1. Details of Module and its structure

Module Detail	
Subject Name	Physics
Course Name	Physics 04 (Physics Part 2, Class XII)
Module Name/Title	Unit 8, Module-07: Nuclear Energy Chapter-12: Atoms
Module Id	Leph_201304_eContent
Pre-requisites	Atomic structure, nucleus, Rutherford experiment, limitations of Rutherford's atomic model m line spectrum of hydrogen, Bohr's postulates, atomic nucleus, radioactivity, stability of nucleus, binding energy per nucleon
Objectives	The students will be able to: • Understand the term Nuclear energy • Know about Fission reaction • Explain Controlled fission reaction in Nuclear Reactor • Know India's atomic energy programme • Understand Nuclear Fusion – energy generation in stars controlled thermonuclear fusion
Keywords	magic number, nuclear energy, fission , thermal neutron uranium 235, nuclear fusion, energy from the sun

2. Development Team

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Mass energy relations, mass defect, binding energy per nucleon and its variation with mass number, nuclear fission and nuclear fusion

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MODULE – 7

3. WORDS YOU MUST KNOW

Let us remember the words and the concepts we are familiar with: -

Atom structure an atom the smallest independent entity of an element .it consists of a small, central, massive and positive core surrounded by orbiting electrons.

nucleus. The central positive core of the atom is called nucleus.

size of an atom The size of an atom is of the order of 10^{-10}m, the size of a nucleus is of the order of 10^{-15} m

nucleons. Nucleus is made up of neutrons and protons, they being the constituents of a nucleus are also called nucleons.

mass number If a nucleus has **Z number of protons** and **N number of neutron**, then its mass number A.

$$A = Z + N$$

A nucleus of an element is represented as $_Z X^A$

Isotopes: - The atoms, of an element, which have the same atomic number (Z), but different mass number (A), are called isotopes. For example $_1H^1$, $_1H^2$ and $_1H^3$ are isotopes. They have same number of protons but different number of neutrons.

Isobars:- The atoms, which have the same mass number (A) , but different atomic number (Z), are called isobars. They are the atoms of different elements, for example, $_1H^3$, $_2He^3$ are isobars.

Isotones: - The atoms, whose nuclei have, same number of neutrons are called isotones.

Nuclear size: - The radius R , of a nucleus having mass number A is given by the expression

$R= R_0 A^{1/3}$, where $R_0 = 1.1\text{x } 10^{-15}$ m

Nuclear density: - Nuclear density = (mass of the nucleus/ volume of the nucleus) Nuclear density is independent of mass number.

Properties of a neutron: - A neutron is a neutral particle carrying no charge, and having mass slightly more than that of a proton. A neutron i9s stable inside the nucleus, but a free neutron is unstable and has a mean life of 1000second.

Nuclear forces: - In spite of a Columbian repulsive force between protons, the nucleons stay inside a nucleus because of a strong attractive force called nuclear force.

a) Nuclear forces are the strongest forces in nature
b) Nuclear forces are short range forces
c) Nuclear forces are saturated forces
d) Nuclear forces are charge independent

e) Nuclear forces are spin dependent, non-central forces.

Atomic mass unit: - One atomic mass unit is defined as $(1/12)^{th}$ of the mass of one $_6C^{12}$ atom.

1 atomic mass unit = 1.66×10^{-27} kg

eV energy gained by an electron when subjected to a potential difference of one volt.

Mass defect: - The difference between the sum of the masses of the nucleons constituting a nucleus and the rest mass of the nucleus is known as **mass defect.**

Binding energy: - Binding energy of a nucleus may be defined as the energy is required to break up a nucleus into its constituent nucleons and to separate them to such a large distance that they may not interact with each other.

OR

The binding energy may also be defined as the surplus energy which the nucleons give up by virtue of their attractions when they become bound together to form a nucleus.

Binding energy per nucleon: - "the average energy required for extracting one nucleon from the nucleus".

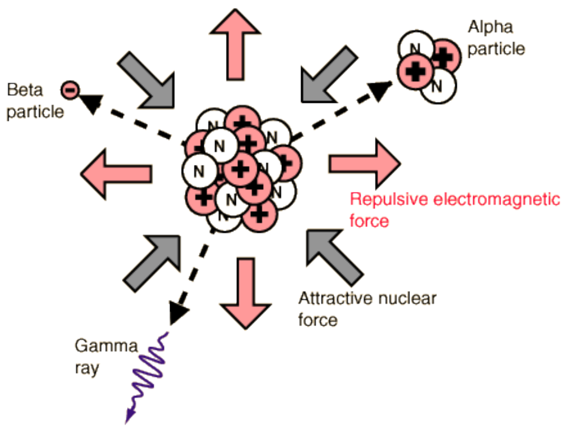
Radioactivity the spontaneous and random disintegration of a nucleus by emission of particles and radiation, in order to become stable called rafioactivity.

4. INTRODUCTION

You have learnt that nucleus has neutrons and protons in an approximately spherical space of 10^{-15} m radius. The nucleus is held together by nuclear forces, which have unique properties like short range, charge independence and strongest in nature. Radioactivity is a phenomenon where nuclei disintegrate to become more stable.

In order to explain the nuclear activity, it is important to recall binding energy which arises due to mass defect, and its equivalent energy.

The phenomenon of radioactivity indicates that particles not supposed to be in the nucleus are also emitted from it; also the gamma radiation from the nucleus suggests that some electromagnetic changes must be occurring inside the nucleus.



Einstein showed from his theory of special relativity. That it is necessary to treat mass as another form of energy. Before the advent of this theory of special relativity it was presumed that mass and energy were conserved separately in a reaction.

However, Einstein showed that mass is another form of energy and one can convert mass-energy into other forms of energy, say kinetic energy and vice-versa.

Einstein gave the famous mass-energy equivalence relation

$$E = mc^2$$

Here the energy equivalent of mass m is related by the above equation and c is the velocity of light in vacuum and is approximately equal 3×10^8 m/s.

Experimental verification of the Einstein's mass-energy relation has been achieved in the study of nuclear reactions amongst nucleons, nuclei, electrons and other more recently discovered particles. **In a reaction the conservation law of energy states that the initial energy and the final energy are equal provided the energy associated with mass is also included.**

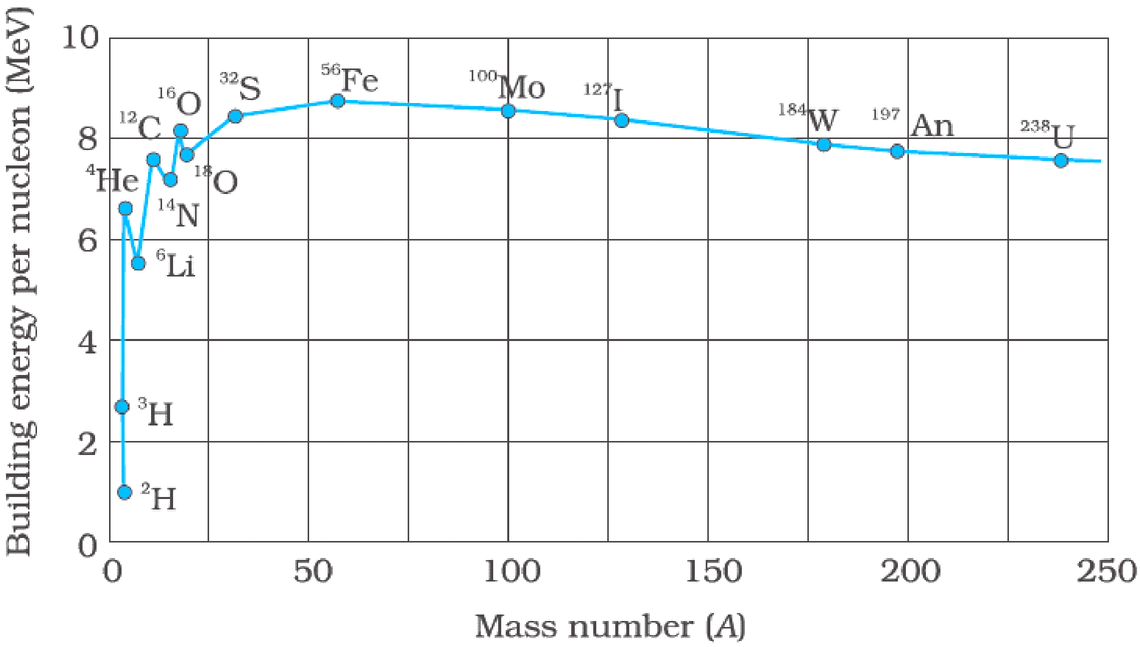
What is the meaning of the mass defect? It is here that Einstein's equivalence of mass and energy plays an important role. Since the mass of the oxygen nucleus is less than the sum of the masses of its constituents (8 protons and 8 neutrons, in the unbound state), the equivalent energy of the oxygen nucleus is less than that of the sum of the equivalent energies of its constituents.

If one wants to break the oxygen nucleus into 8 protons and 8 neutrons, this extra energy $\Delta M\ c^2$, has to be supplied.

BINDING ENERGY

We have learnt that binding energy per nucleon is the average energy per nucleon needed to separate a nucleus into its individual nucleons.

The graph of **binding energy per nucleon versus mass number is given.**



We notice the following **main features** of the graph:

(i) **The binding energy per nucleon, E_{bn}, is practically constant, i.e. practically independent of the atomic number for nuclei of middle mass number (30 < A < 170). The curve has a maximum of about 8.75 MeV for A = 56 and has a value of 7.6 MeV for A = 238.**

(ii) The binding energy per nucleon is lower for both light nuclei (A<30) and Heavy nuclei (A>170).

We can draw some conclusions from these two observations:

(i) **The force is attractive and sufficiently strong to produce a binding energy of a few MeV per nucleon**.

(ii) The constancy of the binding energy in the range 30 < A < 170 is a consequence of the fact that the **nuclear force is short-ranged.**

Consider a particular nucleon inside a sufficiently large nucleus. It will be under the influence of only some of its neighbours, which come within the range of the nuclear force. If any other nucleon is at a distance more than the range of the nuclear force from the particular nucleon it will have no influence on the binding energy of the nucleon under consideration. If a nucleon can have a maximum of p neighbours within the range of nuclear force, its binding energy would be proportional to p.

Let the binding energy of the nucleus be pk, where k is a constant having the dimensions of energy. If we increase A by adding nucleons they will not change the binding energy of a nucleon inside. Since most of the nucleons in a large nucleus reside inside it and not on the surface, the change in binding energy per nucleon would be small. The binding energy per nucleon is a constant and is approximately equal to pk. The property that a given nucleon influences only nucleons close to it is also referred to as **saturation property of the nuclear force.**

(iii) A very heavy nucleus, say A = 240, has lower binding energy per nucleon compared to that of a nucleus with A = 120. Thus if a nucleus A = 240 breaks into two A = 120 nuclei, nucleons get more tightly bound. **This implies energy would be released in the process.**

It has very important implications for energy production through splitting of the nucleus (fission), **which we will consider in this module**

(iv) Consider two very light nuclei (A≤ 10) joining to form a heavier nucleus. The binding energy per nucleon of the fused heavier nuclei is more than the binding energy per nucleon of the lighter nuclei.

This means that the final system is more tightly bound than the initial system.

Again **energy would be released in such a process of fusion**.

This is the source of energy sun, will be **considered in this module.**

5. NUCLEAR ENERGY

The curve of binding energy per nucleon as seen in the graph, has a long flat middle region between A = 30 and A = 170.
In this region the binding energy per nucleon is nearly constant (8.0 MeV).

For the lighter nuclei region, $A < 30$, and for the heavier nuclei region, $A > 170$, the binding energy per nucleon is less than 8.0 MeV,

As we have noted earlier. Now, the greater the binding energy, the less is the total mass of a bound system, such as a nucleus. Consequently, **if nuclei with less total binding energy transform to nuclei with greater binding energy, there will be a net energy release.**

This is what happens when a heavy nucleus decays into two or more intermediate mass fragments (**fission**) or when light nuclei fuse into a heavier nucleus (**fusion.**)

Exothermic chemical reactions underlie conventional energy sources such as coal or petroleum. Here the energies involved are in the range of electron volts. On the other hand, in a nuclear reaction, the energy release is of the order of MeV. Thus, for the same quantity of matter, nuclear sources produce a million times more energy than a chemical source.

Fission of 1 kg of uranium, for example, generates 10^{14} J of energy; compare it with burning of 1 kg of coal that gives 10^{7} J.

6. FISSION

A most important **neutron-induced nuclear reaction is fission.**

An example of fission is when a uranium isotope ${}^{235}_{92}U$ bombarded with a neutron breaks into two intermediate mass nuclear fragments

$$ {}^{1}_{0}n + {}^{235}_{92}U \longrightarrow {}^{236}_{92}U \longrightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr + 3\,{}^{1}_{0}n $$

The same reaction can produce other pairs of intermediate mass fragments

$$ {}^{1}_{0}n + {}^{235}_{92}U \longrightarrow {}^{236}_{92}U \longrightarrow {}^{133}_{51}Sb + {}^{99}_{41}Nb + 4\,{}^{1}_{0}n $$

Or,

as another example

$$ {}^{1}_{0}n + {}^{235}_{92}U \longrightarrow {}^{140}_{64}Xe + {}^{94}_{38}Sr + 2\,{}^{1}_{0}n $$

The **fragment products are radioactive nuclei**; they emit β particles in succession to achieve stable end products.

The energy released (the Q value) in the fission reaction of nuclei like uranium is of the order of 200 MeV per fissioning nucleus.

This is estimated as follows:

Let us take a nucleus with A = 240 breaking into two fragments each of A = 120.

Then binding energy per nucleon for A = 240 nucleus is about 7.6 MeV,

Binding energy per nucleon for the two A = 120 fragment nuclei is about 8.5 MeV.

∴ Gain in binding energy for nucleon is about 0.9 MeV.

Hence the total gain in binding energy is 240 × 0.9 or **216 MeV.**

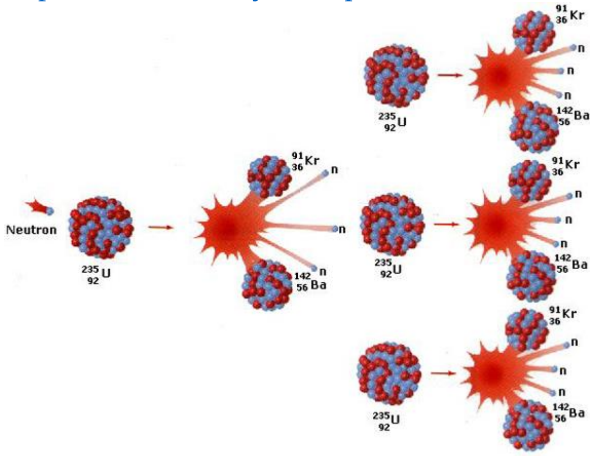
You can calculate this energy

1eV =1.6 x 10^{-19}J

1MeV =1.6 x 10^{-13} J

216 MeV per fission =216 x 1.6 x 10^{-13} J = 345.6 x 10^{-13} J

https://honchemistry.wikispaces.com/Nuclear+Fission+and+You



The neutrons produced in single nucleus fission cause fission in another, each producing energy, due to successive fissions. The successive fissions are called chain reaction. The total energy is so large that it can only be devastating.

The disintegration energy in fission events first appears as the kinetic energy of the fragments and neutrons.

Eventually it is transferred to the surrounding matter appearing as heat. The source of energy in nuclear reactors, which produce electricity, is nuclear fission.

The enormous energy released in an atom bomb comes from **uncontrolled nuclear fission**.

7. CONTROLLED FISSION REACTION- NUCLEAR REACTOR

This is an arrangement to perform controlled nuclear fission reaction and use the energy produced for useful purposes.

Notice one fact of great importance in the fission reactions given in equations.

There is a release of extra neutron (s) in the fission process.

Averagely, **2½ neutrons are released per fission of uranium nucleus. It is a fraction since in some fission events 2 neutrons are produced, in some 3, etc.**

The extra neutrons in turn can initiate fission processes, producing still more neutrons, and so on. This leads to the possibility of a **chain reaction**, as was first suggested by Enrico Fermi.

If the chain reaction is **controlled** suitably, we can get a steady energy output. This is what happens in a nuclear reactor. If the chain reaction is uncontrolled, it leads to explosive energy output, as in a nuclear bomb.

There is, however, a hurdle in sustaining a chain reaction, as described here. It is known experimentally that **slow neutrons (thermal neutrons)** are much more likely to cause fission in isotope $^{235}_{92}U$ than fast neutrons.

Also

Fast neutrons liberated in fission would escape instead of causing another fission reaction.

The average energy of a neutron produced in fission of uranium isotope $^{235}_{92}U$ is 2 MeV.

These neutrons unless slowed down will escape from the reactor without interacting with the uranium nuclei, unless a very large amount of fissionable material is used for sustaining the chain reaction.

What one needs to do is to slow down the fast neutrons by elastic scattering with light nuclei.

In fact, Chadwick's experiments showed that in an elastic collision with hydrogen the neutron almost comes to rest and proton carries away the energy. This is the same situation as when a marble hits head-on an identical marble at rest.

Therefore, in reactors, **light nuclei called moderators** are provided along with the fissionable nuclei for **slowing down fast neutrons. The moderators commonly used are water, heavy water (D_2O) and graphite**.

The **Apsara** reactor at the Bhabha Atomic Research Centre (BARC), Mumbai, uses water as moderator.
The other Indian reactors, which are used for power production, use heavy water as moderator.

K ratio

Because of the use of moderator, it is possible that the **ratio, K**, of number of fission produced by a given generation of neutrons to the number of fission of the preceding generation may be greater than one.

This ratio is called the multiplication factor; it is the **measure of the growth rate of the neutrons in the reactor.**
For K = 1, the operation of the reactors said to be **critical**, which is what we wish it to be for **steady power operation**.

If K becomes **greater than one**, the reaction rate and the reactor power increases exponentially.

Unless the factor K is brought down very close to unity, the reactor will become **supercritical and can even explode.**

The **explosion of the Chernobyl reactor in Ukraine in 1986** is a sad reminder that accidents in a nuclear reactor can be catastrophic.

The reaction rate is controlled through control-rods made out of **neutron-absorbing material such as cadmium**.

In addition to control rods, reactors are provided with safety rods which, when required, can be inserted into the reactor and K can be reduced rapidly to less than unity.

The more abundant isotope ${}^{238}_{92}U$ in naturally occurring uranium is non-fissionable.

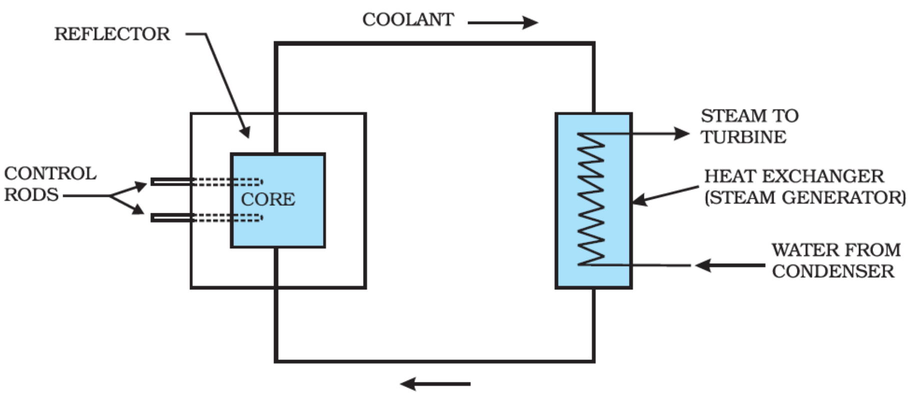
When it captures a neutron, it produces the highly radioactive plutonium through these reactions

$${}^{1}_{0}n + {}^{236}_{92}U \longrightarrow {}^{239}_{92}U \longrightarrow {}^{239}_{93}Np + {}^{-1}_{0}e + \bar{\nu}$$

$${}^{239}_{93}Np \longrightarrow {}^{239}_{94}Pu + {}^{-1}_{0}e + \bar{\nu}$$

Plutonium undergoes fission with slow neutrons.

Figure shows the schematic diagram of a nuclear reactor based on thermal neutron fission.



The **core** of the reactor is the site of nuclear fission. It contains the fuel elements in suitably fabricated form.
The fuel may be say **enriched uranium** (i.e., one that has greater abundance of $^{235}_{92}U$ than naturally occurring uranium).

The core contains a **moderator** to slow down the neutrons.

The core is surrounded by a **reflector** to reduce leakage.

The energy (heat) released in fission is continuously removed by a suitable **coolant.**
A **containment vessel** prevents the escape of radioactive fission products.

The **whole assembly is shielded** to check harmful radiation from coming out.
The reactor can be shut down by means of **rods (made of, for example, cadmium**) that have high absorption of neutrons.

The **coolant transfers heat to a working fluid which in turn may produce steam**.

The steam drives turbines and **generates electricity.**

Like any power reactor, nuclear reactors generate considerable waste products. But nuclear wastes need special care for treatment since they are **radioactive and hazardous**.

Elaborate safety measures, both for

- reactor operation as well as
- handling and reprocessing the spent fuel, are required.

These safety measures are a distinguishing feature of the **Indian Atomic Energy programme.**

An appropriate plan is being evolved to study the possibility of converting radioactive waste into less active and short lived material.

8. INDIA'S ATOMIC ENERGY PROGRAMME

The atomic energy programme in India was launched around the time of independence under the leadership of **Homi J. Bhabha (1909-1966).**

An early historic achievement was the design and construction of the **first nuclear reactor in India (named Apsara**) which went critical on August 4, 1956.

Tarapur Atomic Power Station-

Tarapur Atomic Power Station (T.AP.S.) was the first nuclear power plant in India. The construction of the plant was started in 1962 and the plant went operational in 1969. The 320 MW Tarapur nuclear power station housed two 160 MW boiling water reactors (BWRs), the first in Asia.

https://www.jagranjosh.com/general-knowledge/list-of-nuclear-power-plants-in-india-1503388974-1

It used **enriched uranium** as **fuel** and **water as moderator**. Following this was another notable landmark: the construction of **CIRUS** (Canada India Research U.S.) reactor in 1960. This 40 MW reactor used natural uranium as fuel and heavy water as moderator. Apsara and CIRUS spurred research in a wide range of areas of basic and applied nuclear science.

An important milestone in the first two decades of the programme was the **indigenous design and construction of the plutonium plant at Trombay**, which ushered in the technology of fuel reprocessing (separating useful fissile and fertile nuclear materials from the spent fuel of a reactor) in India.

Research reactors that have been subsequently commissioned include

- ZERLINA,
- PURNIMA (I, II and III),
- DHRUVA and
- KAMINI.

KAMINI is the country's first large research reactor that uses U-233 as fuel. As the name suggests, the primary objective of a research reactor is not generation of power but to provide a facility for research on different aspects of nuclear science and technology.

Research reactors are also an excellent source for production of a variety of radioactive isotopes that find application in diverse fields

- **industry,**
- **medicine and**
- **Agriculture**.

The **main objectives** of the Indian Atomic Energy programme are to provide safe and reliable electric power for the country's social and economic progress and to be self-reliant in all aspects of nuclear technology.

Exploration of **atomic minerals in India** undertaken since the early fifties has indicated that India has limited reserves of uranium, but fairly abundant reserves of thorium.

Accordingly, our country has adopted a three stage strategy of nuclear power generation. **The first stage involves the use of natural uranium as a fuel, with heavy water as moderator.**

The **Plutonium-239 obtained from reprocessing of the discharged fuel from the reactors then serves as a fuel for the second stage** —

The fast breeder reactors-

They are so called because they use fast neutrons for sustaining the chain reaction (hence no moderator is needed) and, besides generating power, also breed more fissile species (plutonium) than they consume.

The **third stage**, most significant in the long term, involves using fast breeder reactors to produce fissile Uranium-233 from Thorium-232 and to build power reactors based on them.

India is currently well into the second stage of the programme and considerable work has also been done on the third — the thorium utilisation stage.

The country has mastered the complex technologies of mineral exploration and mining, fuel fabrication, heavy water production, reactor design, construction and operation, fuel reprocessing, etc. Pressurised Heavy Water Reactors (PHWRs) built at different sites in the country marks the accomplishment of the first stage of the programme.

India is now more than self-sufficient in heavy water production. Elaborate safety measures both in the design and operation of reactors, as also adhering to stringent standards of radiological protection are the hallmark of the Indian Atomic Energy Programme.

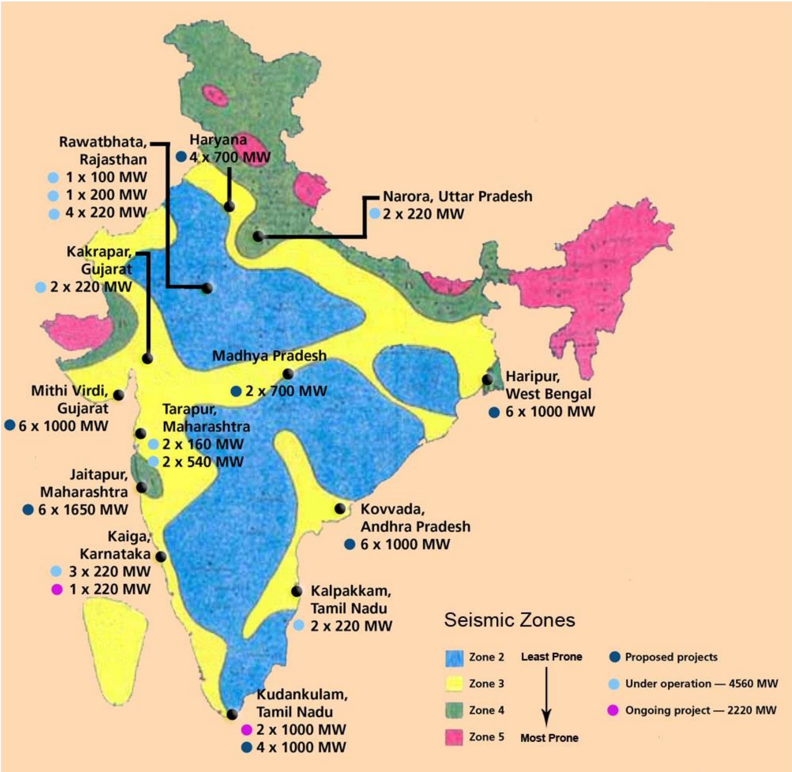
Nuclear power is the fifth-largest source of electricity in India after coal, gas, hydroelectricity and wind power.

As of March 2018, India has 22 nuclear reactors in operation in 7 nuclear power plants, having a total installed capacity of 6,780 MW.

Nuclear power produced a total of 35 TWh of electricity in 2017.

https://en.wikipedia.org/wiki/Nuclear_power_in_India

The nuclear plants should be located in acres, keeping the geographical stability in mind



https://cdn.downtoearth.org.in/dte/userfiles/images/Earth_quake_map.jpg

9. NUCLEAR FUSION – ENERGY GENERATION IN STARS

When two light nuclei fuse to form a larger nucleus, energy is released, since the larger nucleus is more tightly bound, as seen from the binding energy curve. Some examples of such energy liberating nuclear fusion reactions are:

$$ {}_1^1\mathrm{H} + {}_1^1\mathrm{H} \to {}_1^2\mathrm{H} + \mathrm{e}^+ + \nu + 0.42\ \mathrm{MeV} $$

$$ {}_1^2\mathrm{H} + {}_1^2\mathrm{H} \to {}_2^3\mathrm{He} + \mathrm{n} + 3.27\mathrm{MeV} $$

$$ {}_1^2\mathrm{H} + {}_1^2\mathrm{H} \to {}_1^3\mathrm{H} + {}_1^1\mathrm{H} + 4.03\ \mathrm{MeV} $$

Notice

In the **first** reaction, two protons combine to form a deuteron and a positron with a release of 0.42 MeV energy.

In the **second** reaction, two deuterons combine to form the light isotope of helium release 3.27MeV energy

In the **third** reaction two deuterons combine to form a triton and a proton. And an energy released = 4.03 MeV

For fusion to take place,

- The two nuclei **must come close enough so that attractive short-range nuclear force is able to affect them**. However, since they are both positively charged particles, they experience coulomb repulsion. They, therefore, must have enough energy to overcome this **coulomb barrier**. The **height of the barrier** depends on the charges and radii of the two interacting nuclei.
  It can be shown, for example, that the barrier height for two protons is ~ 400 keV, and is higher for nuclei with higher charges.

- We can estimate the **temperature at which two protons** in a proton gas would (averagely) have enough energy to overcome the coulomb barrier: $\left(\frac{3}{2}\right)$k T = Kinetic energy = 400 keV,
  which gives T ~ 3×10^9 K.

When fusion is achieved by raising the temperature of the system so that particles have enough kinetic energy to overcome the coulomb repulsive behaviour, it is called thermonuclear fusion.

Thermonuclear fusion is the source of energy output in the interior of stars. The interior of the sun has a temperature of 1.5×10^7 K, which is considerably less than the estimated temperature required for fusion of particles of average energy.

Clearly, fusion in the sun involves protons whose energies are much above the average energy. The fusion reaction in the sun is a multi-step process in which the hydrogen is turned into helium. Thus, the fuel in the sun is the hydrogen in its core.

The **proton-proton (p, p) cycle** by which this occurs is represented by the following sets of reactions:

$${}_1^1H + {}_1^1H \rightarrow {}_1^2H + e^+ + \nu + 0.42\ MeV \qquad \text{(i)}$$

$$e^+ + e^- \rightarrow \gamma + \gamma + 1.02\ MeV \qquad \text{(ii)}$$

$${}_1^2H + {}_1^1H \rightarrow {}_2^3He + \gamma + 5.49\ MeV \qquad \text{(iii)}$$

$${}_2^3He + {}_2^3He \rightarrow {}_2^4He + {}_1^1H + {}_1^1H + 12.86\ MeV \qquad \text{(iv)}$$

For the fourth reaction to occur, the first three reactions must occur twice, in which case two light helium nuclei unite to form ordinary helium nucleus.

If we consider the combination 2(i) + 2(ii) + 2(iii) +(iv), the net effect is

$$4\,{}_1^1H + 2\,e^- \rightarrow {}_2^4He + 2\nu + 6\gamma + 26.7\ MeV$$

$$(4\,{}_1^1H + 4\,e^-) \rightarrow ({}_2^4He + 2\,e^-) + 2\nu + 6\gamma + 26.7\ MeV$$

Thus, four hydrogen atoms combine to form an ${}^{4}_{2}He$ atom with a release of 26.7 MeV of energy.

Helium is not the only element that can be synthesized in the interior of a star. As the hydrogen in the core gets depleted and becomes helium, the core starts to cool. The star begins to collapse under its own gravity which increases the temperature of the core. If this temperature increases to about 10^8 K, fusion takes place again, this time of helium nuclei into carbon.
This kind of process can generate through fusion higher and higher mass number elements. But elements more massive than those near the peak of the binding energy curve in cannot be so produced.

The age of the sun is about 5×10^9 years and it is estimated that there is enough hydrogen in the sun to keep it going for another 5 billion years.

After that, the hydrogen burning will stop and the sun will begin to cool and will start to collapse under gravity, which will raise the core temperature. The outer envelope of the sun will expand, turning it into the so called red giant. This is the story of every star.

10. CONTROLLED THERMONUCLEAR FUSION

The natural thermonuclear fusion process in a star is replicated in a thermonuclear fusion device. In controlled fusion reactors, the aim is to generate steady power by heating the nuclear fuel to a temperature in the range of 10^8 K. At these temperatures, the fuel is a mixture of positive ions and electrons (plasma). The challenge is to confine this plasma, since no container can stand such a high temperature.
Several countries around the world including India are developing techniques in this connection. If successful, fusion reactors will hopefully supply almost unlimited power to humanity.

11. NUCLEAR HOLOCAUST

The fear of vast amount of energy harming the surroundings is foremost concern of nuclear fission and fusion.

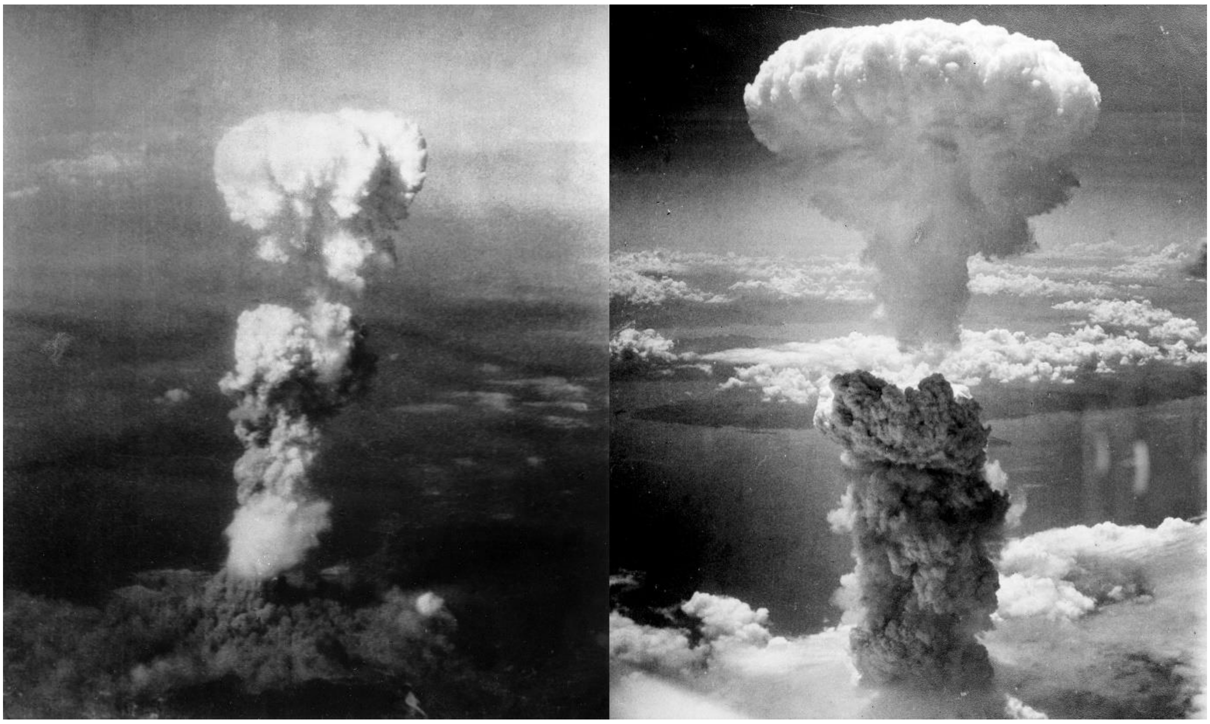
In single **uranium fission** about 0.9×235 MeV (≈200 MeV) of energy is liberated.
If each nucleus of about 50 kg of 235-U undergoes fission the amount of energy involved is about 4×10^{15}J.
This energy is equivalent to about 20,000 tons of TNT, enough for a super explosion.

Uncontrolled release of large nuclear energy is called **an atomic explosion**.

Trinitrotoluene (TNT), or 2,4,6-trinitrotoluene, is a chemical compound with the formula $C_6H_2(NO_2)_3CH_3$. This yellow solid is sometimes used as a reagent in chemical synthesis, but it is best known as an explosive material with convenient handling properties. The explosive yield of TNT is considered to be the standard measure of bombs and other explosives.
https://en.wikipedia.org/wiki/TNT

On August 6, 1945 an atomic device was used in warfare for the first time. The US dropped an atom bomb on Hiroshima, Japan. The explosion was equivalent to 20,000 tons of TNT.

Instantly the radioactive products devastated 10 sq km of the city which had 3,43,000 inhabitants. Of this number 66,000 were killed and 69,000 were injured; more than 67% of the city's structures were destroyed.



https://upload.wikimedia.org/wikipedia/commons/5/54/Atomic_bombing_of_Japan.jpg

High temperature conditions for fusion reactions can be created by exploding a fission bomb. Super-explosions equivalent to 10 megatons of explosive power of TNT were tested in 1954. Such bombs which involve fusion of isotopes of hydrogen, deuterium and tritium are called hydrogen bombs.

It is estimated that a nuclear arsenal sufficient to destroy every form of life on this planet several times over is in position to be triggered by the 'press of a button'. Such a nuclear holocaust will not only destroy the life that exists now but its radioactive fallout will make this planet unfit for life for all times. Scenarios based on theoretical calculations predict a long nuclear winter, as the radioactive waste will hang like a cloud in the earth's atmosphere and will absorb the sun's radiation.

EXAMPLE

Answer the following questions:

(a) Are the equations of nuclear reactions 'balanced' in the sense a chemical equation (e.g. $2 H_2 + O_2 \rightarrow 2 H_2O$) is?
If not, in what sense are they balanced on both sides?

(b) If both the number of protons and the number of neutrons are conserved in each nuclear reaction, in what way is mass converted into energy (or vice-versa) in a nuclear reaction?

(c) A general impression exists that mass-energy inter-conversion takes place only in nuclear reaction and never in chemical reaction. This is strictly speaking, incorrect. Explain.

SOLUTION

(a) A chemical equation is balanced in the sense that the number of atoms of each element is the same on both sides of the equation. A chemical reaction merely alters the original combinations of atoms. In a nuclear reaction, elements may be transmuted. Thus, the number of atoms of each element is not necessarily conserved in a nuclear reaction. However, the number of protons and the number of neutrons are both separately conserved in a nuclear reaction.
[Actually, even this is not strictly true in the realm of very high energies – what is strictly conserved is the total charge and total 'baryon number'. We need not pursue this matter here.]
In nuclear reaction, the number of protons and the number of neutrons are the same on the two sides of the equation.

(b) We know that the binding energy of a nucleus gives a negative contribution to the mass of the nucleus (mass defect). Now, since proton number and neutron number are conserved in a nuclear reaction, the total rest mass of neutrons and protons is the same on either side of a reaction. But the total binding energy of nuclei on the left side need not be the same as that on the right hand side. The difference in these binding energies appears as energy released or absorbed in a nuclear reaction. Since binding energy contributes to mass, we say that the difference in the total mass of nuclei on the two sides get converted into energy or vice-versa.
It is in this sense that a nuclear reaction is an example of mass energy inter-conversion.

(c) From the point of view of mass-energy inter-conversion, a chemical reaction is similar to a nuclear reaction in principle. The energy released or absorbed in a chemical reaction can be traced to the difference in chemical (not nuclear) binding energies of atoms and molecules on the two sides of a reaction. Since, strictly speaking, chemical binding energy also gives a negative contribution (mass defect) to the total mass of an atom or molecule; we can equally well say that the difference in the total mass of atoms or molecules, on the two sides of the chemical reaction gets converted into energy or vice-versa. However, the mass defects involved in a chemical reaction are almost a million times smaller than those in a nuclear reaction. This is the reason for the general impression, (which is incorrect) that mass-energy inter-conversion does not take place in a chemical reaction.

12. SUMMARY

- An atom has a nucleus.
- The nucleus is positively charged.
- The radius of the nucleus is smaller than the radius of an atom by a factor of 10^4.
- More than 99.9% mass of the atom is concentrated in the nucleus.
- On the atomic scale, mass is measured in atomic mass units (u). By definition, 1 atomic mass unit (1u) is 1/12th mass of one atom of 12C;
  $1u = 1.660563 \times 10^{-27}$ kg.

- A nucleus contains a neutral particle called neutron. Its mass is almost the same as that of proton

  The atomic number Z is the number of protons in the atomic nucleus of an element. The mass number A is the total number of protons and neutrons in the atomic nucleus; A = Z+N; Here N denotes the number of neutrons in the nucleus.
- A nuclear species or a nuclide is represented as ${}^{A}_{Z}X$, where X is the chemical symbol of the species.
- Nuclides with the same atomic number Z, but different neutron number N are called isotopes.
- Most elements are mixtures of two or more isotopes. The atomic mass of an element is a weighted average of the masses of its isotopes. The masses are the relative abundances of the isotopes.
- Neutrons and protons are bound in a nucleus by the short-range strong nuclear force. The nuclear force does not distinguish between neutron and proton.
- The nuclear mass M is always less than the total mass, Σm, of its constituents. The difference in mass of a nucleus and its constituents is called the mass defect,

  $\Delta M = (Z\,m_p + (A - Z)m_n) - M$
- Using Einstein's mass energy relation, we express this mass difference in terms of energy as

  $\Delta E = \Delta M\,c^2$

  The energy ΔE represents the binding energy of the nucleus. In the mass number range A = 30 to 170, the binding energy per nucleon is nearly constant, about 8 MeV/nucleon.
- Energies associated with nuclear processes are about a million times larger than chemical process.
- Energy is released when less tightly bound nuclei are transmuted into more tightly bound nuclei. In fission, a heavy nucleus like ${}^{235}_{92}U$ breaks into two smaller fragments, and neutrons
- The fact that more neutrons are produced in fission than are consumed gives the possibility of a chain reaction with each neutron that is produced triggering another fission. The chain reaction is uncontrolled and rapid in a nuclear bomb explosion.
- It is controlled and steady in a nuclear reactor. In a reactor, the value of the neutron multiplication factor k is maintained at 1.
- In fusion, lighter nuclei combine to form a larger nucleus. Fusion of hydrogen nuclei into helium nuclei is the source of energy of all stars including our sun.