials such as lead (Pb). Hence the use of Pb aprons on patients having their teeth X-rayed.

β sources are best shielded using lower atomic number materials such as aluminium (Al). If high atomic number materials are used X-rays can be produced (as in an X-ray tube) so the shielding effect of such materials can be worse than useless.

α rays are absorbed by a few sheets of paper or own tough, horny hides. It is only when consumed that pure α emitters are a problem.
Application – Positron Emission Tomography (PET) Overview:

PET scanning is a non-invasive medical imaging procedure that is very useful for revealing metabolic information (eg cellular activity) rather than just anatomical information (eg location and size) like other forms of medical imaging such as X-rays, Computed Tomography (CT or CAT), ultrasound and Magnetic Resonance Imaging (MRI).

It works by first injecting the patient with a substance that has a radioisotope incorporated into it that produces positrons. Such a material is sometimes referred to as a radiotracer or tracer radioisotope. This substance (e.g. a glucose substitute) then takes between 30 and 90 minutes to accumulate in the tissue under study. The scanning is then performed and takes around 30 to 45 minutes to complete.

When a positron emitted from the radioactive substance encounters an electron in the surrounding tissue, they annihilate each other; producing a pair of gamma photons moving in opposite directions (momentum must be conserved!) that are then recorded by a ring of gamma detectors as shown in the diagram below:

As the gamma photons are always emitted in pairs, it is relatively easy to compute their point of origin (half way along the line joining the two detection points). This is then used to build up a three dimensional image of the region under study as the patient continues to move through the detection ring. Cells that have a high glucose (or the particular tracer radioisotope used) uptake will show up the “brightest” under a PET scan. For glucose, these cells include the brain, the liver and most cancers.

The choice of which radioisotope to use depends on what part of the body is to be examined as it may allow a particular radioisotope-labelled tracer to concentrate in that area.

Some common radioisotopes used that are positron emitters include (approximate half life in brackets):

- **Carbon-11** (20 minutes) – e.g. use of C-11 labelled acetate as a tracer for functional imaging of the pancreas and related diseases
- **Nitrogen-13** (10 minutes) – e.g. use of N-13 labelled ammonia to look at heart function
- **Oxygen-15** (2 minutes) – e.g. use of O-15 labelled water as a tracer for blood flow
- **Fluorine-18** (110 minutes) e.g. use of F-18 labelled glucose to measure the metabolism of glucose in the heart

These radioisotopes are produced in cyclotrons. If a hospital doesn’t have their own cyclotron (most don’t!), the use of PET is usually restricted to Fluorine-18 as it has the longest half life. It is often incorporated in a glucose substitute called fluorodeoxyglucose (or FDG).

Uses:

**Cancer:**

- To assess tumour aggressiveness (how fast a tumour is growing)
- To monitor the success of cancer therapy (see if the cancer is diminishing in size)
- To detect if cancer has spread elsewhere in the body (location of primary site plus any metastases)
- To identify benign and malignant growths

**Heart Disease:**

- To determine what heart tissue is still alive following a suspected heart attack
- To predict the success of angioplasty (balloon) or bypass surgery
- To determine if coronary arteries are blocked by monitoring blood flow using O-15 labelled water as a tracer

**Brain Disorders:**

- To diagnose Alzheimer’s and other dementia
- To determine the location of epileptic seizures prior to surgery
- To diagnose movement disorders like Parkinson’s disease

Summary:

In summary, PET scans can demonstrate the biological functioning of the body before any anatomical changes take place. In other words, they detect changes in cellular activity before structural changes (detected by other forms of medical imaging) occur. They can distinguish between benign and malignant tumours with around 95% accuracy. As the radioactivity is very short-lived, the radiation exposure for the patient is low and there are virtually no side-effects. In recent years, PET scanning has been combined with CT scanning (uses X-rays to get accurate cross-sectional views of a person’s body) so that the size, shape and position of any problems can be more accurately located.

Calculations:

Energy of the photons produced in a positron-electron annihilation.

\[ m = 2 \times 9.11 \times 10^{-31} \text{ kg (positron & electron have the same mass)} \]

\[ E = mc^2 = 2 \times 9.11 \times 10^{-31} \times (3 \times 10^8)^2 = 1.64 \times 10^{-12} \text{ J} = 1.024 \text{ MeV} \]

(This represents 512 keV for each of the two photons produced)
**Topic Four: Nuclear Fission and Fusion.**

**Fission** means splitting into parts.

**Fusion** means joining together.

**Spontaneous and Induced Nuclear Fission**

**Nuclear fission** is the process in which a very heavy nucleus splits into two lighter nuclei.

**Spontaneous fission** can occur with some massive nuclei which can split into two lighter parts called fission fragments.

This process is not common and has no industrial importance.

**Induced fission** occurs when a heavy nucleus absorbs a neutron to form a very excited nucleus which “oscillates” and splits into two positively charged parts and often one or more extra neutrons. The common process in nuclear reactors is when \(^{235}\text{U}_{92}\) absorbs a neutron. ie:

\[
^{235}\text{U}_{92} + ^{1}_0\text{n} \rightarrow ^{236}\text{U}_{92} \rightarrow N_1 + N_2 + \text{neutron}
\]

[The half life of \(^{236}\text{U}_{92}\) is \(<10^{-12}\) seconds. ie. The actual fission occurs almost instantaneously after the neutron absorption.]

A particular case is:

\[
^{235}\text{U}_{92} + ^{1}_0\text{n} \rightarrow ^{141}\text{Ba}_{92} + ^{92}\text{Kr}_{36} + ^{2}_0\text{n}
\]

But many other resulting isotopes can be produced.

In addition the nuclei \(N_1\) & \(N_2\) are usually excited and emit \(\gamma\) rays as they decay to their ground states.

The mass of the Uranium nucleus plus the neutron is greater than the total mass of the product nuclei and neutrons so that energy is emitted in this reaction – it appears as kinetic energy of the product nuclei plus the energies of the emitted \(\gamma\) ray photons.

In a chemical reaction eg when carbon burns in oxygen to give CO and/or CO\(_2\), the amount of energy released when the atoms of C and O combine is usually only a few electron volts (eV). When however nuclear fission occurs millions of eV of energy are produced.

**Explanation of fission:** fission is most easily explained by assuming that a nucleus exists in the form of a liquid drop.

The process occurs as shown in the diagram:

Fission of a \(^{235}\text{U}_{92}\) nucleus after capture of a neutron, according to the liquid drop model.

**Chain Reaction**

In nuclear fission processes, when averaged, more than one neutron is emitted in each fission process. If these neutrons can be used to induce further fissions then a nuclear chain reaction is possible.

Most of the neutrons produced in fission have relatively high energies of 1 or 2 MeV. However, the probability of a \(^{235}\text{U}_{92}\) nucleus absorbing a neutron is very low for fast neutrons and to make a chain reaction possible the neutrons need to be slowed down to energies of less than about 10 eV.

In order to slow down the fast (high energy) neutrons a material called a moderator is used. The most effective moderating materials are those with low masses – approximating those of neutrons themselves. This can be explained if you recall the work done on collisions with momentum conservation earlier this year. Remember! Consider billiard balls of the same mass colliding.

One would therefore expect that the best moderator would contain \(^{1}_1\text{H}\) atoms (mass nucleus \(^{1}_1\text{H} \approx \text{mass } ^{1}_0\text{n})). However there is a snag because \(^{1}_1\text{H}\) tends to absorb neutrons. The result is that it is better to use heavy hydrogen, usually in the form heavy water, to act as a moderator in a nuclear reactor – it absorbs less neutrons than ordinary water does.

The Uranium ore can not be used directly to give energy from a chain reaction in a nuclear reactor. The reason for this is that the fraction of U-235 in naturally occurring Uranium is about 0.8% the rest being U-238. It is with fission of U-235 that reactors usually operate. This means that before use, Uranium ore must be *enriched*. ie. The proportion of U-235 must be increased to several percent to get a power reactor, or about 90% for weapons! This process is both difficult and expensive. It is just possible to produce a reactor operating with natural Uranium but only if the moderator is heavy water – also expensive to produce!
Many neutrons produced in fission are either absorbed by surrounding atoms or escape from the surface of the reactor – it follows that reactors can’t be made small, like tiny batteries (surface areas: volume ratio is too high). Nuclei with $30 < Z < 60$ i.e. in the range of most reactor fission products have $N$ up to about $1.5Z$, they are almost highly radioactive and can undergo many decay processes, emitting $\beta^-$ particles, before stable nuclei appear. This is why if fission fragments and hence energy are released into the surroundings when a reactor malfunctions, it is very dangerous. When fuel rods in reactors needed replacing, the used rods are difficult to handle, very dangerous and hard to get rid of! Some of the fission isotopes eg Cs-137 are useful in industrial radiography, but most are not wanted.

**Nuclear Fusion**

Nuclear fusion is the process in which two nuclei combine to form a single nucleus. Since the mass of any stable nucleus is less than the sum of the masses of its protons and neutrons, it follows that when two small particles combine mass is lost – it fact it is converted into energy \(E=\Delta mc^2\) which can hopefully, in future, be harvested industrially.

An example of a fusion reaction is: $^1_2H + ^1_2H \rightarrow ^1_1H + ^1_1H$

mass $^1_2H = 1.6734934 \times 10^{-27}$ kg
mass $^1_2H = 3.3444164 \times 10^{-27}$ kg
mass $^1_1H = 5.0081494 \times 10^{-27}$ kg
Total mass on LHS = $6.6888328 \times 10^{-27}$ kg
Total mass on RHS = $6.676428 \times 10^{-27}$ kg
difference = $7.19 \times 10^{-3} \times 10^{-27}$ kg

The problems in “taming” the fusion process arise from the fact that when two light nuclei interact, very high kinetic energies are necessary for them to get close enough to overcome the Coulomb repulsion between the two positively charged nuclei.

To get particles with the necessary high kinetic energies, very high temperatures are needed – up to millions of degrees Celsius. At this temperature all atoms and molecules are totally separated into a gaseous PLASMA and no materials can exist to contain, physically, such a high temperature plasma – steel, quartz etc would be molten at temperatures of thousands (not many millions) of degrees. A fusion process can be produced on Earth but not using a mass of particles sufficiently large to produce useful power.

In the interior of the Sun, conditions are such that nuclear fusion processes can occur. The energy output from our Sun is thought to be due to the following set of reactions:

\[
^1_1H + ^1_1H \rightarrow ^2_1H + ^0_1e + \nu + 0.42\text{MeV}
\]

\[
^1_2H + ^1_1H \rightarrow ^3_2\text{He} + \gamma + 5.49\text{MeV}
\]

\[
^3_2\text{He} + ^2_4\text{He} \rightarrow ^4_2\text{He} + 2^1_1H + 12.86\text{MeV}
\]

Other processes are possible in the stars because some of them are hotter than the Sun.

Nuclear fusion, if it can be used, has advantages over fission which is used.

- Fusion produces only stable or slightly radioactive materials. Fission produces heavy, highly dangerous, radioactive materials.
- Fusion uses simple atoms – deuterium, hydrogen etc – these are common on Earth and not themselves radioactive.

So fusion will be safer than fission. The disadvantages of fusion are basically due to problems of plasma containment (magnetic fields are used) and the need to devise new “high temperature resistant” materials and the need to somehow collect efficiently the energy produced.
APPLICATION: Fission Nuclear Power

A nuclear reactor. The heat generated by the fission process in the fuel rods is carried off by hot water or liquid sodium and is used to boil water to steam in the heat exchanger. The steam drives a turbine to generate electricity and is then cooled in the condenser.

The above diagram of a water-moderated power reactor shows the 'workings' of such a power source.

You should note the nature and uses of the following component parts.

**CORE**: the core consists of the fuel rods (enriched uranium) and the moderator, which slows down the neutrons. In this case the moderator is water which becomes very hot.

The fuel rods are stationary but there are also **control rods**, which can be moved in and out to control the rate at which nuclear energy is produced.

The **control (or safety) rods** are usually made of cadmium or boron; both are elements, which absorb neutrons strongly. The control rods are moved in to stop down the rate of reactions and up to speed it all up. The aim is to keep the reaction **just critical** so that the nuclear reactions are maintained at a steady rate by the released neutrons from each fission reactions. This would be impossible if some neutrons were not delayed i.e. emitted up to a few seconds after the reactions, not almost instantaneously. This gives the control rods enough time to react to the situation as required.

Energy is transferred from the reaction in the form of heat energy - it is carried off either by water or liquid sodium, as shown in the diagram above.

The rest of the power reactor is similar to that of a normal coal, oil or natural gas electricity generator.

Nuclear reactors after they have been built can be used to produce electrical power relatively cheaply. They have the advantage that no greenhouse gases are produced continuously, as when oil, natural gas or coal are burnt. In addition we are not likely to run out of the basic fuel - the supply is not limited, as is the supply of fossil fuels.

But, nuclear reactors are dangerous. Admittedly they have extra "shut-down" controls rods which, in case of emergency, can be used to stop the whole thing, but still! They also produce "thermal pollution" of the environment.

Ordinary power stations do this also.

In addition the materials used in the reactors are not "nice" to handle - liquid Sodium is not "nice" nor is Beryllium! Also the isotopes produced are highly radioactive. The other problem is that the ionising radiations produced also destroy (break-down the structure) of building materials - steel, concrete etc., so they weaken and a reactor has, usually, a life-time of only about 30 years - we are then left with a dangerous lump of stuff.

Handling and safely storing old fuel rods is also a problem - reprocessing is dangerous and storage - well, who wants them?

Reactor accidents have occurred in Russia, USA, UK and Korea. These are often said to be due to "technical" problems but such problems are human produced - "human error", which can be never be totally eliminated.

Still, many countries now really do rely on nuclear power - they would be in a real mess economically if it were banned.