# JSR IAS ACADEMY

## GENERAL SCIENCE
## PHYSICS

# NUCLEAR PHYSICS

### Democritus

❖ A Greek Philosopher 'Democritus' in **400 BC** believed that **matter is made up of tiny indestructible units** called atoms.

### John Dalton

❖ Later, in **1803,** John Dalton considered that **elements consist of atoms, which are identical in nature.**

### J J Thomson

❖ J.J.Thomson **discovered cathode rays, known as electrons,** experimentally

### Goldstein

❖ Goldstein **discovered positive rays**, which were **named as protons by Rutherford.**

### James Chadwick

❖ In **1932**, James Chadwick **discovered the chargeless particles called neutrons**.

➢ Presently, a large number of elementary particles like **photon, meson, positron and nutrino** have been discovered.

### Ernest Rutherford

In **1911,** the British scientist, Ernest Rutherford explained that the mass of an atom is concentrated in its central part called **Nucleus.**

### Discovery of radioactivity

❖ In 1896, French physicist **Henri Becquerel** finished his research for the week and stored a certain amount of uranium compound away in a drawer for the week end.

❖ After a week he returned and noticed that **the film had been exposed to some radiation.**

❖ He discovered **uranium radiated something that could affect a photographic plate**.

❖ This phenomenon was called as **Radioactivity**.

❖ Two years later, the Polish physicist **Marie Curie and her husband Pierre Curie** detected radioactivity in **'Pitchblende'**, a tiny black substance.

❖ They were not surprised at the radioactivity of pitchblende, which is known as an ore of uranium. Later, they **discovered that the radiation was more intense from pure uranium.**

❖ Also, it was found that the pitchblende had **less concentration of uranium.**

❖ They concluded that some other substance was present in pitchblende.

❖ After separating this new substance, they discovered that it had unknown chemical properties and it also emitted radiations spontaneously like uranium. They named this new substance as **'Radium'.**

❖ The radioactive elements **emit harmful radioactive radiations** like **alpha rays or beta rays or gamma rays**.

### Definition of radioactivity

❖ The nucleus of **some elements is unstable**.

❖ Such **nuclei undergo nuclear decay** and get **converted into more stable nuclei.**

❖ The phenomenon of **nuclear decay of certain elements with the emission of radiations like alpha, beta, and gamma rays** is called **'radioactivity'** a

❖ the elements, which undergo this phenomenon are called **'radioactive elements'**.

### Natural Radioactivity

❖ The elements such **as uranium and radium undergo radioactivity** and **emit the radiations on their own without any human intervention.**

❖ certain elements on their own is called **'natural radioactivity'**.

❖ The elements whose **atomic number is more than 83** undergo spontaneous radioactivity.

❖ Eg: **uranium, radium**, etc.

❖ There are **only two elements, which have been identified as radioactive substances with atomic number less than 83**.

❖ They are **technetium (Tc)** with atomic number **43** and **promethium (Pm)** with atomic number **61.**

### Artificial Radioactivity (or) Induced Radioactivity

❖ The phenomenon by which even **light elements are made radioactive, by artificial or induced methods**, is called **'artificial radioactivity' or 'man-made radioactivity'**.

❖ This kind of radioactivity was discovered by **Irene Curie and F.Joliot** in **1934.**

❖ Artificial radioactivity is induced in certain lighter elements like **boron, aluminium** etc., **by bombarding them with radiations such as 'alpha particles'** emitted during the natural radioactivity of uranium.

- This also **results in the emission of invisible radiations and elementary particles**.
- During such a disintegration, the nucleus which undergoes disintegration is called **'parent nucleus'** and that which is produced after the disintegration is called a **'daughter nucleus'**.
- The particle, which is used to induce the artificial disintegration is termed as **projectile**
- the particle which is produced after the disintegration is termed as **ejected particle.**
- When the **projectile hits the parent nucleus**, it is converted into an unstable nucleus, which in turn decays **spontaneously emitting the daughter nucleus** along with an ejected particle.

| S.No | Natural radioactivity | Artificial radioactivity |
|---|---|---|
| 1 | Emission of radiation due to self-disintegration of a nucleus. | Emission of radiation due to disintegration of a nucleus through induced process. |
| 2 | Alpha, beta and gamma radiations are emitted. | Mostly elementary particles such as neutron, positron, etc. are emitted. |
| 3 | It is a spontaneous process. | It is an induced process. |
| 4 | Exhibited by elements with atomic number more than 83. | Exhibited by elements with atomic number less than 83. |
| 5 | This cannot be controlled. | This can be controlled. |

If you denote the parent and daughter nuclei as X and Y respectively, then the nuclear disintegration is represented as follows: **X (P,E) Y.**

Here, P and E represent the projectile particle and ejected particle respectively.

**Example:**

$${}_{4}Be^{9} + {}_{2}He^{4} \longrightarrow {}_{6}C^{13*}$$

$${}_{6}C^{13*} \longrightarrow {}_{6}C^{12} + {}_{0}n^{1}$$

In the above nuclear reaction, ${}_{6}C^{13*}$ is unstable and is radioactive. This reaction can be represented as ${}_{4}Be^{9}$ (α, n) ${}_{6}C^{12}$

$${}_{4}Be^{9} + {}_{2}He^{4} \longrightarrow {}_{6}C^{12} + {}_{0}n^{1}$$

**Units of Radioactivity**

**Curie:**

- It is the **traditional unit of radioactivity.**
- **1 curie = 3.7 × 10$^{10}$** disintegrations per second.
- This is actually close to the activity of **1 g of radium 226.**

**Rutherford (Rd):**

- It is **another unit of radioactivity**.
- **1 Rd = 106** disintegrations per second.

**Becquerel (Bq) :**

- The **SI unit of radioactivity** is becquerel.
- It is defined as the **quantity of one disintegration per second.**

**Roentgen (R):**

- The radiation **exposure of γ and x-rays is measured by another unit** called roentgen.
- One roentgen is defined as the quantity of radioactive substance **which produces a charge of 2.58 × 10$^{-4}$ coulomb in 1 kg of air** under standard conditions of pressure, temperature and humidity

DO YOU KNOW? There have been 29 radioactive substances discovered so far. Most of them are rare earth metals and transition metals

DO YOU KNOW? Uranium, named after the planet Uranus, was discovered by Martin Klaproth, a German chemist in a mineral called pitchblende.

**ALPHA, BETA AND GAMMA RAYS**

| Properties | α rays | β rays | α rays |
|---|---|---|---|
| What are they? | Helium nucleus ($_2He^4$) consisting of two protons and two neutrons. | They are electrons ($_{-1}e^0$), basic elementary particle in all atoms. | They are electromagnetic waves consisting of photons. |
| Charge | Positively charged particles. Charge of each alpha particle = +2e | Negatively charged particles. Charge of each beta particle = −e | Neutral particles. Charge of each gamma particle = zero |
| Ionising power | 100 time greater than β rays and 10,000 times greater than γ rays | Comparatively low | Very less ionization power |
| Penetrating power | Low penetrating power (even stopped by a thick paper) | Penetrating power is greater than that of α rays. They can penetrate through a thin metal foil. | They have a very high penetrating power greater than that of β rays. They can penetrate through thick metal blocks. |
| Effect of electric and magnetic field | Deflected by both the fields. (in accordance with Fleming's left hand rule) | Deflected by both the fields; but the direction of deflection is opposite to that for alpha rays. (in accordance with Fleming's left hand rule) | They are not deflected by both the fields. |
| Speed | Their speed ranges from 1/10 to 1/20 times the speed of light. | Their speed can go up to 9/10 times the speed of light. | They travel with the speed of light. |

**Radioactive displacement law**

**In 1913, Soddy and Fajan** framed the displacement laws governing the **daughter nucleus produced during an alpha and beta decay**.

- When a radioactive element **emits an alpha particle,** a daughter nucleus is formed whose **mass number is less by 4 units and the atomic number is less by 2 units,** than the mass number and atomic number of the parent nucleus.
- When a radioactive element **emits a beta particle**, a daughter nucleus is formed whose **mass number is the same and the atomic number is more by 1 unit**, than the atomic number of the parent nucleus.

**Alpha decay**

A nuclear reaction in which an **unstable parent nucleus emits an alpha particle and forms a stable daughter nucleus**, is called 'alpha decay'.

**E.g.**: Decay of **uranium ($U^{238}$)** to **thorium ($Th^{234}$)** with the emission of an alpha particle.

$$_{92}U^{238} \longrightarrow {}_{90}Th^{234} + {}_2He^4 \quad (\alpha\text{ - decay})$$

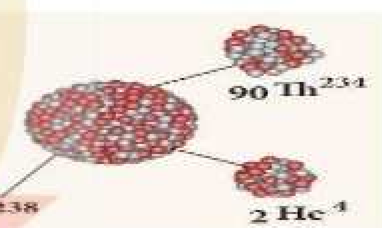


Fig. 6.1 Alpha decay

**Beta decay**

A nuclear reaction, in which an **unstable parent nucleus emits a beta particle and forms a stable daughter nucleus,** is called 'beta decay'.

E.g.: Beta decay of phosphorous.

$$_{15}P^{32} \longrightarrow {}_{16}S^{32} + {}_{-1}e^0 \quad (\beta\text{ - decay})$$

there is **no change in the mass number of the daughter nucleus but the atomic number increases by one**.

In a nuclear reaction, **the element formed as the product nucleus is identified by the atomic number of the resulting nucleus and not by its mass number**

### Gamma decay

- In a $\gamma$ - decay, only the **energy level of the nucleus changes.**
- The **atomic number and mass number of the radioactive nucleus remain the same.**

### NUCLEAR FISSION

- Definition In **1939**, German Scientist **Otto Hahn and F.Strassman** discovered that when a **uranium nucleus is bombarded with a neutron, it breaks up into two smaller nuclei** of comparable mass **along with the emission of a few neutrons and energy.**
- This process of **breaking (splitting) up of a heavier nucleus into two smaller nuclei** with the **release of a large amount of energy and a few neutrons** is called 'nuclear fission'.

E.g.: Nuclear fission of a uranium nucleus (U235)

$$_{92}U^{235} + {}_{0}n^{1} \longrightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3{}_{0}n^{1} + Q\ (\text{energy})$$

The average energy released in each fission process is about **$3.2 \times 10^{-11}$ J.**

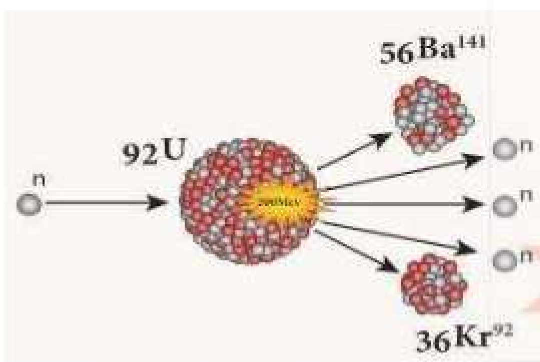



Fig. 6.2 Nuclear fission

### Fissionable materials

A fissionable material is a radioactive element, which undergoes fission in a sustained manner when it absorbs a neutron.

**E.g.: U235, plutonium (Pu239 and Pu241)**

All isotopes of uranium do not undergo nuclear fission when they absorb a neutron.

For example, **natural uranium consists of 99.28 % of $_{92}U^{238}$** and **0.72 % of $_{92}U^{235}$**.

whereas U235 undergoes fission. Hence, **U235 is a fissionable** material and **U238 is nonfissionable.**

### Fertile materials.

There are some radioactive elements, which can be converted into fissionable material. They are called as **fertile materials.**

**E.g.:** Uranium-**238,** Thorium-**232**, Plutonium-**240.**

### Chain Reaction

- A uranium nucleus (U-235) when bombarded with a neutron undergoes fission producing **three neutrons.**
- These three neutrons in turn can cause fission in three other uranium nuclei present in the sample, thus **producing nine neutrons.**
- These **nine neutrons** in turn may produce **twenty seven neutrons** and so on. This is known as **'chain reaction'**.
- A chain reaction is a selfpropagating process in which the number of **neutrons goes on multiplying rapidly almost in a geometrical progression.**

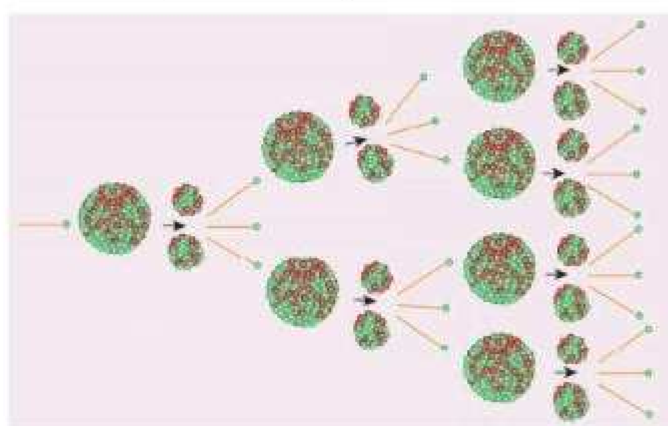
Two kinds of chain reactions are possible. They are:

**(i) controlled chain reaction**

- In the controlled chain reaction the number of neutrons released is maintained to be one.
- This is achieved by absorbing the extra neutrons with a neutron absorber leaving only one neutron to produce further fission.

**(ii)uncontrolled chain reaction.**

- In the uncontrolled chain reaction **the number of neutrons multiplies indefinitely and causes fission in a large amount of the fissile material**.
- This results in the **release of a huge amount of energy within a fraction of a second**.
- Th is kind of **chain reaction is used in the atom bomb to produce an explosion.**



### Critical Mass

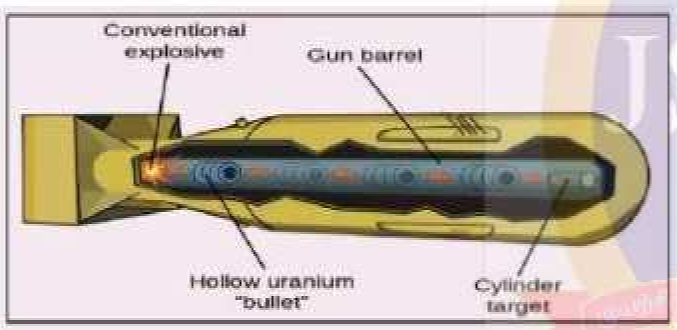
To sustain the chain reaction, **the rate of production of neutrons due to nuclear fission must be more than the rate of its los**s. This can be achieved only when the size (i.e., mass) of the fissionable material is equal to a certain optimum value. Th is is known as **'critical mass'**.

The minimum mass of a fissile material necessary to sustain the chain reaction is called 'critical mass (mc )'.

- If the mass of the fissile material is less than the critical mass, it is termed as **'subcritical'.**
- If the mass of the fi ssile material is more than the critical mass, it is termed as **'supercritical'.**

### Atom bomb

- The **atom bomb is based on the principle of uncontrolled chain reaction.**
- In an **uncontrolled chain reaction, the number of neutrons and the number of fission reactions multiply almost in a geometrical progression.**




### Structure:

- An atom bomb consists of a piece of fissile material whose mass is **subcritical.**
- This piece has a cylindrical void.
- It has a cylindrical fissile material which can fit into this void and its mass is also subcritical.
- Now, the two pieces of fissile material join to form the **supercritical mass**, which leads to an explosion.
- During this explosion **tremendous amount of energy in the form of heat, light and radiation is released.**
- **emission of hazardous radiation** like γ rays, which adversely affect the living creatures.
- This type of atom bombs were **exploded in 1945** at Hiroshima and Nagasaki in Japan during the World War II.

**DO YOU KNOW?**

Electron Volt (eV) is the unit used in nuclear physics to measure the energy of small particles. It is nothing but the energy of one electron when it is accelerated using an electric potential of one volt.

$1 eV = 1.602 \times 10^{-19}$ joule.

1 million electron volt = 1 MeV = $10^6$ eV (mega electron volt)

The energy released in a nuclear fission process is about 200 MeV.

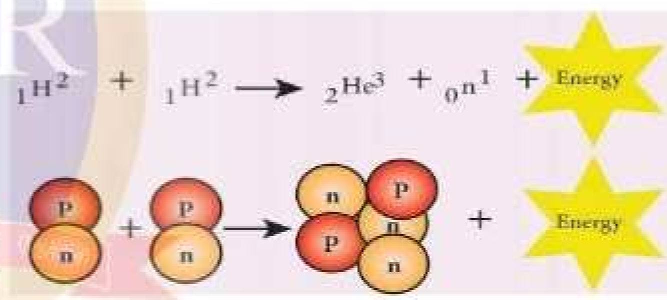
### NUCLEAR FUSION

Similarly, energy can be produced when **two lighter nuclei combine to form a heavier nucleus**. This phenomenon is known as nuclear fusion.

$$\text{E.g.: } {}_1H^2 + {}_1H^2 \rightarrow {}_2He^4 + Q \text{ (Energy)}$$

Here, ${}_1\mathbf{H}^2$ represents an isotope of hydrogen known as **'deuterium'**.

The average energy released in each fusion reaction is about **$3.84 \times 10^{-12}$ J.**




- The **mass of the daughter nucleus formed during a nuclear reaction (fission and fusion) is lesser than the sum of the masses of the two parent nuclei.**
- This difference in mass is called **mass defect**.
- This mass is converted into energy, according to the mass-energy equivalence.
- This **concept of mass-energy equivalence was proposed by Einstein in 1905.**
- It stated that **mass can be converted into energy and vice versa.**

The **relation between mass and energy proposed by Einstein is E= mc²**

where c is the velocity of light in vacuum and is equal to **3 × 108 ms–1.**

DO YOU KNOW? The nuclear bomb that was dropped in Hiroshima during World War II was called as 'Little boy'. It was a gun-type bomb which used a uranium core. The bomb, which was subsequently dropped over Nagasaki was called as 'Fat man'. It was an explosion type bomb, which used a plutonium core.

**Conditions necessary for nuclear fusion**

- Nuclear fusion is **possible only at an extremly high temperature of the order of 107 to 109 K**
- a high pressure to push the hydrogen nuclei closer to fuse with each other.
- Hence, it is named as **'Thermonuclear reaction'.**

DO YOU KNOW? Nuclear fusion is the combination of two lighter nuclei. The charge of both nuclei is positive. According to electrostatic theory, when they come closer they tend to repel each other. This repulsive force will be overcome by the kinetic energy of the nuclei at higher temperature of the order of $10^7$ to $10^9$ K.

**Stellar Energy**

- The stars like our Sun emit a large amount of energy in the form of light and heat. This energy is termed as the **stellar energy.**
- All stars contain a large amount of hydrogen.
- The surface temperature of the stars is very high which is sufficient to induce fusion of the hydrogen nuclei.
- **Fusion reaction that takes place in the cores of the Sun** and other stars results in an enormous amount of energy, which is called as 'stellar energy.
- Thus, **nuclear fusion or thermonuclear reaction** is the source of light and heat energy in the Sun and other stars.

**Hydrogen Bomb**

- Hydrogen bomb is **based on the principle of nuclear fusion.**
- A hydrogen bomb is always designed to have an inbuilt **atom bomb which creates the high temperature and pressure required for fusion when it explodes.**
- The **energy released in a hydrogen bomb (or fusion bomb) is much higher than that released in an atom bomb (or fission bomb).**

| S.No. | NUCLEAR FISSION | NUCLEAR FUSION |
|---|---|---|
| 1 | The process of breaking up (splitting) of a heavy nucleus into two smaller nuclei is called **'nuclear fission'**. | Nuclear fusion is the combination of two lighter nuclei to form a heavier nucleus. |
| 2 | Can be performed at room temperature. | Extremely high temperature and pressure is needed. |
| 3 | Alpha, beta and gamma radiations are emitted. | Alpha rays, positrons, and neutrinos are emitted. |
| 4 | Fission leads to emission of gamma radiation. This triggers the mutation in the human gene and causes genetic transform diseases. | Only light and heat energy is emitted. |

DO YOU KNOW? Sun fuses about 620 million metric tons of hydrogen each second and radiates about $3.8 \times 10^{26}$ joule of energy per second. When this energy is radiated towards the Earth, it decreases in its intensity. When it reaches the Earth its value is about 1.4 kilo joule per unit area in unit time.

DO YOU KNOW? How old is our mother Earth? Any guess?? It is nearly $4.54 \times 10^9$ years (around 45 Crore 40 lakh years). Wow!!

## SAFETY MEASURES

- The radioactive elements present in the soil and rocks, the house hold appliances like **television, microwave ovens, cell phones and the X-rays used in hospitals.**
- These radiations **do not produce any severe effects** as they are very low in intensity.
- The second source of radiation exposure is man-made.
- Improper and careless handling of radioactive materials release harmful radiations in our environment.
- These radiations are very harmful to the human body.
- A person who is exposed to radiations very closely or for a longer duration, is at a greater health risk and can be affected genetically.

### Permitted range

**The International Commission on Radiological Protection (ICRP)** has recommended certain maximum permissible exposure limits to radiation

- **Safe limit** of overall exposure to radiation is given as **20 milli sievert per year.**
- **In terms of roentgen,** the safe limit of receiving the radiation is about **100 mR per week.**
- **If the exposure is 100 R**, it may cause **fatal diseases like leukemia (death of red blood corpuscle in the blood) or cancer.**
- When the body is **exposed to about 600 R**, it **leads to death.**

DO YOU KNOW?

*Dosimeter is a device used to detect the levels of exposure to an ionizing radiation. It is frequently used in the environments where exposure to radiation may occur such as nuclear power plants and medical imaging facilities. Pocket dosimeter is used to provide the wearer with an immediate reading of his/her exposure to X-rays and γ rays.

### Preventive measures

- Radioactive materials should be kept in a **thick walled lead container.**
- **Lead coated aprons and lead gloves** should be used while working with hazardous radioactive materials.
- You should **avoid eating while handling radioactive materials.**
- The radioactive materials **should be handled only by tongs or by a remote control device.**
- **Dosimeters** should be **worn by the users to check the level of radiation.**