

Topic 6 + 13

Atomic and Nuclear Physics

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F-Period
IB Physics

6.1.4 Identify the fundamental charge with the concept of charge quantization

Electric charges are quantized i.e. they occur and are transferred, only in quanta or discrete bundles. All quantities of electric charge exist in integral multiples of $e = 1.6 \times 10^{-19} \text{ C}$. This value is referred to as the fundamental charge and is the charge on an electron and a proton in equal magnitude but having opposite signs on each. The charge on a proton is $+e$ while an electron has a charge of $-e$.

6.1.5 Describe and explain thermionic emission

When atoms of an element in the gaseous state are placed in an electric field, electrons striking individual atoms excite or ionize them to a higher energy state. To return to a stable low-energy state, the gaseous atoms release energy in the form of electromagnetic radiation, often visible light. This process is the basis for gas discharge tubes and fluorescent lamps and tubes. Depending on the particular gaseous element in question, a characteristic emission spectrum is seen consisting of wavelengths of em radiation specific to that element. For example, sodium gas emits intense yellow light when ionized which is the basis of sodium lamps used as fog headlights on automobiles. The following diagram illustrates thermionic emission:

6.1.6 State the properties of cathode rays, and identify cathode rays with electrons

Cathode rays are beams of electrons created in an electric field. Positive and negative electrodes (anode and cathode) are placed in an evacuated chamber. When a small heating filament increases the temperature of the cathode, it releases electrons, which are accelerated by the electric field between the anode and cathode. This beam of electrons can then be further manipulated i.e. its kinetic energy and angular orientation can be varied by a series of control electrodes. Cathode rays travel in straight lines and cast sharp shadows. They have energy and can do work. They are deflected by electric and magnetic fields and have a negative charge.

6.1.9 Describe Rutherford's/Geiger and Marsden's alpha scattering experiment.

Rutherford's experiment led to the discovery of a small, dense, positively charged core in the atom called the nucleus. The experiment involved firing a beam of positively charged alpha particles at a thin gold foil and surrounding the apparatus with a phosphorescent screen that would register the impact positions of the alpha particles after passing through the foil. The vast majority of the alpha particles passed straight through the foil undeflected but a tiny proportion of them were either deflected or rebounded straight back. This indicated that the atom consisted primarily of negatively charged particles but has a concentrated central core of positive charge that balances the net charge on the atom to electrical neutrality. The fact that only very few particles were repelled, but that they were repelled very sharply, illustrates the relatively minuscule size of the nucleus, its high density and concentrated positive charge. A schematic diagram of the apparatus is shown below:

6.1.10 Deduce Rutherford's conclusion that the atom has a small massive positive nucleus surrounded by electrons.

See Obj. 6.1.9

6.1.11 Evaluate the implications of Rutherford's model of the atom

Rutherford's atomic model implied that electrons or tiny negatively charged particles orbited the nucleus at relatively vast distances in comparison to the nucleus' size. This atomic model was analogous to the orbits of the planets around the sun and was thus seen as elegant and appealing. Much like the sun keeps the planets in orbit due to the centripetal gravitational force that is a function of its mass, the nucleus was seen as exerting a similar electrical centripetal force on the electrons that prevented them from escaping the atom and releasing their energy in the form of em radiation.

6.2.1 Demonstrate an understanding of radioactive decay.

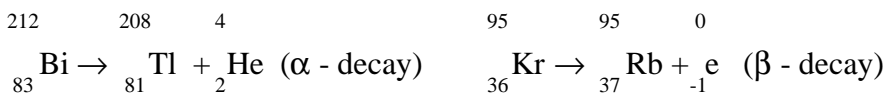
Radioactivity is the property of an unstable atomic nucleus of emitting radiation to return to a stable state. When an isotope of an element has a sufficiently larger number of neutrons than the common isotope, the strong nuclear force binding the nucleus is insufficient to overcome the electromagnetic force acting between the nucleus and its surrounding negatively charged cloud of electrons. Hence, to fall back to a stable state, the nucleus emits radiation. This emission of radiation alters the structure of the nucleus and thus changes the chemical makeup of the atom into that of another element. Thus, the Alchemists' dream becomes a reality and one element undergoes a transmutation into another element.

6.2.2 Identify alpha and beta particles, and gamma radiation, by means of their properties and experimental verification.

The three types of radioactive decay are denoted by the first three letters of the Greek alphabet as alpha, beta and gamma decay. Alpha decay involves a radioactive nucleus giving off positively charged alpha particles (Helium Nuclei: 2 protons+2 neutrons). Alpha particles are the least penetrating form of radiation. Beta decay is the release of a free electron or a positron (anti-electron) as a result of changes inside the nucleus. Beta radiation is more penetrating than alpha radiation. Gamma decay occurs when an unstable nucleus releases its excess energy in the form of high frequency photons of electromagnetic radiation known as gamma rays. Gamma rays are the most penetrating form of radiation.

6.2.3 Identify the products of alpha and beta decay in simple one step transformations.

When alpha and beta decay occur, mass and energy are conserved, hence the sum of the atomic numbers and mass numbers of the reactants and products are equal. In the case of beta decay, however, for energy to be conserved, a tiny neutral particle with negligible mass known as a neutrino or antineutrino (ν) is also produced in addition to the beta particle and the product nuclei. Examples of beta and alpha decay reactions follow:



6.2.4 Describe the use of ionizing properties for detecting radiation

All forms of nuclear radiation have the property of being able to ionize neutral atoms. This property can be used to detect radioactivity and its intensity. The ideal illustration of the ionizing property of radiation is the Geiger-Muller tube. In this device, a gas, generally Argon is placed in a tube and an electric voltage is applied across the tube. This voltage, in itself, is of insufficient magnitude to ionize the gas atoms. However, incoming radiation strikes an argon atom and bridges the energy gap required for the atom to

ionize. The ejected electron from the ionization then accelerates towards another Ar atom inducing a series of ionizations. This sets up an avalanche current in the tube, which is detected as an electrical pulse by circuitry in the tube. Hence the number of radiation particles can be counted as an absolute number of electrical pulses.

6.2.5 Identify the proton (atomic) number, Z and nucleon (mass) number, A, for nuclear isotopes

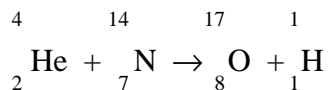
The atomic number, Z, of an element is the number of protons in a single nucleus of that element. The mass number, A, is the total number of nucleons in a nucleus of that element i.e. # protons + # neutrons. The following nomenclature is used to denote elements participating in nuclear reactions where X is the element in question:

$$\begin{matrix} A \\ X \\ Z \end{matrix}$$

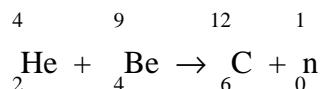
For examples of the usage of this nomenclature, see obj. 6.2.4

6.2.6 Describe the process of artificial transmutation and solve related problems

Artificial transmutation is the process through which a non-spontaneous nuclear reaction is induced artificially to transform atoms of one element into another. Innumerable such reactions are feasible and a few examples of significance are shown below:

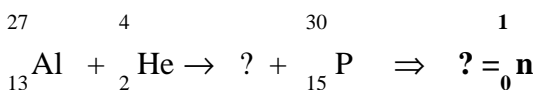


This was the first artificial nuclear reaction achieved by Rutherford. α -particles were used to bombard stable nitrogen atoms and stable oxygen and hydrogen atoms were produced.

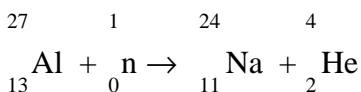


The above transmutation is the central nuclear reaction involved in James Chadwick's discovery of the neutron in 1932. Alpha particles bombarding a beryllium target produce stable carbon-12 and a neutron.

Example 1. Complete the following nuclear reaction:



Example 2. Find the Q value of the following reaction:



$$\Delta m = (26.981541 \text{ u} + 1.008665 \text{ u}) - (23.990964 \text{ u} + 4.002603 \text{ u})$$

$$Q = \Delta m(931.5 \text{ MeV}/c^2) \Rightarrow Q = (-3.4 \times 10^{-3} \text{ u})(931.5 \text{ MeV}/c^2) \Rightarrow Q = \boxed{-3.13 \text{ MeV}}$$

The negative Q value for this reaction indicates that it is not spontaneous and endothermic i.e. energy must be applied to the system artificially for the reaction to proceed.

6.2.7 Describe how the reaction between N and He led to the discovery of the proton

6.2.8 Identify the proton as the nucleus of the hydrogen atom with a positive charge |e|

The hydrogen atom has both atomic and mass numbers of 1. This indicates that the hydrogen nucleus has one proton and no neutrons. The proton, hence, is the hydrogen nucleus in its entirety and the net charge on the atom is balanced by one electron in the cloud around the nucleus. The nucleus has a charge of +e and the electron has a charge of -e.

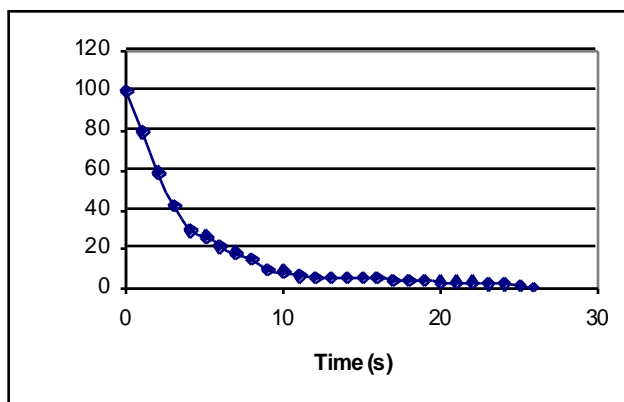
6.2.9 Recognize that radioactive decay is a random process for individual atoms but that the average rate of decay is exponential, and is independent of physical and chemical conditions.

Radioactive decay, on an average probabilistic scale has an exponential rate. A decaying isotope halves in quantity every time a fixed time interval elapses. This time interval is known as the half-life of the substance. However, for an individual atom, there is not a 100% probability that decay will occur, rather, the exponential decay rate is a macroscopic trend. Radioactive decay, as a process, is independent of its surroundings i.e. temperature, pressure, ambient matter and so on. This is the reasoning behind the use of highly accurate atomic clocks such as the cesium clock.

6.2.10 Define the term 'half-life'

The half-life of a radioactive isotope is the time it takes to decay to half its original amount. The half-life is a constant for every particular isotope and does not vary with the amount of a sample remaining i.e. a 1 kg sample of ^{235}U will take the same amount of time to decay from 1 kg to 0.5 kg as it will to decay from 0.5 kg to 0.25 kg.

6.2.11 Determine the half-life of a nuclide from a decay curve



Time (s)	# Nuclei
0	100
1	79
2	58
3	42
4	29
5	26
6	21
7	18
8	15
9	9
10	8

The above experimental decay curve for a radioactive isotope and the adjoining table of values can be used to determine the half-life of the isotope in question. It can be noted that to decay from 100 nuclei to 50 nuclei, a time of 2.5 seconds is required. $[(2,58)+(3,42)]/2 = (2.5, 50)$. Similarly, to decay from 50 nuclei to 26 nuclei which is approximately another half-life, 2.5 seconds elapse once again. Thus, the half-life of this isotope is 2.5 seconds. The approximations used in this example are a consequence of experimental error as well as the inherent randomness of radioactive decay on a microscopic scale.

6.2.12 Apply the concept of half-life in simple calculations involving small integral numbers of half-lives.

Example 1. The ^{14}C content decreases after the death of a living system with a half-life of 5739 years. If an archeologist finds an ancient firepit containing partially consumed firewood, and the ^{14}C content of the wood is only 12.5% that of an equal carbon sample from a present-day tree, what is the age of the ancient site.?

Fractional isotope content = $1/2^n \Rightarrow$ # half-lives elapsed = n

$$12.5\% = 1/8 = 1/2^3 \Rightarrow n = 3$$

$$T_{1/2} \text{ } ^{14}\text{C} = 5739 \text{ years} \Rightarrow 3 T_{1/2} = \boxed{17217 \text{ years}}$$

Example 2. A Geiger counter registers an initial reading of 3200 counts, measuring a radioactive substance and 100 counts 30 hours later. What is the half-life of this substance?

Fractional isotope content = $1/2^n \Rightarrow$ # half-lives elapsed = n

$$100/3200 = 1/32 = 1/2^5 \Rightarrow n=5$$

$$5T_{1/2} = 30 \text{ hours} \Rightarrow \boxed{T_{1/2} = 6 \text{ hours}}$$

Topic 13

Atomic and Nuclear Physics

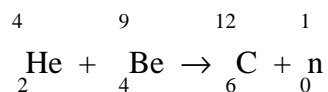
HL Extension

13.2.1 Describe the mass spectrometer and its use to determine accurate nuclear masses.

13.2.2 Describe in detail Chadwick's discovery of the neutron.

In 1932, James Chadwick conducted an experiment that proved the existence of a neutral particle in the nucleus having approximately the same mass as the proton—the neutron. The existence of this particle had already been postulated by numerous physicists including Rutherford, but no clear demonstration of their existence had been successfully undertaken. Free neutrons having no charge, are not readily observable, however, they do have mass, and hence, momentum. Chadwick used this property of the neutron to make it detectable. The experiment he conducted was as follows:

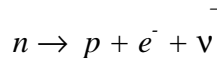
A sample of radioactive Polonium-210 undergoing alpha decay was placed near a beryllium target. The alpha particles from the source bombarded the target and ejected neutrons from the beryllium nuclei by the following reaction:



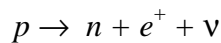
The released neutrons then went on to strike a sheet of paraffin wax from which they ejected protons in a series of one-to-one elastic collisions in which, momentum and kinetic energy were conserved. The ejected protons then entered an ionization chamber, where they struck an electrically charged plate that was connected to an amplifier whereby the energy of the protons could be measured. Using principles of kinetic energy and momentum conservation, Chadwick deduced the mass of the unknown particle as being almost equal to that of the proton. The apparatus he used is diagrammatically shown below:

13.2.3 Describe the mechanism for positive and negative beta decay including the postulation of the neutrino.

Unstable nuclei that undergo beta decay essentially stabilize themselves by converting a proton into a neutron or vice-versa and thus balance the charge, mass and forces acting on the nucleus. Two types of beta decay occur, positive and negative. Negative beta decay involves a nucleus with an excess neutron converting it into a proton by releasing an electron and antineutrino. The mechanism is shown below:

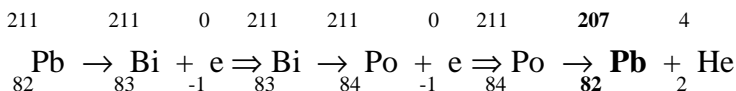
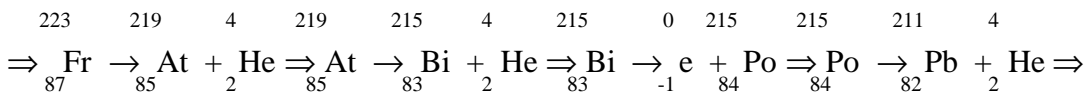
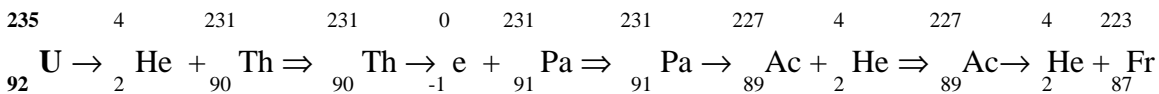


The neutron, transmutes into a proton which stays in the nucleus while an electron and an antineutrino are released. The neutrino and its antiparticle the antineutrino were postulated when it was found that the beta decay process does not completely obey the law of conservation of energy if a neutron transforms into a proton and electron with no other products. The neutrino/antineutrino balances the reaction and has more recently, been observed otherwise. The neutrino/antineutrino's mass is negligible and is not exactly known. In positive beta decay, a proton transmutes into a neutron releasing the antiparticles of both the products of negative beta decay i.e. a positron (anti-electron) and a neutrino. The mechanism is as follows:



13.2.4 Deduce the products of sequential nuclear decays and the changes of Z and A in decay chains

When the product of a certain nuclear decay is still unstable, this product further decays and a series of sequential decays may ensue until a stable product is formed. The ideal example of sequential decays is the decay of ^{235}U . ^{235}U can decay through a number of combinations of reaction mechanisms, a common sequence is shown below:



The final product, ^{207}Pb is a stable isotope hence the decay sequence proceeds no further.

13.2.5 Solve problems using the radioactive decay law.

The radioactive decay law states that the rate of decay of an isotope : $\Delta N/\Delta t = -\lambda N$ where N is the number of nuclei and λ is the decay constant and : $N = N_0 e^{-\lambda t}$ where N_0 is the initial # of nuclei.

Example 1. Radon gas has a half-life of 3.83 days. If a radon gas sample has a mass of 3.00 g, what mass will remain after two days have passed?

$$T_{1/2} = \ln 2 / \lambda \Rightarrow \lambda = \ln 2 / (3.83 \times 24 \times 3600) = 2.1 \times 10^{-6} \text{ s}^{-1}$$

$$N_0 = 3.00 \text{ g} \Rightarrow N = (3.00 \text{ g})e^{-(2.1 \times 10^{-6} \text{ 1/s})(330912 \text{ s})} = \boxed{1.49 \text{ g}}$$

13.2.6 Deduce the relationship between half-life and the decay constant.

$$N = N_0/2 \Rightarrow 2 = e^{\lambda t} \Rightarrow \ln 2 = \lambda T_{1/2} \Rightarrow \lambda = \ln 2 / T_{1/2}$$

13.2.7 Explain why the proton-proton nuclear model requires a nuclear force and describe the characteristics of that force.

Protons repel each other through the electromagnetic force acting strongly between them as they are concentrated in the nucleus. Additionally, they are attracted to the negatively charged outer regions of the atom. Hence, some force must be present that holds the nucleus together. This is the strong nuclear force that is extremely powerful at a short range but whose strength recedes very rapidly as distances grow to anything larger than sub-nuclear displacements of approximately 1 femtometer.

13.3.1 Describe the characteristics of atomic emission and absorption spectra.

Atomic emission spectra consist of the characteristic wavelengths of electromagnetic radiation emitted by an element in the excited state. They are composed of a series of thin finite lines corresponding to particular wavelengths on a black background representing the wavelengths of light not emitted by that particular element. Absorption spectra are the exact inverse of emission spectra. They appear to be continuous spectra with a series of black lines representing wavelengths of light absorbed by the atom of the particular element. These lines correspond to the same wavelengths as the bright lines on the emission spectra since atoms absorb and emit light of the same set of frequencies.

13.3.2 State Bohr's postulates

Bohr postulated that the electrons in an atom orbit the nucleus at fixed distances corresponding to finite energy levels. His four basic assumptions are as follows:

1. The electron moves in circular orbits around the proton under the coulomb force of attraction which acts as the centripetal force.
2. Only certain electron orbits are stable. These are the orbits in which the hydrogen atom does not emit energy in the form of radiation. Hence, the total energy of the atom remains constant, and classical mechanics can be used to describe the electron's motion.
3. Radiation is emitted by the hydrogen atom when an electron "jumps" from a more energetic state to a lower state. The "jump" cannot be visualized or treated classically. In particular, the frequency, f , of the radiation emitted in the jump is related to the change in the atom's energy and is independent of the frequency of the electron's orbital motion.

The frequency of the emitted radiation is:

$$E_i - E_f = hf$$

where E_i is the energy of the initial state, E_f is the energy of the final state, h is Planck's constant and $E_i > E_f$.

4. The size of the allowed electron orbits is determined by a condition imposed on the electron's angular momentum: the allowed orbits are those for which the electron's orbital angular momentum about the nucleus is an integral multiple of $h/2\pi$.

$$mvr = nh/2\pi \quad n=1,2,3\dots$$

13.3.3 Describe the spectrum of atomic hydrogen and account for it using Bohr's model.

The emission spectrum of atomic hydrogen exhibits a series of bright lines on a black background corresponding to particular wavelengths of em radiation emitted by excited hydrogen gas. These particular wavelengths also correspond to jumps to and from particular energy levels of electrons in the hydrogen atom. The lines corresponding to wavelengths in the visible spectrum are at 410.2 nm, 434.1 nm, 486.1 nm and 656.3 nm. The relationship between the emitted wavelengths and the corresponding electron jumps are quantified by the Rydberg formula:

$$1/\lambda = R_H(1/n_f^2 - 1/n_i^2)$$

where R_H is the Rydberg constant having a value of $1.097373 \times 10^7 \text{ m}^{-1}$. This equation was derived by Bohr combining Planck's Law ($E=hc/\lambda$) and the equation for the allowed energies of the hydrogen atom: $E_n = -13.6/n^2 \text{ eV}$.

13.3.4 Evaluate the successes and limitations of Bohr's model.

Bohr's atomic model was a tremendous success in the area of atomic physics since it

- a) Accounted for atomic spectra of hydrogen and other elements.
- b) Gave an expression for the radius of the hydrogen atom.
- c) Gave us a model of what the atom looks like and how it behaves.

However, the Bohr model had certain weaknesses, as follow, which were corrected by modifications to the theory by amongst others, De Broglie, Pauli and Schrodinger

- a) Electrons do not move in perfect circular orbits as he postulated, but in random patterns that cannot be classically studied.
- b) The Bohr theory applied only to atoms having one electron such as hydrogen and needed modification to be extended to other elements.

13.3.5 Describe and interpret a Frank-Hertz type experiment and explain its importance.

13.4.1 State and apply Einstein's mass-energy equivalence.

Einstein proposed that particles travelling at speeds close to c can convert its mass into energy and vice-versa. Hence, the energy of a relativistic body is a function of its mass in the form:

$$E=mc^2 \quad (c = 3.0 \times 10^8 \text{ m/s})$$

This equation forms the basis for modern atomic and nuclear physics since it accounts for the enormous amounts of energy released in nuclear reactions compared to conventional exothermic processes. This will be applied in numerous following objectives.

13.4.2 Define the terms ‘unified mass unit’, ‘mass defect’ and ‘binding energy’.

The unified mass unit, u , is a unit of mass devised for conveniently dealing with masses of particles on an atomic scale. $1 u = 1.660559 \times 10^{-27} \text{ kg}$. The carbon atom is the reference mass for the unified mass unit having a mass of exactly $12u$. Mass defect is the difference between the sum of the masses of all the nucleons (protons and neutrons) in an atomic nucleus and the mass of the nucleus itself. This difference in mass corresponds to the relativistic mass-energy equivalence applying to subatomic particles in that the mass difference, when multiplied by c^2 yields the total binding energy of the nucleus which is the energy that must be applied to the nucleus to separate it into its nucleons.

13.4.3 Use the mass defect to calculate binding energies for nuclides.

Example 1. Calculate the total binding energy of ^{20}Ne .

Neon has a total of 20 nucleons, 10 protons and 10 neutrons

$$\begin{aligned}\Rightarrow \Delta m (\text{mass defect}) &= [10(m_p) + 10(m_n)] - (m ^{20}\text{Ne}) \\ &= [10(1.007276 u) + 10(1.008665 u)] - (19.992439 u) \\ &= 0.167 u\end{aligned}$$

$$\begin{aligned}Q (\text{Binding Energy}) &= \Delta m(931.5 \text{ MeV}/u) = (0.167 u)(931.5 \text{ MeV}/u) \\ &= \boxed{155.5 \text{ MeV}}\end{aligned}$$

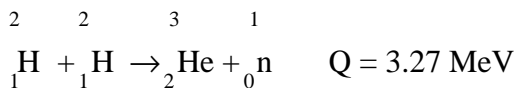
13.4.5 Describe the process of nuclear fission and chain reactions.

Nuclear fission occurs when a heavy nucleus such as ^{235}U splits or fissions, into two smaller nuclei. In such a reaction, the total rest mass of the products is less than the original rest mass of the heavy nucleus and the remaining mass is converted into energy by Einstein’s mass energy equivalence. The process of nuclear fission can be artificially induced by bombarding a heavy nucleus with neutrons. When a neutron strikes, it is captured or absorbed by the nucleus and the excess energy of the nucleus causes it to undergo violent oscillations. The nucleus becomes highly distorted and finally splits into two fragment nuclei to stabilize energetically and emits several neutrons as well as massive amounts of energy. If a large sample of heavy nuclei is bombarded with neutrons, the product neutrons emitted from one fission emerge and bombard other nuclei leading to a series of uncontrolled fissions also known as a chain reaction. This chain reaction, if not controlled releases enormous amounts of energy through mass-energy conversion and is the basis of a fission nuclear bomb. If other heavy nuclei are placed in the sample that absorb product neutrons, the chain reaction and number of fissions can be controlled. This type of a controlled fission reaction is the type that is used in a nuclear power plant to produce energy for peaceful purposes. The below diagram illustrates a chain reaction.

13.4.6 Describe and evaluate the social impact of fission processes when compared to alternative energy sources.

13.4.7 Describe the process of nuclear fusion

Nuclear fusion is the process by which two light nuclei combine or fuse to form a heavier nucleus releasing vast amounts of energy corresponding to a smaller rest mass for the product nucleus than the reactant nuclei. Controlled nuclear fusion has not yet been achieved since it involves the containment of a plasma at extremely high temperatures. The sun creates its energy through nuclear fusion at temperatures of approximately 10^7 K. Generally, the proposed fusion reaction for a fusion power plant would be the fusion of two heavy hydrogen (Deuterium) nuclei by the following mechanism:



The Q value is the total energy output of this reaction. However, a number of conditions must be met for a controlled thermonuclear fusion reaction for energy purposes to be successful. Firstly, the major problem in obtaining energy from nuclear fusion is the fact that the Coulomb repulsion force between two charged nuclei must be overcome before they can fuse. To achieve this, the nuclei must be given sufficient kinetic energy to overcome this force. This can be achieved by heating the fuel to extremely high temperatures in the range of 10^8 K which is higher than the interior temperature of the sun. Such a temperature is extremely difficult to obtain in a laboratory or power plant. At this temperature, the atoms are ionized and the system is converted into a delocalized 'soup' of nuclei and electrons known as a plasma.

Additionally, two other conditions must be met for a thermonuclear reactor to be successful: plasma ion density, n and plasma confinement time, τ . Both these variables must be high enough to ensure that more energy is released than is required to heat the plasma. For a deuterium-deuterium reaction, for a net power output to be obtained:

$$n\tau \geq 10^{14} \text{ s/cm}^3$$

