Nuclear Physics

Nuclear physics is the branch of physics that studies the interactions between atoms and their constituents.

The branch of science that studies the structure of nuclei, their formation and stability.

The application of nuclear physics is mostly in the field of power generation using nuclear energy.

Splitting a nucleus to produce energy is called nuclear fission and combining two neutrons to produce energy is called nuclear fusion.

Atomic theory:

Average atom diameter is 0.000000001m. or 1× 10-9m.

Nanometer - A unit used to measure small lengths. One nanometer = 1× 10-9 m.

Basic atomic particles

- Electron
- Proton
- Neutron

Protons (p):

- Located within the nucleus
- Positively charged particles.
- The value of their positive charge is equal to the value of negative charge acquired by the electrons.

Neutrons (n):

- Located within the nucleus.
- Does not contain electricity.
- All nuclei except hydrogen (protium) have neutrons.
- Protons + Neutrons = Nucleons.
- Its mass is equal to the mass of a proton and the mass of a neutron is 1.6 × 10-24 kg.

Electrons (e):

- Oppositely charged particles.
- They revolve around the nucleus in circular orbits.
- The mass of an atom depends only on the mass of protons and neutrons inside the nucleus

Atoms are neutral - the total negative charge of all the electrons outside the nucleus is equal to the total positive charge of the protons inside the nucleus.

They knew that the protons in the nucleus of an atom determine what that element is.

(eg) A hydrogen atom if there is only one proton in the nucleus of an atom.

An oxygen atom has eight protons in its nucleus.

Atomic number and mass number:

Atomic number (z):

- Atomic number is the total number of electrons or protons found in an atom.
- Denoted by the letter Z.
- If you know the atomic number, you can find the number of electrons or protons in that atom.

Mass Number (A):

- The total mass of an atom is found in its nucleus.
- The mass number is equal to the sum of the total number of protons and neutrons in the nucleus.
- Mass number or atomic mass = number of protons + number of neutrons
- $A = p + n$

Lithium mass number (A) = 3 + 4 = 7.

Sodium mass number (A) = 11 + 12 = 23.

Isotopes:

- Atoms of the same element have the same atomic number and different mass numbers. They are isotopes.

- For example the hydrogen atom has three isotopes.
- Protium (1H1), Deuterium (1H2), Tritium (1H3).

Isobars:

- Atoms having the same mass number and different atomic numbers are called isobars.
- E.g. Calcium (20Ca40) and Argon - (18Ar40).
- Competence
- Bonding ability is the ability of one atom to bond with another atom.
- It is measured by how many hydrogen atoms an atom can hold.
- Eg, one oxygen atom combines with two hydrogen atoms to form a water molecule. Therefore, the covalent bond of oxygen is two.

Nuclear principles:

Dalton's Nuclear Principle:

- Published in 1808.
- Matter is made up of very small particles called atoms.
- An atom cannot be created or destroyed.
- Atom is the smallest indivisible particle.
- Did not give any explanation about the positive and negative charges found in the atom.

Limitations of the Dalton Atomic Principle:

- It is false that an atom is an indivisible particle.
- Atoms of the same element have different atomic masses (isotopes).
- Atoms of different elements have the same atomic mass (isobars).

Thomson's Principles:

- Published in 1897.
- He compared the atom to a watermelon.
- He called opposite charges as electrons.
- According to this principle the atom has no electric charge.
- Awarded the Nobel Prize in 1906 for the discovery of the electron.

Limitations of the Thomson Atomic Principle:

- Unable to explain how a positively charged sphere protects itself from electro neutrality attracting negatively charged electrons.
- Describes protons and electrons only. Not talking about neutrons.

Rutherford's Nuclear theory:

- He bombarded a thin gold plate with positively charged alpha rays. He issued a nuclear policy based on the test.
- An atom must contain mostly vacuum.
- The area from which the charged rays are reflected back must be charged throughout the area.
- He was awarded the Nobel Prize in Chemistry for this policy.
- Nucleus is electronegative. Most of the mass of the atom is located in the center.
- Electrons move in circular orbits around the nucleus.
- The nucleus is very small in size compared to the size of the atom.

Ions:

- Atoms that have a positive or negative charge are called ions.
- An atom gains a positive charge by losing one or more electrons. These are Nerayani
- An atom acquires an opposite charge by gaining one or more electrons. These are opposites

Chemical Addition Rules:

1. **Law of Conservation of Mass.**
   - 1774
   - Lavoisier
   - The total mass of the products formed during a chemical reaction is equal to the total mass of the reactants".
   - "Mass cannot be created or destroyed by a chemical reaction",
   - This law can also be called law of mass extinction.

- Ammonia formation reaction from nitrogen and hydrogen (Haber method) .

2. **Law of Invariance.**
   - Year 1779
   - Joseph Proust
   - More than one element combines in a specific mass ratio to form a compound."
   - He discovered that compounds containing two or more elements contain the elements in the same proportions, regardless of where they are obtained and who prepares them.
   - For example, whether we get water from rain, well, sea or river, the mass of hydrogen and oxygen in it is always in the ratio of 1:8.
3. **Multiplying Ratio Law.**
4. **K- Lussac's law of mass coupling.**

Radioactivity:

Radiological discovery:

- Henri Beccorel 1896 observed that whenever a photographic plate was placed near uranium it was exposed to photochromic radiation.
- Realized that uranium emits some radiation.
- This phenomenon is called radiation.
- Uranium was identified as a radioactive element.
- Marie Curie, along with Pierre Curie, discovered radioactivity from a dark colored mineral called Pitch Blunt.
- Emits radioactivity similar to uranium. They named it Radium.
- Radioactive elements emit concentrated rays such as alpha, beta and gamma rays.

Definition of radioactivity:

- Nuclei of some elements are unstable.
- These nuclei disintegrate and become slightly more stable nuclei. The event itself is radiation.

- Radioactivity is the process by which nuclei decay and emit alpha, beta and gamma rays.
- All the elements that undergo this event are 'radioactive elements'.
- Elements with atomic number greater than 82 are capable of spontaneously emitting radiation. E.g. Uranium, Radium,
- Technetium (43) and bromium (61) are the only two elements with atomic number less than 82 that are radioactive so far.
- So far 29 radioactive substances have been discovered

Artificial radiation

'Synthetic radioactivity' is the process of induced conversion of some light elements into radioactive elements.

Irene Curie and F. Joliet discovered

Natural radiation

1. It is a spontaneous fission phenomenon of nucleus.
2. Alpha, beta and gamma rays are emitted.
3. It is a spontaneous event.
4. These usually occur in elements with atomic numbers greater than 83.
5. It cannot be controlled.

Artificial radiation

- It is a phenomenon of induced decay of nucleus.
- Mostly elementary particles like neutron, positron are emitted.
- It is a triggered event.
- These usually occur in elements with atomic numbers less than 83.
- It can be controlled.

A unit of radioactivity

Curie: The archaic unit of radioactivity.

A rate of 3.7 × 1010 decays per second from a radioactive substance is called one curie.

This is roughly equivalent to the decay caused by 1 gram of radium 226.

1 Curie = Amount of radioactive element that gives 3.7 × 1010 decays in one second

Rutherford (Rd): Another unit of radioactivity.

A radioactive substance is defined as one Rutherford if the amount of radioactive decay emitted per second is 106.

One Rutherford (Rd) = dose of radioactive element that gives 106 disintegrations in one second

Beccoral (Bq): The international (SI) unit of radioactivity is the beccoral.

It is defined as the amount of radioactive decay emitted per second as one pectoral.

Röntgen : A unit of radioactivity emitted by gamma (γ) and X rays.

A roentgen is the quantity of radioactive material that produces 2.58 × 10-4 coulomb charges in 1 kilogram of air at constant pressure, temperature and humidity.

Alpha, beta and gamma rays

1. Radioactive nuclei emit dangerous rays.
2. They are given as three radioactive particles.
3. Alpha (α), beta (β) and gamma (γ) rays.

Law of radiative migration:

Sadi and Fajan

Nuclei are formed during α and β decay

When an element emits an α-particle, its mass number is reduced by four and its atomic number by two, forming a new nucleus.

When an element emits a β-particle, its mass number remains unchanged and its atomic number increases by one to form a new nucleus.

α - Decay

- The process by which an unstable parent nucleus emits an α particle to become a stable daughter nucleus is called α-decay.
- (Eg): Uranium 238 (U238) decays, emits an α particle, and becomes thorium - 234 (Th234).

- 92U238 → 90Th234 + 2He4 (α - decay)
- A parent nucleus undergoes α decay and its mass number decreases by four and atomic number by two to form a new nucleus.

β - Decay

- The process by which the unstable parent nucleus emits a β particle and becomes a stable daughter nucleus is called β-decay.
- Example β - decay of phosphorus
- 15P32 → 16S32 + -1e0 (β - decay)
- During β - decay there is an increase in atomic number by one, with no change in mass number.
- Note: The nucleus of a new element appearing in a nuclear reaction is known by its atomic number, not its mass number.

γ - Gamach decomposition

During Gamach decay only the 'energy level' of the nucleus changes. Its atomic number and mass number remain unchanged.

Nuclear fission

Autobahn and F. Strassmann discovered in 1939.

Nuclear fission occurs when the nucleus of a heavy atom splits into two smaller nuclei, releasing high-energy neutrons.

Example:

Nuclear Fission of Uranium 235 (U235).

92U235 + 0n1 → 56Ba141 + 36Kr92 + 30n1 + Q (energy)

An average energy of 3.2 × 10-11 J is released per fission.

Fissionable materials:

- A substance is fissionable if it absorbs neutrons and causes fission.
- Example: Uranium 235 (U235) Plutonium 239 and Plutonium 241 (Pu239 and Pu241)
- Not all isotopes of uranium undergo fission by absorbing neutrons. Uranium 238 does not undergo fission. Uranium 235 is a fissile material.

- Some non-fissile radioactive elements can be converted into fissile material by absorbing neutrons. These are called rich objects.

Example: Uranium 238, Thorium 232, Plutonium 240

Continuity:

- Uranium (U-235) undergoes nuclear fission when struck with a neutron, releasing three neutrons.
- These three neutrons cause the next three uranium fissions to produce nine neutrons.
- These nine neutrons again cause the next 27 neutrons to be produced. Similarly, this event continues. Hence it is called a continuous action.
- The number of neutrons increases exponentially in the exponential series by the process of spontaneous diffusion.

a) Controlled Continuity

- In a controlled chain reaction the number of neutrons emitted is maintained at 'one'.
- Of the neutrons emitted by the absorbing material, only one neutron is allowed to interact and the other neutrons are absorbed.
- The energy released through this interaction is used constructively.
- Controlled reactivity is used to generate steady, controlled power throughout a nuclear reactor.

b) Uncontrolled Continuity

- In this type of reaction neutrons multiply and due to this more fissile material is produced.
- At the end most of the energy is released within one second.
- Detonation of nuclear bomb is done using chain reaction.
- Atomic bomb
- Works on the principle of 'Uncontrolled Continuity'.
- A large explosion occurs with high energy in a very short period of time.

System:

- A small fraction of fissionable matter of variable mass is placed in the nucleus.
- This compartment contains a cylindrical cavity. A cylindrical slitting material is placed to fit the vacuum. Its mass must be less than the transition mass. This cylinder is inserted into the vacuum for the detonation of the nuclear bomb. When these two parts come together and reach supercritical mass, a nuclear explosion occurs.
- During a nuclear explosion, very high energy levels of heat, light and radiation are released.
- Camac radiations are also released.
- In 1945, during World War II, such atomic bombs were dropped on Hiroshima and Nagasaki in Japan.
- The atomic bomb dropped on Hiroshima city was called "Little boy" and it was an atomic bomb containing uranium.
- The atomic bomb dropped on Nagasaki is known as "Fat man". Contains plutonium.

Electron Volt:

The electron volt [eV] is the unit for measuring the energy of small particles in nuclear physics.

It is the energy of an electron accelerated using a voltage of one volt.

1eV = 1.602 × 10-19 joule.

1 million electron volts = 1 MeV = 106 eV

(mega electron volt)

The average energy released by nuclear fission is 200 MeV.

Nuclear fusion:

- The phenomenon where two lighter nuclei combine to form a heavier nucleus is called "Nuclear Fusion".
- Example: 1H2 + 1H2 → 2H4 + Q (energy)

- 1H2 stands for deuterium, an isotope of hydrogen.
- The average energy released during each nuclear fusion is 3.814 × 10-12 J.
- During nuclear reactions (fusion and fission) the mass of the resulting nucleus is less than the sum of the masses of the two parent nuclei.
- Mass - the ratio between the mass of the mother nucleus and the mass of the child nucleus. This material is converted into energy (mass-energy equation).
- This concept was proposed by Einstein in 1905 through the mass-energy equation.
- The mass-energy equation asserts that mass becomes energy and energy becomes mass.
- The relation for the mass-energy equation is E = mc2. where c is the speed of light. In vacuum its value is 3 × 108 mV-1.

Conditions for nuclear fusion:

- Nuclear fusion takes place only at very high temperatures of 107 to 109 K and at high pressures.
- In this case, the nuclei of the hydrogen atom move closer to each other and nuclear fusion takes place.
- This is called 'thermonuclear fusion'.

Hydrogen bomb:

- Hydrogen bomb works on the principle of nuclear fusion.
- A nuclear bomb is detonated to create the required high temperature and pressure. After this, nuclear fusion takes place in the hydrogen, releasing an uncontrollable amount of energy.
- The energy produced by a hydrogen bomb (nuclear fusion) is greater than the energy produced by an atomic bomb (nuclear fission).

Nuclear fission:

- The process by which heavy nuclei split into lighter nuclei is called 'nuclear fission'.

- This phenomenon can also occur at room temperature
- Alpha, beta and gamma rays are released.
- Nuclear fission emits gamma rays which induce genetic mutations in human genes and cause hereditary diseases.

Nuclear fusion:

- The phenomenon in which two light atoms combine to form heavier nuclei is called nuclear fusion.
- Nuclear fusion requires high temperature and pressure
- Alpha rays, positrons and neutrinos are emitted.
- Heat and light are emitted.
- 620 million metric tons of hydrogen nuclear fusion takes place in the Sun every second. 3.8 × 1026 Joules of energy are radiated in one second.

Uses of radioactivity:

Agriculture:

- Phosphorus isotope P-32 is used to increase crop production.
- Radioisotopes are also used to protect agricultural produce from spoilage by microorganisms such as insects and parasites.
- Keep onions and potatoes from rotting with a little radiation
- Can also protect pulses from sprouting during storage.

Medicine:

It is classified into two types and used in medicine.

i. Diagnosis
ii. Radiation therapy

- Sodium - 24 (Na24) helps the heart to function properly.
- Iodine-131 (I131) helps in curing anterior cervical cancer.
- Iron - 59 (Fe59) helps in diagnosis and treatment of anemia.
- Phosphorus-32 (P32) is used in the treatment of skin diseases.
- Cobalt-60 (Co60) and gold-198 (Au198), an isotope of gold, are used to treat skin cancer.

- Irradiation of micro-organisms found in surgical instruments.

Factory:

- Californium - 252 (Cf252) - Used to detect explosives in aircraft cargo.
- Am241 (Am241) – Used as a smoke detector in factories.

Archaeological survey:

Carbon dating estimates the age of objects by measuring the amount of radioactive carbon they contain.

Safety measures:

Allowable amount

A safe dose of radiation exposure for a year is 20 millisieverts.

The radiation, expressed in roentgen units, should be 100 ml roentgen per week.

Radiation exposure of 100 R can cause leukemia (destruction of red blood cells), a very serious complication. Radiation exposure is lethal at 600 R.

Preventive measures:

- Radioactive materials should be kept in thick-walled containers.
- Mandatory wearing of medical gloves and medical gown in irradiated areas.
- By wearing a dosimeter, the radiation dose can be measured from time to time.

Nuclear reactor:

It is a place where controlled nuclear fission takes place and produces electricity. In 1942, the first nuclear reactor was built in Chicago, USA. Partial components of a nuclear reactor.

(i) **Fuel:** Fuel is the fissionable material. The most commonly used fuel is uranium.

(ii) **Attenuator:** Attenuator is used to reduce high energy neutrons to low energy neutrons. Graphite and hard water are commonly used quenchers.

(iii) **Controlling salts:** Boron and cadmium salts are mostly used as controlling salts. They are capable of absorbing neutrons.

(iv) **Cooler:** Cooler is used to remove the heat generated inside the nuclear reactor. Some solvents are water, air, and helium.

(v) **Barrier:** A thick concrete wall is built around the nuclear reactor.

- Benefits of nuclear reactor
- Used for power generation.
- Used to make radioactive isotopes.
- Some nuclear reactors are used for research in the field of nuclear physics.
- Production reactors are used to convert non-fissile materials into fissile materials.

Indian nuclear power plants:

- The Indian Atomic Energy Commission (AEC) was set up in Mumbai in August 1948 by the Indian Department of Scientific Research.
- Dr. Homi Jahangir Baba was the first to take charge as the President. It is now known as Baba Atomic Research Center (BARC).
- In India's power generation, nuclear power is the fifth resource.
- Tarapur Nuclear Power Plant is India's first nuclear power plant.
- Maharashtra, Rajasthan, Gujarat, Uttar Pradesh and Karnataka have seven nuclear power plants, one each and Tamil Nadu has two nuclear power plants.
- Kalpakkam and Kudankulam are two nuclear power plants located in Tamil Nadu.
- Apsara was the first nuclear reactor built in Asia and India.
- There are currently 22 nuclear reactors in operation in India.