NUCLEAR FISSION

The story of discovery of fission is very fascinating. In the year 1938, Enrico Fermi, Otto Hahn and others irradiated uranium nuclei with slow neutrons to produce transuranic elements (having Z greater than 92), which do not occur in nature. When incident neutrons were ~~captured~~ captured by the uranium nuclei, the neutron-proton ratio increased. In reducing this ratio, it was expected that uranium would become β-active. That is a neutron would essentially behave as if it has changed into a proton resulting in the release of a β-particle and some energy according to the equation:

$$^{238}_{92}U + ^{1}_{0}n \longrightarrow ^{239}_{93}Np + ^{0}_{-1}e + Q$$

In this process, a new transuranic element having atomic number 93 was expected to be produced. In fact, Fermi and his co-researchers observed β-activities with half-lives differents from any of the known values for heavy elements in the vicinity of uranium. From those observations, they concluded that transuranic elements had been produced. And to identify the element, they carried out chemical analysis but failed.

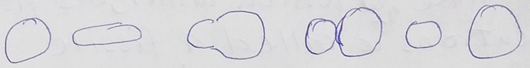
In the same year, Otto Hahn and Fritz Strassmann carried out a series of experiments and established that barium, an element of intermediate mass number rather than a transuranic element, was one of the products of the reaction and it was accompanied by release of nearly 200MeV of energy. This result—the product of slow neutron bombardment of uranium was barium—was completely unexpected and defied all knowledge of nuclear physics of that time. These findings were reported in Nature in December, 1938.

Initially, Lise Meitner and Otto Frisch explained these results on the basis of liquid drop model of nucleus and named this process nuclear fission using the analogy with biological cell division. Later on, Bohr and Wheeler calkulated the amount of energy released in the process, confirming the physical basis of this model.

MECHANISM OF NUCLEAR FISSION

In the year 1939, Bohr and Wheeler developed the theory of fission using the analogy between nuclear forces and the forces which bind molecules in a liquid. They predicted that $^{235}_{92}U$ was more fissile than $^{238}_{92}U$. If we show the schematics of nuclear fission of $^{235}_{92}U$ by thermal neutrons according to the equation

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{36}Ba + ^{92}_{36}Kr + 3^{1}_{0}n + Q$$



time →

Nuclear fission of a nucleus according to the Liquid drop model

The emitted neutrons have energy of the order of a few MeV and $Q \simeq 200\,MeV$

However, Bohr and Wheeler treated the nucleus as a charged spherically symmetric liquid drop in its equilibrium (lowest energy) state. According to them, when a nucleus captures a thermal neutron, the binding energy (BE) of this neutron, which is 6-8 MeV per atomic mass unit for ^{235}U, is released. This energy excites the nucleus and distorts its shape. While the force of surface tension tries to restore the original shape, the Coulomb force tends to distort it further. As a result, it oscillates between spherical and dumb bell shapes as shown above, depending on the energy of excitation. When the energy gained by the nucleus is large, the amplitude of these oscillations pushes the nucleus into dumb bell shape. When the distance between the two charge centres exceeds a critical value, electrostatic repulsion between them overcomes nuclear surface tension and pushes the nucleus into two parts resulting in fission.

A substance like $^{235}_{92}U$ which undergoes fission by thermal neutrons is called a fissile material, Other fissile materials are $^{233}_{90}Th$, $^{233}_{92}U$ and $^{239}_{93}Pu$. You may note that all these nuclei have odd mass number and even atomic number.

We can estimate the amount of energy released in the fission of $^{235}_{92}U$ by calculating the mass defect.

NUCLEAR CHAIN REACTION

You have now learnt that when a neutron is captured by $^{235}_{92}U$, it splits into two fragments and 2-3 neutrons are emitted. These are capable of causing further fissions. This immediatel presented the exciting possibility of maintaining a fission chain reaction in which each fission event removes one neutron and replaces the by more than two. When the rate of production of neutrons equals the rate of loss of neutrons, the reaction is said to be self-sustained. The device designed to maintain a self-sustained and controlled chain reaction is called a nuclear reactor.

Nuclear reactors are usually classified according to the purpose for which they are used. So a nuclear power reactor is used to produce electricity and a research reactor is used to produce radioisotopes for medical purposes, carrying out experiments for

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refinements or applied research. We also categorise nuclear reactors as fast and thermal, depending on the energy of neutrons causing fission. In India, we have thermal power reactors at Tarapore, Marora, Kota, Kaiga etc. At Kalpakkam, we are developing a fast breeder research reactor.

NUCLEAR FUSION

You now know that uranium nucleus can be made to split into lighter nuclei resulting in release of huge amount of energy. You may now ask: Can we combine lighter nuclei to produce energy? To discover answer to this question, you will ~~know~~ note that the binding energy per nucleon increases in the binding energy per nucleon (BE/A) curve, as we go from hydrogen to helium. It means that helium is more stable than hydrogen. Consider the following reaction:

$$ {}_1D^2 + {}_1D^2 \longrightarrow {}_2He^4 + Q $$

You can easily calculate the B.E of reactents and products:

Total B.E of reactants, $BE_1 = 2 \times 2.22 = 4.44$ MeV

Total B.E of products, $BE_2 = 28.295$ MeV

$$ Q = (BE_2 - BE_1) \simeq 24 \text{ MeV} $$

∴ Note that the energy released per nucleon in this reaction is $24/4 = 6$ MeV. which is nearly seven times the energy released per nucleon (200/238 = 0.83 MeV) in a nuclear fission event.

Therefore, nuclear fusion is the process in which two light nuclei combine to form a heavier nucleus.

Fusion process presents itself as a more viable energy option. However, the process of fusion is more difficult to achieve than nuclear fission because both the deuterons are positively charged. When we try to bring them together to fuse into one nucleus, they repel each other very strongly and the reaction is ordinarily impossible. To achieve this reaction, the deuterons have to be heated to nearly 10 million Kelvin so that they acquire sufficient kinetic energy to overcome repulsion before they collide to fuse into helium nucleus. But the problems associated with maintaining such high temperatures continuously and containing the reactants together has not yet been solved fully. The controlled thermonuclear reaction necessary for harnessing this source of energy is however not far now.

Almost inexhaustible amount of deuterium (heavy hydrogen) is present in the ocean. Once we begin harness this source, our energy problem should be solved for ever. We will get an endless supply of cheap electricity without any pollution.

PHY 102 ①

CHEMICAL ~~NUCLEAR~~ REACTIONS:

Chemical reaction is the formation of a new compound molecule due to rearrangement of valence electrons in interacting atoms and molecules with the release or absorption of energy.

In this process, the nucleus is not affected at and even the electrons in the inner orbits remain unaffected. An example of a chemical reaction is the interaction of carbon atoms with oxygen molecules to produce carbon dioxide [Carbon(IV) oxid

$$C + O_2 \rightarrow CO_2 + 4.08\,eV$$

In this chemical reaction, 4.08eV energy is release for each reacting carbon atom. It is called the binding energy (B.E) of CO_2 molecule. Reactions wh result in release of energy are said to be exothermic. While chemical reactions which require energy to be supplied to be initiated ar endothermic.

For example, if 4.08eV of energy is given to a CO_2 molecule under suitable conditions, it will breakup into its constituents:

$$CO_2 + 4.08\,eV \rightarrow C + O_2$$

In the above equation, 4.08eV energy leaves the system to form CO_2 gas. Therefore, the mass of C molecule will be less than the total mass of C & C by mass equivalent of 4.08eV. The loss of mass Δm can be calculated using the relation $E = mc^2$

$$\Delta m = \frac{4.08 \times 1.602 \times 10^{-19}}{9 \times 10^{16}} = 7.26 \times 10^{-36} kg$$

Such a small change in mass cannot be detected and we say that the mass is conserved in chemical reactions, though slight change of mass does occur.

The important points to be noted in chemical reactions are;

1. Energies of the order of 10eV are involved
2. Change of mass is of the order of 10^{-35} kg, which is extremely small and we say that the mass is conserved.
3. The total number of atoms of each type on the right hand side of the chemical equation is always equal to the total number of atoms of each type on the left hand side.

NUCLEAR REACTIONS

In nuclear reactions, the nuclei, not electrons of the reactants interact with each other. They result in the formation of new elements. This process is also called transmutation of nuclei. In ~~react~~ nuclear reactions energies of the order of MeV involved.

The phenomenon of nuclear transmutation or nuclear reaction was discovered by Lord Rutherford in the year 1919. He ~~bound~~ bombarded nitrogen gas with high energy α-particle of energy 7.7MeV obtained from a polonium source. He observed that hydrogen transformed into oxygen. This change was accompanied by high energy protons:

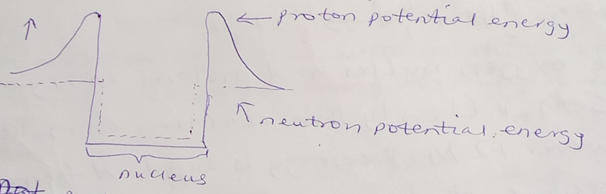
$$^{4}_{2}He + ^{14}_{7}N \rightarrow ^{17}_{8}O + ^{1}_{1}H$$

The oxygen nuclei and protons carry away 6.5 MeV. Clearly this reaction can occur. However, 1.2 MeV energy is supplied from outside, therefore, it is an endothermic nuclear reaction. When aluminium is bombarded by 7.7MeV alpha particles from polonium, the following nuclear reaction takes place and 10.7MeV energy is released:

$$^{27}_{13}Al + ^{4}_{2}He \rightarrow ^{30}_{14}Si + ^{1}_{1}H$$

In this case, we see that more energy is released than the input energy: It is an exothermic reaction. Note that there is a gain of nearly 3 MeV energy per reaction, which is approximately 700,000 times the energy released in burning of one carbon atom. But this reaction can't be used for production of energy because out of 125,000 incident alpha particles only one succeeds in producing the reaction. Hence on the whole, there is much more energy spent than produced.

However, we know that the entire positive charge of an atom is concentrated in its nucleus, whose size is of the order of 10^{-15} m. The nucleus is surrounded by electrons revolving in certain specified orbits. These create a strong electrostatic potential barrier (also called the coulomb barrier) as shown below



~~Bot~~ Proton and neutron potential energies near a nucleus

The Coulomb barrier is about 3 MeV for carbon nuclei and 20 MeV for lead nuclei. It means that a charged projectile aimed at a nucleus will experience strong repulsion by the coulomb barrier of the target nucleus. If the kinetic energy of projectile is not large enough to netrate the barrier, it will come back without producing any nuclear reaction for a proton to enter a carbon nucleus and produce transmutation, its energy should be more than 3 MeV or so. It is because of the large amounts of energy involved in nuclear reactions that we do not observe these reactions in everyday life at ordinary temperatures and pressures.

Nuclear reactions can also be produced by protons, deuterons, neutrons and other light nuclei. Of these, neutrons are the best projectiles for producing nuclear reactions: being neutral particles, they do not experience coulomb repulsion. Thus even thermal neutrons (ie neutrons having energy 0.0253 eV) can penetrate the target nucleus and produce a nuclear reaction.

Some typical examples of nuclear reactions produced by protons, deutrons and neutrons are:

$$^{6}_{3}Li + ^{1}_{1}H \rightarrow ^{3}_{2}He + ^{4}_{2}He \quad \ldots (1)$$

$$^{10}_{5}B + ^{2}_{1}H \rightarrow 3\,^{4}_{2}He \quad \ldots (2)$$

$$^{10}_{5}B + n \rightarrow ^{7}_{3}Li + ^{4}_{2}He \quad \ldots (3)$$

Like chemical reactions, nuclear reactions also follow conservations laws. We state these now.

ENERGY IN THE SUN AND STARS

The stars like our sun are very massive objects. They have been continuously emitting tremendous amount of energy for the last billions of years. Such a huge amount of energy cannot be obtained by burning conventional fuels like coal. Nuclear fission can also not be the source of this energy, because heavy elements do not exist in the sun in large quantity. The sun mainly consists of hydrogen and helium gases. Then you may like to know: What is the source of energy in the sun? This question has engaged human intellect for long. As a child, you must have gazed the sky when you learnt the rhyme: Twinkle twinkle little star. How I wonder what you are!

You may know that the huge mass of the sun produces extremely strong gravitational field, which compresses its constituents gases by enormous pressure resulting in in the rise of temperature to millions of kelvin at its centre. It has been estimated that the temperature at the centre of the sun is 20 million kelvin. At such high temperatures and pressures, gas molecules travel at high speeds and collide setting in thermonuclear reactions and resulting in the release of large amount of energy.

Be proposed that fusion of hydrogen into helium is responsible for the energy produced in stars.

$$4\,{}^1_1H \rightarrow {}^4_2He + 2\,{}^0_{+1}e + Q$$

The overall result here is: four hydrogen nuclei fuse into a helium nucleus with the release of two positrons (electron-like microscope particles of the same mass but positive charge) and 26.8 MeV energy. The tremendous amount of energy released in a thermo-nuclear reaction is the source of energy in stars. The quantity of hydrogen in the sun is sufficient to keep it shining for nearly 8 billion years more.

CALCULATIONS

Calculate the energy released in the nuclear reactions given below;

(1) ${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{141}_{36}Ba + {}^{92}_{36}Kr + 3{}^{1}_{0}n + Q$

(2) ${}^{10}_{5}B + {}^{2}_{1}D \rightarrow 3{}^{4}_{2}He + Q$

Given that $m({}^{235}U) = 235.0439u$;
$m({}^{1}n) = 1.008665u$;
$m({}^{141}Ba) = 140.9139u$;
$m({}^{92}Kr) = 91.8973u$;
$m({}^{10}B) = 10.01294u$;
$m({}^{2}D) = 2.014103u$;
$m({}^{4}He) = 4.002604u$;

Solution:

1.

Reactants	Mass	Products	Mass
${}^{235}U$	235.0439u	${}^{141}_{36}Ba$	140.9139u
${}^{1}n$	1.008665u	${}^{92}_{36}Kr$	91.8973u
		$3 \times {}^{1}n$	3.025995u
		Total mass	235.837195u
Total mass	236.052565u		
Mass defect	0.21537u		
Energy released	$0.21537 \times 931 = 200$ MeV		

2.

${}^{10}B$	10.01294u	${}^{4}_{2}He$	4.002604u
${}^{2}D$	2.014103u	$3 \times He$	12.007812u
Total mass	12.027043u	Total mass	12.007812u
Mass defect	0.019231u		
Energy released	$0.019231 \times 931 = 17.904061$ MeV		

PHY 102 (10)

1. What is the lost of ~~energy~~ mass Δm in the chemical reaction, $C + O_2 \rightarrow CO_2 + 4.08$, 4.08eV energy is released for each reacting carbon atom?

Solution:

$E = mc^2$

$$\Delta m = \frac{4.08 \times 1.602 \times 10^{-19}}{9 \times 10^{16}} = 7.26 \times 10^{-36} kg.$$

2. Complete the equations of nuclear reactions:

(a) $^{19}_{9}F + ^{1}_{1}H \rightarrow ^{16}_{8}O + ? \Rightarrow ^{19}_{9}F + ^{1}_{1}H \rightarrow ^{16}_{8}O + ^{4}_{2}He$

(b) $^{27}_{13}Al + ^{1}_{0}n \rightarrow ? + ^{4}_{2}He \Rightarrow ^{27}_{13}Al + ^{1}_{0}n \rightarrow ^{24}_{11}Na + ^{4}_{2}He$

(c) $^{234}_{90}Th \rightarrow ^{234}_{91}Pa + ? \Rightarrow ^{234}_{90}Th \rightarrow ^{}_{91}Pa + ^{0}_{-1}e$

(d) $^{63}_{29}Cu + ^{2}_{1}D \rightarrow ^{64}_{30}Zn + ? \Rightarrow ^{63}_{29}Cu + ^{2}_{1}D \rightarrow ^{64}_{30}Zn + ^{1}_{0}n$

3. Calculate the energy released in the nuclear reaction given below

$^{10}_{5}B + ^{2}_{1}D \rightarrow 3\,^{4}_{2}He + Q$

Given that $m(^{10}B) = 10.01294\,u$; $m(^{2}_{1}D) = 2.014103\,u$, and $m(^{4}_{2}He) = 4.002604\,u$. Answer: 17.9 MeV

(10)

4. Why does a $^{238}_{92}U$ nucleaus become β-active after absorbing a neutron?

5. Out of $^{238}_{92}U$, ^{141}Ba, ^{239}Pu, and $^{12}_{6}C$, which nucleus is fissible?

6. How much energy is released when $^{235}_{92}U$ undergoes nuclear fission?

7. What type of reactors are used in India for power generation?

8. How much $^{235}_{92}U$ undergoes fission in an atomic bomb which release energy equivalent to 20,000 tons of TNT. (Given that 1g of TNT gives out 1000 calorie of heat).

9. How does a nuclear reaction differ from a chemical reaction?

10. What is the use of moderator in a fission reactor?

11. What is the use of absorber in a fission reactor?

12. What is the source of energy in the sun?

13.

ELEMENTARY PARTICLES &
FORCES OF NATURE (12)

The world is made up of elementary particles called quarks, which include the up, down, charm, strange, top, and bottom quarks and leptons, which include the electron, the muon, the tau, and their corresponding neutrons. But how do these particles interact? How do they form the world you see around you? ~~find out in this activity~~.

The four fundamental forces of Nature

1. Electromagnetism causes: like charged objects to repel each other ~~and~~ and oppositely charged objects to attract each other. The electromagnetic force binds negative electrons to the positive nuclei in atoms and underlies the interactions between atoms, its force carrier particle is a photon.
2. The strong force binds quarks together while the electromagnetic force works to repel the positively charged protons in the nucleus of an atom, the strong force is stronger

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and overrides these effects. The particle that carries the strong force is called gluon, so-named because it so tightly "glues" quarks together into larger particles like photons and neutrons. The strong force is also responsible for binding protons and neutrons together in the nucleus

3 Gravity is the phenomenon by which massive bodies such as planets and stars, are attracted to one another. The warps and curves in the fabric of space and time are a result of how these massive objects influence one another through gravity. Any object with mass exerts a gravitational pull on any other object with mass. You don't fly off Earth's surface because Earth has a gravitational pull on you.

4 The weak force is responsible for different types of particle decays, including a process called beta decay. This can occur when an atom's nucleus contains too many protons or too many neutrons — a neutron that turns into a proton undergoes beta minus decay, a proton that changes into a neutron experience beta plus decay.