

Chapter # 12

Nuclear and Particle Physics

STUDENT'S LEARNING OUTCOMES (SLO's)

After studying this unit, the students will be able to:

- state that nucleon number and charge are conserved in nuclear processes
- describe the composition, mass and charge of α -, β - and γ -radiations [both β^- (electrons) and β^+ (positrons) are included]
- Explain that an anti-particle has the same mass but opposite charge to the corresponding particle [give the example that a positron is the anti-particle of an electron]
- state that (electron) anti-neutrinos are produced during β^- -decay and (electron) neutrinos are produced during β^+ decay
- Explain that α -particles have discrete energies but that β -particles have a continuous range of energies because (anti)neutrinos are emitted in β -decay
- Describe quarks and anti-quarks (as a fundamental [including that there are six flavors] of quark: up, down, strange, charm, top and bottom)
- describe protons and neutrons in terms of their quark composition
- state that a hadron may be either a baryon (consisting of three quarks) or a meson (consisting of one quark and an antiquark)
- describe the changes to quark composition that take place during β^- and β^+ decay
- state that electrons and neutrinos are fundamental particles called leptons
- State, W, Z, gluon, and photons as fundamental particles called exchange particles or force carriers
- State the Higgs Boson as a fundamental particle which is responsible for the particle's mass.
- Explain that every subatomic particle has a corresponding anti-particle [that has the same mass as a given particle but opposite electric or magnetic properties according to the Standard Model of Particle Physics]
- Explain that there are various contending theories about what 'mass' and 'force' are generated from (e.g. that these are generated from quantum fields when they are energized, or from multi dimensional 'strings' that vibrate in higher dimensions to give rise to particles (no further technical knowledge beyond these simple descriptions is expected at this level))
- Illustrate that anti-particles usually have the same weight, but opposite charge, compared to their matter Counterparts
- State that most of the matter in the observable universe is matter
- Describe the asymmetry of matter and anti-matter in the universe as an unsolved mystery
- Describe annihilation reactions [a particle meets its corresponding anti-particle, they undergo annihilation reactions in which either all the mass is converted to heat and light energy, or some mass is left over in the form of new sub-atomic particles.]

12.1 STRUCTURE AND PROPERTIES OF THE NUCLEUS



1. Describe the structure and properties of the nucleus.

Ans. Structure and Properties of the Nucleus

The atomic nucleus comprises two types of particles: **protons and neutrons**. A **proton** is the nucleus of the simplest atom, hydrogen, called a **protium**. The proton has a positive charge of the same magnitude as that of the electron (1.6×10^{-19} C) and its mass is 1.67×10^{-27} kg. The **neutron** is electrically neutral and its mass is nearly the same as that of proton. The **nucleus** has two types of particles (neutrons and protons) called nucleons.

Besides hydrogen, the nuclei of all other elements consist of both neutrons and protons. The different nuclei are called **nuclides**. The number of protons in a nucleus is called the **atomic number Z**. The total number of nucleons, (the sum of neutrons and protons) **A** is called the **atomic mass number**, or simply **mass number**. It is written as:

$$A = N + Z$$

where **N** represents the neutron number.

In order to specify the given nuclei, the symbol **X** is commonly used as ${}^A_Z\text{X}$, where **X** is the chemical symbol for the element. To indicate the mass of atomic particles, instead of kilogram, unified mass scale (**u**) is generally used.

By definition $1u$ is exactly one twelfth the mass of carbon-12 atom ($1u = 1.6606 \times 10^{-27} \text{ kg} = 931 \text{ MeV}$). Using this value of u , the mass of a proton is $1.007276 u$ and that of a neutron is $1.008665 u$ while that of an electron is $0.00055 u$.

For a particular atom (e.g., carbon), nuclei are found to contain different numbers of neutrons, although they all have the same number of protons. For example, carbon nuclei always have 6 protons, but they may have different number of neutrons. **Nuclei that contain the same number of protons but different numbers of neutrons are called isotopes.** Isotopes of carbon are $^{12}_6\text{C}$, $^{13}_6\text{C}$ and $^{14}_6\text{C}$, amongst them $^{12}_6\text{C}$ and $^{13}_6\text{C}$ are stable but $^{14}_6\text{C}$ is unstable and decays into nitrogen along with the emission of β and neutrino.

12.2 FUNDAMENTAL FORCES OF NATURE



2. Describe the four fundamental forces found in nature.

Ans. Fundamental Forces in Nature

The four fundamental forces in nature are **gravity, electromagnetism, weak nuclear force, and strong nuclear force.**

1. Gravitational force

Gravitational force or gravity is one of the four fundamental forces of nature. It is the weakest of the four but it is a long-range force. It is an attractive force and arises due to the gravitational interaction between the bodies. The gravitational force between two bodies is proportional to the product of their masses and inversely proportional to the square of the distance between them. When considered for massive objects, such as the Sun, or giant planets, gravitational force is considered to be significant as the masses of these objects are large. However, on an atomic level, this force is considered to be negligibly weak.

2. Electromagnetic force

The **electromagnetic force** is responsible for electric field and magnetic field interactions. Like the gravitational force, the electromagnetic force follows an inverse square law but is much stronger than gravity. It governs a vast range of phenomena, from atomic structure, chemical bonding, electricity, magnetism, and light propagation.

3. Nuclear Forces

Nuclear forces are the strongest attractive forces. Electromagnetism holds the matter together, but there was no explanation on how the nucleus is held together in the atom. If we only consider the forces of electromagnetism and gravity, the nucleus should fly off in different directions. The stability of the nucleus implies that another force should exist within the nucleus which is stronger than the gravitational force and electromagnetic force. This is where nuclear forces come into play.

4. Strong Nuclear Force and weak Nuclear Force

Strong nuclear forces are responsible for holding the nuclei of atoms together. They only exist inside the nucleus. So, we call them as short-range forces. The strong nuclear force acts as an attractive force between all nucleons. Thus, protons attract each other via the strong nuclear forces at the same time they repel each other via the electric force. A neutron, being electrically neutral, can attract other neutrons or protons via the strong nuclear force. **Weak nuclear forces** are responsible for the radioactive decay, particularly the beta decay and interactions involving neutrino. Unlike the other fundamental forces, the weak force can **change the identity of particles**, making it essential for processes like nuclear fusion in stars and the decay of unstable atomic nuclei. The relative strength and range of the four forces are given in Table 1.

Table 1: Relative strength and range of four fundamental forces

Force	Approximate Relative Strength (compared to strong force)	Range
Gravity	10^{-38}	∞
Weak nuclear force	10^{-13}	$< 10^{-18} \text{ m}$
Electromagnetic	10^{-2}	∞
Strong nuclear force	1	$< 10^{-15} \text{ m}$

1. **The nucleus is directly proportional to:**
 (A) Atomic number Z (B) Mass number A ✓
 (C) Square of atomic number
 (D) Cube of mass number
2. **Which force is responsible for holding the nucleons together in a nucleus?**
 (A) Gravitational force (B) Electromagnetic force
 (C) Strong nuclear force ✓ (D) Weak nuclear force
3. **The charge of nucleus is due to:**
 (A) Neutrons (B) Protons ✓
 (C) Electrons (D) Both (A) and (B)
4. **The unit of nuclear radius is typically:**
 (A) Metre (B) Angstrom
 (C) Nanometre (D) Femtometre ✓
5. **If a nucleus has 20 protons and 22 neutrons, its mass number and atomic number respectively are:**
 (A) 42 and 20 ✓ (B) 20 and 22
 (C) 22 and 20 (D) 42 and 22
6. **The stability of a nucleus depends mainly on the:**
 (A) Number of electrons (B) Mass number
 (C) Neutron-to-proton ratio ✓ (D) Binding energy of electrons
7. **Which fundamental force is responsible for keeping electrons bond to the nucleus?**
 (A) Weak nuclear force (B) Gravitational force
 (C) Electromagnetic force ✓ (D) Strong nuclear force
8. **The force responsible for the radioactive beta decay is:**
 (A) Weak nuclear force ✓ (B) Strong nuclear force
 (C) Gravitational force (D) Electromagnetic force
9. **Which of the following particles mediates the electromagnetic forces?**
 (A) Photon ✓ (B) Gluon
 (C) W and Z bosons (D) Graviton
10. **The particles that mediate the strong nuclear force are called:**
 (A) Photons (B) Gravitons
 (C) Gluons ✓ (D) W bosons

12.3 MATTER AND ANTI-MATTER



3. Write a note on anti-particles.

Ans. Anti-particles

Anti-particles are counterparts of regular particles in physics, with the same mass but opposite electric charge and some other quantum properties.

Fundamental particles have their anti-particles. The rest masses of the anti-particles are the same as that of their corresponding particles but with opposite charges and magnetic moments. For example, positron is the anti-particle of an electron. It is represented by e^+ . The rest mass of the positron is the same as that of an electron but it carries positive charge with magnitude the same as that of an electron. It is noted that the positron was the first discovered anti-particle. After that a lot of anti-particles were discovered. Usually, the anti-particles are represented by a letter with a bar over it, e.g., anti-proton is represented by $\bar{p}$ anti-neutrino by $\bar{\nu}$ and so on.

The quarks and leptons have been recognized as the fundamental particles also known as elementary particles among the too many discovered particles. These elementary particles have also anti-particles.

For Your Information

1. A particle accelerator is a huge machine that accelerates charged particles, such as electrons, protons, or ions, to extremely high energies and speeds, approaching the speed of light.
2. Linear Accelerators, Cyclotrons and Betatrons are important particle accelerators.

Do you know?

- (i) The cosmic rays are high-energy particles coming from the outer-space with unknown sources. Their source may be the Sun or the other stars. These particles consist mostly of protons, neutrons and heavier nuclei, which are continually bombarding the Earth. When these particles interact with the atoms of the gases of the Earth's atmosphere, they produce showers of secondary particles which rain down on us all the time.
- (ii) When nuclei of unstable radioactive element say ^{235}U undergo fission reactions in the nuclear reactors, they emit a variety of particles, such as; neutrons, neutrinos, α -particles, photons, electrons and positrons.
- (iii) When the charged particles, such as electrons and protons are accelerated by an accelerator and then bombarded on the target material, which is hydrogen, these accelerated charged particles may also collide head-on with each other. As a result, the debris from these reactions contain particles like pions, kaons, muons and even anti-protons.



4. What is the difference between matter and anti-matter? Discuss the reasons why our universe is almost entirely composed of matter.

Ans. Difference between Matter and Anti-matter

Matter is composed of particles like protons, neutrons, and electrons. Whereas anti-matter consists of anti-particles corresponding to those in matter.

For example;

- Proton $\leftrightarrow$ Anti-proton (same mass, opposite charge)
- Electron $\leftrightarrow$ Positron (same mass, positive charge)

When a particle and an anti-particle meet, they annihilate each other, releasing energy.

Why Our Universe is Almost Entirely Matter?

1. **Asymmetry in the Early Universe (Baryon Asymmetry)**

- During the Big Bang, matter and anti-matter should have been produced in equal amounts.
- However, tiny differences in how matter and anti-matter behaved (possible due to violations of certain symmetries like (P symmetry) led to a slight excess of matter.

2. **Annihilation**

- After the Big Bang, most matter and anti-matter annihilated each other.
- The small surplus of matter (about 1 extra particle for every billion particle-antiparticle pairs) was left over and formed the universe we see today.

3. **Lack of Anti-matter in the Observable Universe**

We do not see large regions of anti-matter in space because matter-antimatter boundaries would produce high-energy gamma-rays from constant annihilation and we do not observe that.



5. Describe the process of pair production.

Ans. Pair Production

Definition

A Phenomenon in which energy is directly converted into matter, specially into a particle and its corresponding anti-particle is known as pair production.

Explanation

Pair production occurs when a γ -ray (high energy photon) passes nearby an atomic nucleus. As a result, an electron-positron pair is emitted; Fig. 1. The presence of a third particle, such as a nucleus, is necessary to conserve linear momentum.

According to the law of mass-energy equivalence, the minimum energy of a photon for pair production must be

equal to the sum of the rest-mass energies of the created particles. The rest-mass energy of the electron-positron pair is $2m_0 c^2 = 1.02 \text{ MeV}$ which has been verified experimentally. A gamma ray photon with energy less than 1.02 MeV cannot produce an electron-positron pair whereas a photon with energy greater than 1.02 MeV creates an electron-positron pair and the excess energy goes into the kinetic energies of the particles.

Note: The process of pair production satisfies the laws of conservation of charge, momentum and energy. It can occur for any particle and anti-particle.

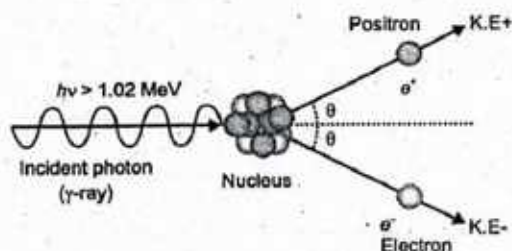


Fig. 1: A high energetic photon (γ -ray) interacting with a nucleus and results into an electron and a positron pair.

Do you know?

The pair production cannot take place in vacuum or space. The pair production can happen only in the presence of an external object like an atomic nucleus which can experience some recoil during the collision process to conserve the energy and the momentum at the same time.



6. Explain the phenomenon of pair annihilation with an example. What is the utility of this principle in the medical field?

Ans. Pair annihilation

Definition

Pair annihilation is a process in which a particle and its corresponding anti-particle collide and destroy each other, converting their mass into energy, usually in the form of gamma-ray photons.

Explanation

It is the opposite process of pair production. For example, when an electron and a positron interact to each other, they annihilate into two gamma ray photons; Fig. 2. The reaction can be written as:



The energy of each gamma ray photon is 0.51 MeV which is equal to the rest-mass energy of an electron or a positron, i.e., $E = m_0c^2$. In an annihilation reaction, energy and momentum are conserved. Besides the electron and positron annihilation, the annihilation reactions of other particles and their anti-particles can also be carried out e.g., proton and anti-proton, lepton and anti-lepton, quark and anti-quark, etc.

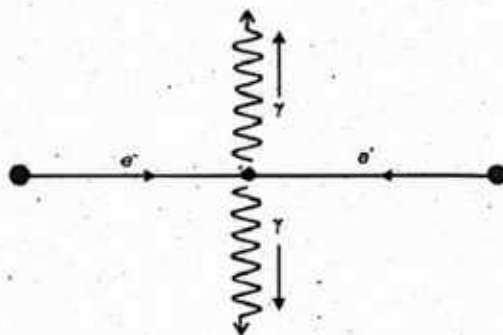


Fig. 2: Annihilation of matter

Utility of Pair Annihilation in Medical Field

The principle of pair annihilation is fundamental to a widely used imaging technique in the medical field called Positron Emission Tomography (PET). Let us know how it is applied.

1. Positron Emission Tomography (PET)

- Pair annihilation occurs when a positron (a positively charged electron) emitted by a radioactive tracer meets an electron in the body.
- When these two particles collide, they annihilate each other and produce two gamma-ray photons.
- PET scanners detect these simultaneous gamma rays, allowing for very accurate localization of the annihilation events.

2. Practical Applications

(i) Cancer Detection and Monitoring

PET scans can identify tumors based on their high metabolic activity.

(ii) Neurology

PET is used to study brain function, detect abnormalities like Alzheimer's disease, and monitor brain tumors.

(iii) Cardiology

It helps assess blood flow and detect areas of the heart muscle with poor perfusion.



1. The anti-particle of electron is:

- (A) Proton (B) Positron ✓
(C) Neutrino (D) Anti-proton

2. When a particle and its anti-particle meet, what happens?

- (A) They bounce off (B) They fuse
(C) They annihilate, releasing energy ✓
(D) They become dark matter

3. Which scientist is credited with predicting the existence of anti-matter?

- (A) Albert Einstein (B) Paul Dirac ✓
(C) Niels Bohr (D) Richard Feynman

4. In which type of reaction are matter and anti-matter created from energy?

- (A) Nuclear fission (B) Combustion

- (C) Pair production ✓ (D) Fusion

5. What would happen if anti-matter came into contact with the Earth's atmosphere?

- (A) Nothing (B) It would cool down
(C) It would instantly annihilate with matter, releasing large amounts of energy ✓
(D) It would sink into the Earth's core

6. Which of the following medical technologies uses the concept of anti-matter?

- (A) MRI (B) X-ray
(C) CT scan (D) PET scan ✓

7. Pair production can only occur if the photon has energy:

- (A) Less than 0.5 MeV (B) Exactly 0.51 MeV
(C) Greater than 1.02 MeV ✓ (D) Greater than 0.1 MeV

8. Which of the following is conserved during pair production?
 (A) Energy only (B) Momentum only
 (C) Mass only (D) Energy and momentum ✓
9. In matter-antimatter annihilation, the energy released appears in the form of:
 (A) Alpha particles (B) Neutrinos
 (C) Photons (gamma rays) ✓ (D) Electrons
10. Pair production is a process in which a photon is converted into:
 (A) Two protons (B) A neutron and a positron
 (C) Two neutrons (D) An electron and a positron ✓
11. In annihilation, an electron and a positron combine to produce:
 (A) One gamma photon (B) Two gamma photons ✓
 (C) Three gamma photons (D) A proton and a neutron
12. Which conservation laws are obeyed during pair production and annihilation?
 (A) Only energy (B) Only Charge
 (C) Energy, momentum, and charge ✓ (D) Only mass

12.4 RADIOACTIVITY



7. What is meant by radioactivity? Compare the properties and behaviour of three types of radiations.

Ans. Radioactivity

Definition

Radioactivity is the spontaneous process by which unstable atomic nuclei lose energy by emitting radiation.

Explanation

It has been observed that the nuclei whose atomic numbers are greater than 82 are found naturally unstable, and these nuclei spontaneously emit radiations. Such nuclei are called **radioactive** and the emission of radiation is known as **natural radioactivity**. These radiations are of three types, α , β and γ -radiations. Unstable isotopes can also be produced artificially in the laboratory by nuclear reactions. This occurs when a stable element is bombarded with high-energy particles, such as neutrons, protons, alpha particles, or gamma rays, causing it to become unstable and emit radiations. This is called **artificial radioactivity** and radioactive isotopes are named **radioisotopes** or **radionuclides**.

The α -particles, β -particles and γ -radiations behave differently when passed through the electric field; Fig. 4. It is seen that α -particles deflect towards the negative terminal of the electric field, showing that they have a positive charge. The deflection of β -particles is more than the α -particles, proving that they are lighter particles than α -particles. The β -particles are fast-moving electrons and move with speeds up to 0.9995 of the speed of light. The γ -radiations pass through the electric field without deflection, showing that they have no charge.

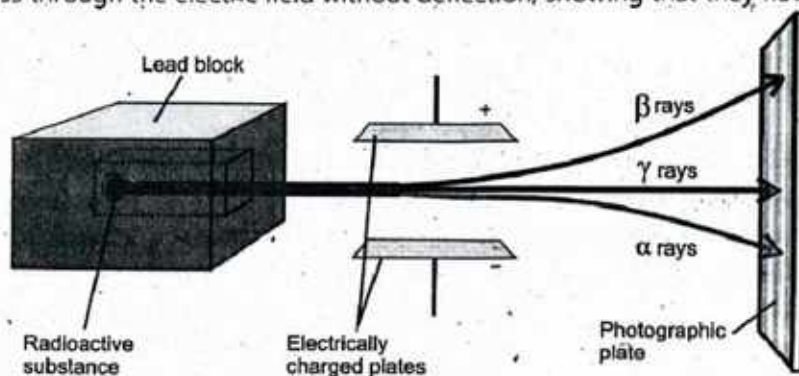


Fig. 4: The three radioactive radiations, namely alpha, beta and gamma rays.

1. Properties and Behaviour of α -Particles

Properties of α -Particles

- Composition:** They consist of 2 protons and 2 neutrons (same as helium nucleus).
- Charge:** +2 positive charge, due to 2 protons.
- Mass:** Relatively heavy (mass $\approx$ 4 atomic mass units)
- Speed:** Typically travel at about 5% to 10%, the speed of light, depending on the energy from the radioactive source.
- Ionizing Power:** Very high—they can ionize many atoms in a short distance due to their mass and charge.
- Penetrating Power:** Very low—they can be stopped by a sheet of paper, human skin, or even a few centimetres

of air.

- (vii) **Source:** They are emitted by heavy unstable nuclei, like uranium-238, radon-222, or polonium-210 during radioactive decay.

Behaviour of α -Particles

- (i) **In Air:** Quickly lose energy and travel only a few centimetres.
- (ii) **In Biological Tissues:** Cannot penetrate the outer layer of dead skin but are highly dangerous if ingested or inhaled, causing intense localized damage (e.g., lung cancer from radon gas).
- (iii) **In Electric and Magnetic Fields:** Deflected because they are charged particles. The direction and degree of deflection depend on their charge-to-mass ratio and the strength of the field.
- (iv) **Nuclear Reactions:** Alpha particles can initiate nuclear reactions, especially in particle accelerators or fusion research.
- (v) **Scattering Experiments:** Used in historical experiments (e.g., Rutherford gold foil experiment), revealing the nuclear structure of atoms.

Properties and Behaviour of β -Particles

Properties of β -Particles

- (i) **Composition:**
- **Beta-minus (β^-):** A high speed electron emitted from a neutron converting to a proton.
 - **Beta-plus (β^+):** A high speed positron (positive electron) emitted from a proton converting to a neutron.
- (ii) **Charge:**
- β^- : -1 (negative)
 - β^+ : +1 (positive)
- (iii) **Mass:** Very high (about $\frac{1}{1836}$ of a proton's mass)
- (iv) **Speed:** Can travel at up to 99% the speed of light, depending on energy.
- (v) **Ionizing Power:** Moderate—not as strong as alpha particles, but still enough to damage biological tissue.
- (vi) **Penetrating Power:** Moderate—can pass through paper, but stopped by a few millimetres of aluminium or plastic.
- (vii) **Source:** Emitted during beta decay from radioactive nuclei such as carbon-14, strontium-90, or tritium.

Behaviour of β -Particles

- (i) **In Air:** Travel several metres before being stopped.
- (ii) **In Biological Tissues:** Can penetrate skin and damage living cells. External exposure is more dangerous than with α -particles.
- (iii) **In Electric and Magnetic Fields**
- Deflected strongly, since they are light and charged.
 - β^- and β^+ are deflected in opposite directions due to their opposite charges.
- (iv) **Anti-matter Behaviour (for β^+):** Positrons quickly annihilate with electrons, producing gamma rays.
- (v) **Detection:** Easily detected by Geiger-Muller counters or scintillation detectors due to their charge and speed.

Properties and Behaviour of γ Radiations

Properties of γ Radiations

- (i) **Nature**
- Gamma rays are photon.
 - They have no mass and no electric charge.
- (ii) **Origin**
- Emitted from the nucleus of an atom during radioactive decay.
 - Typically released when a nucleus moves from a higher-energy state to the lower-energy state.
- (iii) **Penetrating Power**
- Extremely penetrating; can pass through most materials.
 - Stopped only by thick layers of dense materials like lead or several centimetres of concrete.
- (iv) **Speed:** Travel at the speed of light ($3 \times 10^8 \text{ ms}^{-1}$).

(v) **Wavelength of Energy**

- Very short wavelength (< 10 picometres)
- Very high frequency and energy (higher than X-rays)

Behaviour of γ -Rays

(i) **Interaction with Matter**

- Do not ionize atoms directly like alpha or beta particles.
- Cause ionization indirectly by interacting with electrons through:
 - Photoelectric effect
 - Common effect
 - Pair production (at very high energies)

(ii) **Biological Effects**

- Highly penetrating, so they can damage internal tissues and DNA.
- Used in cancer radiotherapy due to their ability to kill cells.

(iii) **Shielding**

- Require dense shielding (e.g., lead or concrete) to reduce exposure.
- Standard safety measures include time, distance and shielding.

(iv) **Detection**

Detected using devices like Geiger-Muller counters, scintillation detectors, or gamma cameras.



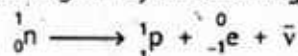
8. Elaborate the phenomenon of beta-positive decay and β -negative decay with examples.

Ans. (i) β^- -decay

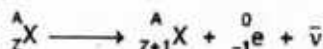
There are two types of β -decay:

- (i) β^- -decay (ii) β^+ -decay

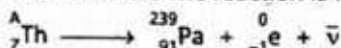
Some nuclides have neutron-to-proton ratio (N/P) too large and are the source of β -decay. The β -particles are not the orbital electrons but they are created within the nucleus at the moment of emission. In this process, a neutron in the nucleus decays into a proton and an electron, plus another particle called anti-neutrino which is the anti-particle of neutrino. The neutrino is denoted by ν (nu) and anti-neutrino is denoted by a bar over the ν . The decay process is given by the following relation:



One of the neutrons changes to a proton and in order to conserve charge, it emits an electron. These electrons are called beta particles. However, they are indistinguishable from orbital electrons. Both the neutrino and the anti-neutrino have zero charge and very small mass, that is why they are very difficult to observe when passing through the matter. No nucleons are lost when a β -particle is emitted, and the total number of nucleons A remains the same but the mass number Z changes. Beta decay process can be written as:

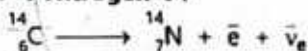


From this equation, it is clear that the parent element of atomic number Z is transmuted to another element of atomic number (Z+1). An example is the isotope of thorium, which is unstable and decays into protactinium by beta emission. The reaction is represented as:



Examples of beta negative decay are:

1. Carbon-14 $\rightarrow$ Nitrogen-14

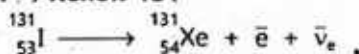


Use: This decay is the basis for radiocarbon dating.

For your information

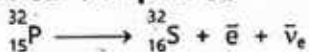
The neutrino was first proposed by Wolfgang Pauli in 1930 to obey the energy conservation in the beta-minus and beta-plus decays. Later in 1953, neutrino was detected by F. Reines and C. L. Cowan in a high-power nuclear reactor. On this discovery, F. Reines received the Nobel prize in 1995.

2. **Iodine-131 → Xenon-131**



Use: Iodine-131 is used in medical diagnostic and therapy, especially for thyroid issues.

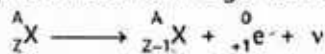
3. **Phosphorus-32 → Sulphur-32**



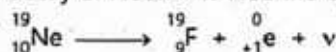
Use: Used in biological and medical research, particularly in DNA/RNA labelling.

(ii) **β^+ -Decay**

There are also nuclides that have neutron-to-proton ratio (N/P) too small for stability and decay by emitting a positron instead of an electron. The positron (e^+) has the same mass as the electron but it has a positive charge. The positron is the anti-particle of the electron. In this process, a proton in the nucleus decays into a neutron and a positron, plus a neutrino. The generalized decay is given below:

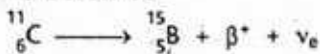


An example of a decay of Neon into Fluorine by emitting positron and neutrino is:

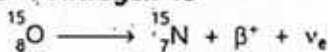


Examples of Beta-positive decay are:

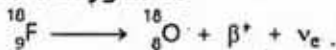
1. **Carbon-11 → Boron-11**



2. **Oxygen-15 → Nitrogen-15**



3. **Fluorine-18 → Oxygen-18**



9. Explain with the help of the graphs that alpha particles have discrete energies and beta particles have a continuous range of energies.

Ans. Energy of Alpha and Beta Particles in Radioactive Decay

In both α -decay and β -decay, for a particular radionuclide, the same amount of energy is released.

In α -decay of a particular radionuclide, every emitted α -particle has the same sharply defined kinetic energy. When the number of α -particles is plotted against kinetic energy, there are distinct spikes that appear on the graph; Fig. 5. This demonstrates that **α -particles have discrete energies**.

However, in the case of β -particle emission, energy is shared between β -particle and anti-neutrino in varying proportions.

The sum of electron (or positron) energy and the anti-neutrino's (or neutrino's) energy, however, in every case remains the same. Thus, in β -decay, the energy of an electron or a positron may range from zero to a maximum value. When the number of β -particles is plotted against kinetic energy, the graph shows a curve; Fig. 6. This demonstrates that beta particles (electrons or positrons) have a continuous range of energies. The principle of conservation of momentum and energy applies in both alpha and beta emission.

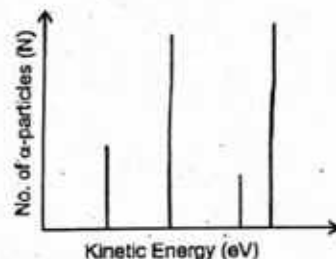


Fig. 5: Discrete energy values of α -particles

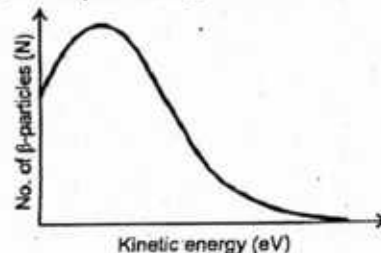


Fig. 6: Continuous spectrum of β -particles.



10. Write a note alpha-decay. Also write the equation of gamma-radiation.

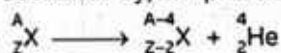
Ans. α , β and γ -decay

The process of emitting α -particles, β -particles and γ -radiations from the nucleus is called α -decay, β -decay and γ -decay, respectively.

α-Decay

If the nucleus has more protons than the number of neutrons, the electrostatic force of repulsion becomes greater than the strong nuclear force of attraction. In this case, the nucleus becomes unstable and emits alpha particles in radioactive decay.

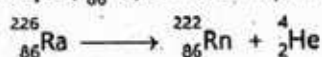
An α-particle is equivalent to a helium (He) nucleus which consists of two protons and two neutrons. This means the nucleus loses two protons and neutrons in the α-decay. Hence, the atomic number Z decreases by 2 while its mass number A decreases by 4. Alpha decay can be written in general as:



Here ${}^A_ZX$ is the parent nucleus which decays into the daughter nucleus ${}^{A-4}_{Z-2}X$ and ${}^4_2\text{He}$ is the alpha particle.

In the α-decay, it is experimentally observed that the number of nucleons (A) and electric charge are conserved. An example of α-decay is given below:

A radium-226 isotope (${}^{226}_{86}\text{Ra}$) emits an alpha particle and decays into a daughter nucleus radon-222 (${}^{222}_{86}\text{Rn}$).



In this nuclear reaction, the **daughter** nucleus (${}^{222}_{86}\text{Rn}$) is different from the **parent** nucleus (${}^{226}_{86}\text{Ra}$). This transition of one element into another is called the **transmutation** of the elements. It is experimentally found that the mass of the parent nucleus is greater than the total mass of the daughter nucleus and the mass of the α-particle. Thus, the total mass-energy ($E = mc^2$) of the decay products is less than the mass-energy of the original nuclide. This difference in mass-energy is called the **disintegration energy Q** , or the **Q -value** of the decay.

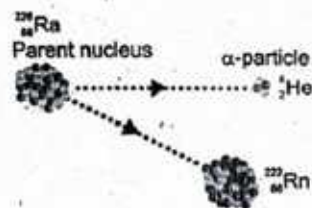


Fig. 7: α-decay

γ-Radiation

The emission of γ-radiation from a nucleus is generally represented by the equation:



where ${}^A_ZX^*$ represents an excited nucleus while ${}^A_ZX$ shows ground state of the nucleus.



11. Summarize the nature of alpha, beta and gamma radiations in tabular form.

Ans. The summary of Nature of Alpha, Beta and Gamma Radiations

Characteristics	α-particles	β-particles	γ-rays
1. Nature	Helium nuclei of charge $2e$	Electron or positrons from the nucleus of charge $\pm e$	E. M. waves from excited nuclei with no charge
2. Typical sources	Radon-222	Strontium-94	Cobalt-60
3. Ionization (Ion pairs mm^{-1} in air)	About 10^4	About 102	About 1
4. Range in air	Several centimetres	Several metres	Obeys inverse square law
5. Absorbed by	A paper	1-5 mm of Al sheet	1-10 cm of lead sheet
6. Energy spectrum	Emitted with the same energy	Variable energy	Variable energy
7. Speed	$\sim 10^7 \text{ m s}^{-1}$	$\sim 1 \times 10^8 \text{ m s}^{-1}$	$\sim 3 \times 10^8 \text{ m s}^{-1}$



- Which of the following particles has the highest penetrating power?
(A) Gamma rays ✓ (B) Alpha particles
(C) Beta particles (D) Neutrons
- In alpha-decay, the mass number of the nucleus:
(A) Increases by 4 (B) Decreases by 4 ✓
(C) Increases by 2 (D) Remains unchanged
- Beta-decay results in the emission of:
(A) A helium nucleus (B) A electron or positron ✓
(C) A photon (D) A neutron
- Which of the following is not affected by electric and magnetic fields?
(A) Alpha particles (B) Beta particles
(C) Gamma rays ✓ (D) Electrons

5. Which radioactive emission increases the atomic number by 1 but leaves the mass number unchanged?
 (A) Alpha emission (B) Gamma emission
 (C) Beta-plus emission (D) Beta-minus emission ✓
6. The SI Unit of radioactivity is:
 (A) Curie (B) Becquerel ✓
 (C) Rutherford (D) Sievert
7. The particle emitted in alpha decay is:
 (A) Helium nucleus ✓ (B) Electron
 (C) Neutron (D) Positron
8. In Beta-minus decays, a neutron transforms into:
 (A) A proton and an electron
 (B) A proton and a positron
 (C) A neutron and a neutrino
 (D) A photon and an electron ✓
9. Which radiation is deflected by electric and magnetic fields?
 (A) Alpha and beta ✓ (B) Gamma only
 (C) Alpha only (D) Gamma and beta
10. During Beta-minus decay, the atomic number of the nucleus:
 (A) Decreases by 1 (B) Remains unchanged
 (C) Increases by 2 (D) Increases by 1 ✓
11. In beta-plus decay, which particle is emitted?
 (A) Electron (B) Neutron
 (C) Positron ✓ (D) Proton
12. In alpha-decay, the atomic number of the nucleus:
 (A) Increases by 2 (B) Decreases by 2 ✓
 (C) Increases by 4 (D) Remains unchanged
13. Which type of decay is the most penetrating?
 (A) Alpha (B) Beta
 (C) Gamma ✓ (D) None of these
14. Which of the following radiation types can be stopped by a sheet of paper?
 (A) Alpha ✓ (B) Beta
 (C) Gamma (D) All of these
15. Gamma rays are a form of;
 (A) Sound waves (B) Charged Σ particles
 (C) Electromagnetic radiation ✓
 (D) Nuclear matter

12.5 FUNDAMENTAL PARTICLES



12. Describe the classification of elementary particles.

Ans. Elementary Particles

Elementary particles are the most fundamental building blocks of matter and energy. They are classified primarily according to the **standard model of particle physics**, which groups particles based on their properties such as mass, charge, and spin. The classification of elementary particles is as follows:

1. Fermions (Matter particles)

Fermions are particles that make up matter. They have half integer spin (e.g., $1/2$) and obey the Pauli exclusion principle, meaning no two identical fermions can occupy the same quantum state.

Fermions are divided into two main categories:

(a) Quarks

Quarks combine to form protons, neutrons, and other hadrons. There are 6 types (flavours) of quarks.

- Up (u) • Down (d) • Charm (c)
- Strong (s) • Top (t)
- Bottom (b)

They carry colour charge and interact via the strong nuclear force.

(b) Leptons

Leptons do not experience the strong force. There are also 6 types of leptons.

- Electron (e) • Electron neutrino (ν_e) • Muon (μ)
- Muon neutrino ($\nu - \mu$) • Tau (τ) • Tau neutrino ($\nu - \tau$)

Each charged lepton has a corresponding neutrino. Each of the above particles also has an anti-particle.

2. Bosons (Force Carriers)

Bosons have integer spin (e.g., 0 or 1) and are responsible for mediating the fundamental forces.

(a) Gauge Bosons (Spin-1)

They mediate the fundamental interactions:

- Photon (γ) - Electromagnetic force
- w^+ , w^- , z^0 bosons - Weak nuclear force
- Gluons (g) - Strong nuclear force (8 types)
- Graviton (hypothetical) - Gravity (not yet experimentally confirmed)

(b) Higgs Boson (Spin-0)

Responsible for giving mass to other particles via the Higgs mechanism.



13. Write a note on the particles which can be classified on the basis of four fundamental forces that act on them.

Ans. The gravitational force affects all particles. Its impact at the subatomic level is so minimal that it is generally disregarded at the sub-atomic level. The electromagnetic force, which acts on all electrically charged particles, is well understood and can be considered, when necessary; however, in this chapter, we will largely ignore its effects.

Particles can be broadly classified based on whether they interact via the strong force or do not. Those that experience the strong force are known as **hadrons**, while those that do not, are called **leptons**. Examples of hadrons include protons, neutrons, and pions, whereas electrons and neutrinos are classified as leptons.

Hadrons

Hadrons are composite subatomic particles that can be further divided into two broad categories: some are bosons, referred to as **mesons** such as pion, while others are fermions, known as **baryons**, with protons and neutrons being the key examples. Baryons are made of an odd number of quarks (usually three quarks), and mesons are made up of an even number of quarks (usually two quarks: one quark and one anti-quark).

Leptons

The leptons interact only through weak or electromagnetic interactions. No experiments have yet been able to reveal any internal structure for the leptons; **they appear to be truly fundamental particles** that cannot be split into smaller particles. All known leptons have spin $\frac{1}{2}$, so they all are fermions. The **six known leptons** are grouped as three pairs of particles as shown in the table below. Each pair includes a charged particle (e^- , μ^- , τ^-), its associated neutrino and corresponding anti-particles. Charged leptons can combine with other particles to form various composite particles such as atoms and positronium, while neutrinos rarely interact with anything, and are consequently rarely observed. The best-known of all leptons is the electron.

Table 2: The lepton family

Family	Particle	Symbol	Mass (MeV/c ²)	Charge q	Antiparticle
Electron	Electron	e^-	0.511	-1	e^+
	Electron neutrino	ν_e	$\Rightarrow 1 \times 10^{-7}$	0	$\bar{\nu}_e$
Muon	Muon	μ^-	105.7	-1	μ^+
	Muon neutrino	ν_μ	$\Rightarrow 1 \times 10^{-7}$	0	$\bar{\nu}_\mu$
Tau	Tau	τ^-	1777	-1	τ^+
	Tau Neutrino	ν_τ	$\Rightarrow 1 \times 10^{-7}$	0	$\bar{\nu}_\tau$

12.6 QUARKS



14. Describe protons and neutrons in terms of their quark combination.

Ans. All quarks have a spin and an electric charge.

Quarks are invisible. They never appear on their own. All hadrons are considered to be made up of combinations of quarks, and their properties are described by looking at their quark content.

Mesons consist of a quark-antiquark pair. For example, a π^+ meson is a $u\bar{d}$ combination. A π^0 can be made of $u\bar{u}$. Each baryon, on the other hand, consists of three quarks.

Protons and neutrons are baryons, meaning they are made up of three quarks each.

(i) Proton

Composed of two up quarks and one down quark.

- Quark combination: uud

- Charge: $+\frac{2}{3} + \frac{2}{3} + \left(-\frac{1}{3}\right) = +1$

Neutron



Proton



(ii) Neutron

Composed of one up quark and two down quarks.

- Quark combination: udd
- Charge: $+\frac{2}{3} + \left(-\frac{1}{3}\right) + \left(-\frac{1}{3}\right) = 0$

These combinations explain the electric charge of each particle and are held together by the strong force, mediated by particles called gluons.

Mesons are quark-antiquark pairs. Consider the meson π^+ , which consists of an up-quark u and an antidown quark $\bar{d}$. We see that the charge quantum number of the up-quark is $+1/3$ and that of the antidown quark is $+2/3$. This adds nicely to a charge quantum number of $+1$ for the π^+ meson; that is, $q(u) = 2/3 + 1/3 = +1$.

Table 3: Quark flavours

Particle	Symbol	Charge (q)	Mass (MeV/c^2)	Antiparticle	Charge (q)
Up	u	$+\frac{2}{3}$	5	$\bar{u}$	$-\frac{2}{3}$
Down	d	$-\frac{1}{3}$	10	$\bar{d}$	$+\frac{1}{3}$
Charm	c	$+\frac{2}{3}$	1500	$\bar{c}$	$-\frac{2}{3}$
Strange	s	$-\frac{1}{3}$	200	$\bar{s}$	$+\frac{1}{3}$
Top	t	$+\frac{2}{3}$	175000	$\bar{t}$	$-\frac{2}{3}$
Bottom	b	$-\frac{1}{3}$	4300	$\bar{b}$	$+\frac{1}{3}$



15. What is colour change theory of quarks? Explain.

Ans. Not long after the quark theory was proposed, it was suggested that quarks have another property (or quality) called colour, or "colour charge" (analogous to electric charge). According to this theory, each flavour of quark can have one of three colours, usually designated red, green, and blue. Note that the names "colour" and "flavour" have nothing to do with our senses, but are purely whimsical—as are other names, such as charm, in this new field. The anti-quarks are coloured antired, antigreen, and antiblue. Baryons are made up of three quarks, one of each colour. Mesons consist of a quark-anti-quark pair of a particular colour and its anti-colour. Both baryons and mesons are thus colourless or white. Each quark is assumed to carry a colour charge, analogous to an electric charge, and the strong force between quarks is referred to as the colour force. This theory of the strong force is called quantum chromodynamics or QCD, to indicate that the force acts between colour charges (and not between, say, electric charges). The strong force between two hadrons is considered to be a force between the quarks that make them up.

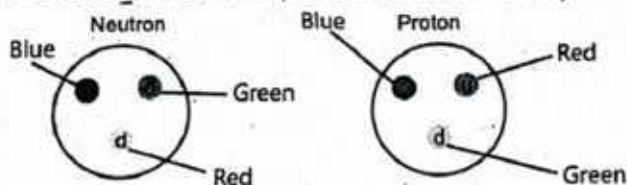


Fig. 8 (a): Colourless baryons:
 $\text{blue} + \text{red} + \text{green} = \text{white}$

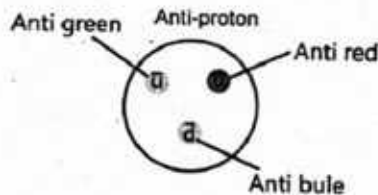


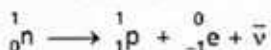
Fig. 8 (b) A colourless anti-baryons:
 $\text{anti-blue} + \text{anti-red} + \text{anti-green} = \text{white}$.



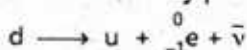
16. Write a note on beta decay in terms of quarks.

Ans. Beta Decay in Terms of Quarks

When a neutron in the nucleus decays into a proton and an electron (beta particle), an anti-neutrino is also produced in the reaction and the decay process is given as:



Now, we can identify that a neutron with composition udd can convert into a proton with composition uud by changing a down quark into an up quark. The fundamental decay process can now be expressed as:



Do you know?

A neutron is stable only inside a nucleus. Free neutrons decay with a half-life of 900 s.



- Which of the following is a fundamental particle?
(A) Proton (B) Neutron (C) Electron ✓ (D) Alpha particle
- Which of the following is not a lepton?
(A) Electron (B) Neutrinos (C) Muon (D) Proton ✓
- Quarks are the building blocks of:
(A) Electron (B) Protons and neutrons ✓ (C) Photons (D) Neutrinos
- How many types (flavours) of quarks are known?
(A) 3 (B) 4 (C) 5 (D) 6 ✓
- Which of the following particles is massless?
(A) Neutron (B) Photon ✓ (C) Electron (D) Neutrino
- The particle responsible for giving mass to other particles is the:
(A) Electron (B) Neutron (C) Higgs boson ✓ (D) Proton
- What is the charge on a down quark?
(A) $+\frac{2}{3}e$ (B) $-\frac{1}{3}e$ ✓ (C) $-1e$ (D) 0
- Quarks combine to form:
(A) Leptons (B) Nucleons (C) Photons (D) Mesons and baryons ✓
- Which of the following particles is a lepton?
(A) Proton (B) Neutron (C) Neutrino ✓ (D) Gluon
- What is the rest-mass of a photon?
(A) Equal to electron mass (B) Very large (C) Zero ✓ (D) Equal to proton mass
- Which two quarks make up a neutron?
(A) Up and down ✓ (B) Down and strange (C) Top and bottom (D) Up and charm
- Quarks are held together by which fundamental force?
(A) Gravitational force (B) Weak nuclear force (C) Electromagnetic force (D) Strong nuclear force ✓
- Which particle is hypothetical and has not yet been experimentally confirmed?
(A) Gluon (B) Higgs boson (C) Graviton ✓ (D) Electron
- Which quark is heaviest?
(A) Strange (B) Bottom (C) Top ✓ (D) Charm
- Which combination of quarks makes up a proton?
(A) uud ✓ (B) udd (C) ddu (D) uuu
- Which field is associated with the Higgs boson?
(A) Magnetic field (B) Gravitational field (C) Higgs field ✓ (D) Quantum field
- A meson is made up of:
(A) Two quarks (B) Three quarks (C) One quark and one anti-quark ✓ (D) One proton and one neutron
- What is quark composition of a neutron?
(A) uud (B) uuu (C) ddd (D) udd ✓
- What are the charges of up and down quarks respectively?
(A) $+\frac{2}{3}e, -\frac{1}{3}e$ ✓ (B) $-\frac{1}{3}e, +\frac{2}{3}e$ (C) $+1e, -1e$ (D) 0, +1
- Which of the following is not a flavour of quark?
(A) Top (B) Bottom (C) Muon ✓ (D) Strange

12.7 HIGGS BOSON



17. Write a note on Higgs Bosons.

Ans. Higgs Boson

Fundamental particles are considered to be the six quarks, the six leptons and the gauge bosons (Higgs bosons), which are the carriers of the fundamental forces. Leptons and quarks interact with each other by sending and receiving bosons. For example, electromagnetic interactions occur when two positively charged particles send and receive (exchange) photons. The photons are said to "carry" the force between charged particles.

Likewise, attraction between two quarks in an atomic nucleus occurs when two quarks send and receive gluons. Similarly, the W^+ , W^- and Z are the bosons that are the carriers of weak nuclear force and gravitons are the carriers of gravitational force. The Higgs boson is associated with the Higg's field that permeates all of the space. Its crucial role is that it provides explanation for how the other particles get mass by interacting with it.

The particles that interact strongly with Higg's field get more mass such as carriers of electroweak interaction i.e., W^+ , W^- and Z bosons whereas the particles like photons do not interact with Higg's field and hence, their rest mass is considered zero. Higgs boson has a mass of around 125 giga-electron-volts (GeV/c^2) and decays rapidly into other particles.

Key Facts

Here are some key facts:

1. The Higgs boson gets its mass from its interactions with its associated Higg's field.
2. It can be a unique portal to find the conditions of universe shortly after the Big Bang and signs of dark matter due to its distinctive characteristics and properties.



- | | |
|---|--|
| <p>1. The Higgs bosons is often referred as:
 (A) Golden particle ✓ (B) Dark matter particle
 (C) Super symmetry particle
 (D) Quantum field</p> <p>2. What does the Higgs bosons explain in the standard model particle physics?
 (A) Nature of gravity (B) Speed of light
 (C) Origin of mass ✓ (D) Colour of quarks</p> <p>3. The field associated with Higgs boson is called:
 (A) Electromagnetic field (B) Higgs field ✓
 (C) Gravitational field
 (D) Quantum chromodynamics field</p> <p>4. The approximate mass of the Higgs boson is:
 (A) $1 \frac{\text{GeV}}{c^2}$ (B) $10 \frac{\text{GeV}}{c^2}$
 (C) $15 \frac{\text{GeV}}{c^2}$ (D) $125 \frac{\text{GeV}}{c^2}$ ✓</p> | <p>5. The Higgs boson is a type of:
 (A) Lepton (B) Quark
 (C) Boson ✓ (D) Fermion</p> <p>6. Which fundamental force is directly associated with the Higgs mechanism?
 (A) Stronger nuclear force (B) Weak nuclear force ✓
 (C) Electromagnetic force (D) Gravitational force</p> <p>7. The Higgs boson field is present:
 (A) Only in particle accelerators
 (B) Only near black holes
 (C) Everywhere in the universe ✓
 (D) Only in dark matter regions</p> <p>8. The particle which does not interact with the Higgs field is:
 (A) Photon ✓ (B) Electron
 (C) W boson (D) Z boson</p> |
|---|--|

12.8 CONSERVATION LAWS



18. Explain the law of conservation of energy and momentum in electron-positron pair annihilation.

Ans. In electron-positron pair annihilation, an electron (e^-) and a positron (e^+) collide and annihilate each other, typically producing two photons (gamma rays). This law of conservation of energy and the law of conservation of momentum govern this process.

1. Law of Conservation of Energy

Statement

This law states that the total energy before the annihilation must equal the total energy after.

(i) Before Annihilation

- The total energy is the sum of the rest energy of the electron and proton (each has rest-mass m_e) and any kinetic energy they might have.

- Rest energy of each particle:

$$E = m_e c^2$$

- Total rest energy = $2 m_e c^2$

For your information

Hadrons

Mesons, e.g. pions, kaons

baryons, e.g. protons, neutrons, omega, sigma and lambda particles

Non-hadrons

Leptons, including electrons, muon, neutrinos

photons, gravitons

(ii) **After Annihilation**

- The energy is carried by the two photons produced.
- Each photon has energy $E = hf$
- The total photon energy must equal the total energy before annihilation.

So, if the particles are at rest:

$$2 m_e c^2 = 2 hf \quad \text{or} \quad hf = m_e c^2$$

2. Law of Conservation of Momentum

Statement

This law states that the total momentum before the annihilation must equal the total momentum after.

- If the electron and positron are at rest or their momenta cancel (i.e., they approach each other with equal and opposite momenta), then the total momentum before annihilation is zero.
- Therefore, the two photons must be emitted in opposite directions with equal momenta to conserve total momentum:

$$\vec{p}_1 + \vec{p}_2 = 0 \quad \text{or} \quad \vec{p}_1 = -\vec{p}_2$$

Since photons have momentum $p = \frac{E}{c}$, this condition ensures that momentum is conserved.

12.9 THE ASYMMETRY OF MATTER AND ANTI-MATTER IN THE UNIVERSE



19. Is the problem asymmetry of matter and anti matter is still mystery? Explain.

Ans. There is the asymmetry between matter and anti-matter. This is the most remarkable features of our universe. A number of hypothesis are existed which show that the universe consists almost entirely of matter rather than anti-matter. e.g., the universe is assumed to be composed up 5% of ordinary matter (electrons, protons and neutrons), 71% of hydrogen atoms and 24% of helium atoms, there are no any contribution of anti-hydrogen or anti-helium atoms in the composition of the universe.

The experimental results explain that the matter and anti-matter asymmetry is indeed due to the violation of conservation of baryon number. i.e., there is imbalance number of baryons and its anti-baryons. Now if the particle-antiparticle symmetry is also violated, then there will be a mechanism for making more quarks than anti-quarks, more leptons than anti-leptons and eventually more matter than anti-matter. Hence, it is concluded that the problem asymmetry of matter and anti-matter is still mystery.

12.10 MOST OF THE MATTER IN THE OBSERVABLE UNIVERSE IS PLASMA



20. Discuss that most of the matter of our observable universe is plasma.

Ans. Our universe consists of about 27% of unknown matter called dark matter and about 68% a mysterious antigravity material known as dark energy. By adding 27% and 68% we have 95%. It means 95% universe is out of our thinking, i.e., we know nothing about 95% of the universe.

On the other hand, the 5% of the universe that we know about it, is an ordinary matter, where hydrogen and helium are almost in the plasma state. Therefore, these figures indicate that 95% of the 5% of the observable universe is the plasma state, while the remaining 5% is in the form of matter. Hence, it is concluded that most of the matter in the observable universe is plasma.

12.11 THE THEORIES ABOUT THE FORCES BETWEEN THE MASSES OF PARTICLES



21. Describe the theories about the forces between the masses of particles.

Ans. To explain the interactions between the masses of the particles through different mediators, we have the following two theories, the quantum field theory and the string theory.

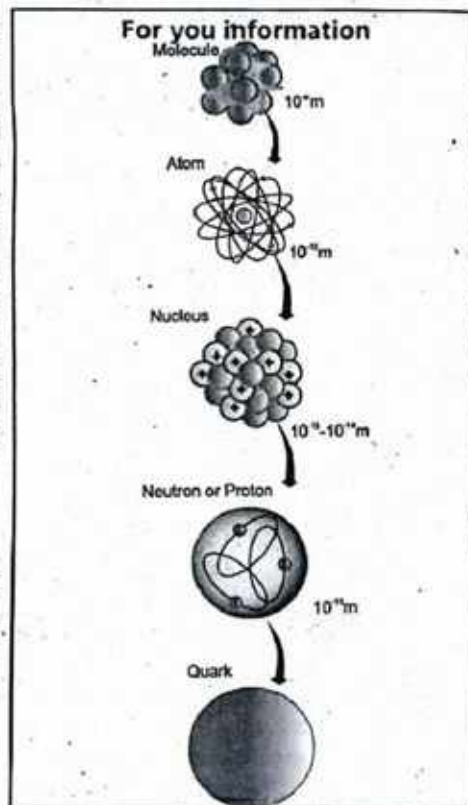
1. The Quantum Field Theory

According to this theory, each particle is represented by a field called quantum field and it is responsible to transmit a force from one particle to another by a mediator. For example, let a positively charged particle

produces an electric field in the space around it. This charged particle exerts an attractive force on a nearby negatively charged particle through its field. Moreover, the field can also carry energy and momentum from one particle to another. Where the energy and momentum of all fields are quantized. The quanta that exchange momentum and energy from one type of particle to another in their field are called field particles. Thus, we can say that the interactions between particles are described in terms of the exchange of field particle or quanta which are all bosons. For example, the electromagnetic force is mediated by photons called quanta of the electromagnetic field. Similarly, the strong nuclear force is mediated by field particles called gluons, the electro-weak force is mediated by the field particles called Bosons (W^+ and Z) and the gravitational forces is mediated by field particles called gravitons.

String Theory

String Theory is an advanced concept in theoretical physics proposing that the fundamental particles of the universe, instead of being point-like, are actually tiny, vibrating strings. These strings can be open or closed loops, and their vibrations determine the properties of particles, including mass and force. String Theory framework, offering a potential theory of everything, still remains unproved experimentally.



12.12 THE STANDARD MODEL



22. Write a note on the standard model of elementary particles.

Ans. The standard model is the collection of theories that describe the smallest experimentally observed particles of matter and interaction between energy and matter. Three categories of particles form the standard model; Fig. 9. Matter, which makes up only 5% of the universe is composed of quarks and leptons. The fundamental bosons provide three forces: electromagnetism, the strong nuclear force and the weak nuclear force. The Higgs boson provides an explanation for how the other particles get mass.

This model is still considered incomplete. Currently, it is unable to explain many important features of the known universe such as: (i) gravity (ii) dark matter (27% of the universe) (iii) dark energy (68% of the universe).



Fig. 9: Elementary particles in the standard model.



- The observable universe is dominated by**
 - Anti-matter
 - A perfect balanced of matter and anti-matter
 - Matter ✓
 - Dark matter only
- What is the term used to describe the observed imbalance between matter and anti-matter?**
 - Pair production
 - Symmetry breaking
 - Annihilation
 - Baryon Symmetry ✓
- The study of matter-antimatter asymmetry helps scientists to understand:**
 - The shape of galaxies
- Most of the visible matter in the universe exists in the form of:**
 - Solid
 - Liquid
 - Gas
 - Plasma ✓
- Which of the following is an example of plasma found naturally in the universe?**
 - Ice bergs
 - Stars, including the Sun ✓
 - Oceans
 - Planet's solid surfaces

6. Which process primarily maintains plasma in stars?
 (A) Nuclear fusion ✓ (B) Chemical reactions
 (C) Evaporation (D) Freezing
7. According to string theory, fundamental particles are:
 (A) Points in space (B) Solid sphere
 (C) Electromagnetic waves
 (D) One-dimensional strings ✓
8. The concept of supersymmetry in string theory proposes a symmetry between:
 (A) Energy and mass
 (B) Electric and magnetic fields
 (C) Fermions and bosons ✓
 (D) Space and fields
9. The standard model of particle physics is based on:
 (A) Classical field theory (B) Quantum mechanics only
 (C) String theory (D) Quantum field theory ✓
10. Which type of particle naturally appears in string theory, helping it include gravity?
 (A) Proton (B) Gluon
 (C) Graviton ✓ (D) Neutrino
11. The standard model describes which of the following fundamental forces?
 (A) Gravity, electromagnetic and weak
 (B) Strong, weak and gravity
 (C) Electromagnetic, weak and strong ✓
 (D) All four fundamental forces
12. The force not included in the standard model is:
 (A) Gravity ✓ (B) Electromagnetic
 (C) Weak nuclear (D) Strong nuclear
13. Which particle gives mass to other particles in the standard model?
 (A) Electron (B) Neutrino
 (C) Higgs's ✓ (D) Proton
14. What mediates the weak nuclear force in the standard model?
 (A) photon (B) Gluon
 (C) Higgs boson (D) W and Z boson ✓

ADDITIONAL SHORT ANSWER QUESTIONS



Q.1 What is the weakest and strongest fundamental force?

Ans. Strong nuclear force is the strongest fundamental force whereas gravitational force is the weakest fundamental force.

Q.2 Which force is responsible for radioactive beta decay and for holding the nucleus of an atom together?

Ans. Weak nuclear force is responsible for radioactive beta decay and strong nuclear force is responsible for holding the nucleus of an atom together.

Q.3 What is anti-matter?

Ans. It is made up of anti-particles, which have the same mass but opposite charge and quantum properties compared to their matter counterparts.

Q.4 What happens when matter and anti-matter meet?

Ans. They annihilate each other, releasing energy in the form of photons.

Q.5 What is annihilation?

Ans. It is the process where a particle and its corresponding anti-particle destroy each other and release energy.

Q.6 Where is anti-matter found?

Ans. It is found in particle accelerators, cosmic rays, and is produced in some radioactive decays.

Q.7 Why is there more matter than anti-matter in the universe?

Ans. The exact reason is unknown but is a major unsolved question in physics, possible due to asymmetry in the early universe.

Q.8 What is pair production?

Ans. It is the process in which energy is converted into a particle and its anti-particle, usually an electron and a positron.

Q.9 What is required for pair production to occur?

Ans. A high-energy photon (usually gamma ray) and the presence of a nucleus to conserve momentum.

Q.10 What is the minimum energy required for pair production?

Ans. At least 1.02 MeV, which is the combined rest-mass energy of an electron (0.51 MeV) and a positron (0.51 MeV).

Q.11 Is energy conserved in pair production?

Ans. Yes, total energy (including rest-mass and K.E.) is conserved.

Q.12 What happens to the positron after pair production?

Ans. It usually quickly annihilates with an electron, producing two gamma photons.

Q.13 Can pair production occur in space?

Ans. No, it needs a nearby nucleus or particle to conserve momentum.

Q.14 Is radioactivity affected by temperature or pressure?

Ans. No, radioactivity is a nuclear property and is not affected by physical or chemical changes.

Q.15 Name one use of radioactivity in medicine.

Ans. Cancer treatment (radiotherapy using gamma rays).

Q.16 What is alpha decay?

Ans. It is a nuclear reaction in which an unstable nucleus emits an alpha particle (2 protons and 2 neutrons).

Q.17 What is the effect of alpha decay on the nucleus?

Ans. The mass number decreases by four and the atomic number decreases by 2.

Q.18 What is beta decay?

Ans. It is the emission of a beta particle (an electron and positron) from a nucleus when a neutron changes into a proton or vice versa.

Q.19 What is the effect of beta minus decay on the nucleus?

Ans. A neutron becomes a proton, so the atomic number increases by 1, but the mass number remains the same.

Q.20 What is the effect of beta plus decay on the nucleus?

Ans. A proton becomes a neutron, so the atomic number decreases by 1, and mass number stays the same.

Q.21 What is gamma decay?

Ans. It is the emission of gamma radiation (high energy photons) from a nucleus without changing its mass or atomic number.

Q.22 Arrange alpha, beta and gamma radiation in order of increasing penetrating power?

Ans. Alpha < Beta < Gamma.

Q.23 What are fundamental particles?

Ans. They are the smallest building blocks of matter that cannot be broken down further.

Q.24 What are the three main categories of fundamental particles?

Ans. Quarks, leptons and bosons.

Q.25 Name the six types of quarks.

Ans. Up, Down, Charm, Strange, Top, Bottom.

Q.26 Name the six types of leptons.

Ans. Electron, Muon, tau, and their corresponding neutrinos (Electron neutrino, Muon neutrino, Tau neutrino)

Q.27 What are bosons?

Ans. They are force carrier particles that mediate interactions between other particles.

Q.28 Name the four fundamental force carrier bosons.

Ans. Photon, Gluon, W and Z bosons, Graviton.

Q.29 What is the Higgs boson?

Ans. It is a particle responsible for giving mass to other fundamental particles through the Higgs field.

Q.30 What are fermions?

Ans. They are particles that make up matter, including quarks and leptons.

Q.31 Name the bosons in the Standard Model.

Ans. Photon, gluon, W and Z boson, and the Higgs boson.

Q.32 What is the role of the Higgs boson in the Standard Model?

Ans. It gives mass to other particles through the Higgs field.

Q.33 What are the fundamental forces included in the Standard Model?

Ans. Electromagnetic, weak nuclear and strong nuclear forces.

Q.34 What is matter anti-matter asymmetry?

Ans. It refers to the observed imbalance where the universe is dominated by matter, even though matter and anti-matter should have been created in equal amounts during the Big Bang.

Q.35 Why is anti-matter rare in the universe today?

Ans. Most of it annihilated with matter after the Big Bang; only a small excess of matter remained.

Q.36 Can pair production take place in vacuum? Explain.

Ans. No, pair production cannot take place in vacuum.

Explanation: In vacuum there is no heavy nucleus. Pair production always takes place in the presence of a heavy nucleus to conserve the momentum. Pair production without the presence of heavy nucleus is a violation of law of conservation of momentum.

Q.37 It is possible to create a single electron from energy? Explain.

Ans. No, it is not possible to create a single electron from energy.

Explanation: Creation of single electron from energy will be violation of law of conservation of charge and momentum. So, to conserve charge and momentum, energy (photon) is changed into an electron-positron pairs which then move in opposite directions.

SOLVED EXERCISE

MULTIPLE CHOICE QUESTIONS

Tick (✓) the correct answer.

12.1 Which one of the following is the fundamental particle?

- (a) Proton (b) Neutron (c) Electron✓ (d) Meson

12.2 The first discovered anti-particle is:

- (a) anti-proton (b) anti-neutrino (c) anti-photon (d) anti-electron✓

12.3 Which one of the following pair of particles creates annihilation?

- (a) proton-proton (b) proton-neutron (c) neutron-photon (d) electron-positron✓

12.4 The strong nuclear force between the two particles is mediated by:

- (a) gluons✓ (b) photon (c) mesons (d) gravitons

12.5 Which one of the following forces interacts between two particles through photons?

- (a) Strong nuclear force (b) Weak force (c) Electromagnetic force✓ (d) Gravitational force

12.6 When a neutron changes into a proton, then we will observe

- (a) β^- -decay✓ (b) β^+ -decay (c) γ -decay (d) α -decay

12.7 Baryon is formed by combination of:

- (a) 2 quarks (b) 3 quarks✓ (c) 4 quarks (d) A quark and an anti-quark

12.8 Which one of the following forces has negligible effect between the elementary particles?

- (a) Strong nuclear force (b) Weak force (c) Gravitational force✓ (d) Electromagnetic force

12.9 Which particles are produced by strong interaction?

- (a) Graviton (b) Leptons (c) Hadrons✓ (d) Mesons

12.10 A strong nuclear force exists between the nucleons of:

- (a) p - p (b) n - n (c) p - n (d) all of these✓

12.11 Which one of the following radiation/particles has the highest ionization power?

- (a) α ✓ (b) β^+ (c) β^- (d) γ

12.12 Which one of the following has the highest penetrating power?

- (a) α (b) β^+ (c) β^- (d) γ ✓

12.13 A change occurs in atomic number of a nucleus but its mass number remains the same by decay of:

- (a) α (b) β^+ ✓ (c) γ (d) α and γ

12.14 In a nucleus, a neutron changes into a proton, the atomic number changes by one, the mass number will:

- (a) decrease (b) increase (c) remain the same✓ (d) none of these

12.15 The electroweak theory was introduced by:

- (a) Dirac (b) Einstein (c) Anderson (d) Dr. Abdul Salam✓

12.16 The asymmetry of matter and anti-matter is due to imbalance number of:

- (a) hadron (b) lepton (c) baryon✓ (d) photons

- 12.17 Which one of the following particle is responsible for the mass of the fundamental particle?
- (a) Quarks (b) Anti-quark (c) Lepton (d) Higgs boson ✓
- 12.18 A proton is composed of up and down quarks, the order of quarks is:
- (a) udd (b) udu (c) uud ✓ (d) dud
- 12.19 The number of quarks that composed of a neutron is:
- (a) 2 (b) 3 ✓ (c) 4 (d) 5

SHORT ANSWER QUESTIONS

12.1 What do different isotopes of a given element have in common? How are they different?

Ans. Isotopes of a given element have the same number of protons. They also usually have similar chemical properties because chemical behaviour mostly depends on the number of electrons, which matches the number of protons.

However, isotopes differ in the number of neutrons in their nuclei. This difference in neutrons causes isotopes to have different atomic masses. Sometimes, these mass differences can slightly affect physical properties (like density or rates of diffusion), and some isotopes may be radioactive while others are stable.

12.2 Identify the element that has 87 nucleons and 50 neutrons.

Ans. Nucleons = Protons + Neutrons

Given that: there are 87 nucleons and 50 neutrons.

So, the number of protons is:

$$\text{Protons} = 87 - 50 = 37$$

The number of protons determines the element. An element with 37 protons is rubidium (Rb).

12.3 What are the similarities and differences between the strong nuclear force and the electromagnetic force?

Ans. Similarities between the Strong Nuclear Force and the Electromagnetic Force

(i) Both are fundamental forces of nature.

(ii) Both involve particles.

The strong force acts on quarks and between nucleons, while the electromagnetic force acts on particles with electric charge.

(iii) Both have force carriers.

The strong force is mediated by gluons, and the electromagnetic force is mediated by photons.

(iv) Both follow the principles of quantum field theory.

They are described by specific quantum theories.

Differences between the Strong Nuclear Force and the Electromagnetic Force

The primary difference between the strong nuclear force and the electromagnetic force lies in their range, strength, and the particles they act upon.

The strong nuclear force is the strongest of the four fundamental forces, holding protons and neutrons together within the atomic nucleus, but its range is extremely short (10^{-15} metres or 1 femtometre). The electromagnetic force while weaker than the strong nuclear force, has infinite range and acts between all charged parts.

12.4 Fill in the missing particle or nucleus:



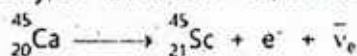
Ans. (a) ${}^{45}_{20}\text{Ca} \longrightarrow ? + e^{-} + \bar{\nu}_e$

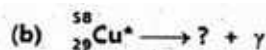
This is β^{-} -decay, where a neutron in the nucleus converts into a proton, emitting an electron (e^{-}), and an electron anti-neutrino ($\bar{\nu}_e$).

In β^{-} -decay:

The mass number A remains the same and the atomic number Z increases by 1. So, the original nucleus is calcium-45 (Ca-45), with $Z = 20$ and $A = 45$.

After β^{-} -decay, $Z = 21$ and $A = 45$, which corresponds to scandium-45 (Sc-45). Thus, answer is:



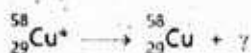


Here, the asterisk (*) indicates that Copper-58 is in an excited state.

This is a gamma-decay, where:

The nucleus emits a gamma photon to move from an excited state to a lower energy (ground) state. The mass number A and atomic number Z do not change.

So, the final product is the same nucleus in a non-excited state, i.e., Copper-58 in its ground state. Thus, answer is:



12.5 Why neutrino must be released in the positron emission?

Ans. In positron emission (called β^+ -decay), a proton inside a nucleus transforms into a neutron, releasing a positron (e^+) and a neutrino:



Now, why must a neutrino be emitted? There are two main reasons:

1. Conservation of Energy and Momentum

If the decay only produce a neutron and a positron, their momenta and energies would have to exactly balance each other. But experiments show that the positron's energy varies continuously up to a maximum (it is not fixed). This indicates a third particle must be carrying away some of the energy and momentum. That third particle is the neutrino.

2. Conservation of Angular Momentum (Spin)

The proton, neutron, and positron all have spin $\frac{1}{2}$ (in units of $\hbar$). To conserve total angular momentum properly during decay, you need another particle with spin $\frac{1}{2}$, namely the neutrino. Without the neutrino, spin conservation would be violated.

12.6 Distinguish between fermions and bosons.

Ans. Fermions

Spin: Half-integer (e.g., $\frac{1}{2}$, $-\frac{1}{2}$, $\frac{3}{2}$, etc.)

Role: Make up matter (building blocks of atoms)

Examples: Electrons, protons, neutrons, quark,

Boson:

Spin: Integer (e.g., 0, 1, 2, etc.)

Role: Mediate forces (force carriers)

Examples: Photons, gluons, w and z bosons, Higgs bosons

12.7 How does strong force hold the nucleus?

Ans. The strong force (or strong nuclear force) holds the nucleus together by binding protons and neutrons (collectively called nucleons) inside the atomic nucleus.

Let us understand how does it work:

- Protons are positively charged and by electromagnetic force, they would strongly repel each other.
- However, the strong force acts between all nucleons and is much stronger than the electromagnetic force but only over very short distances (about 10^{-15} metres or 1 femtometre)
- The strong force is attractive at these short ranges, overpowering the proton-proton, proton-neutrons, and neutron-neutron pairs with about the same strength.
- At very short distances (even closer than 1 femtometre), the strong force becomes repulsive to prevent nucleons from collapsing into a single point.

At an even deeper level, this force is explained by quantum chromo-dynamics-nucleons are made of quarks, and quarks are bound by exchanging gluons, the carriers of the strong interaction.

12.8 Can there be pair production for photons having energy 20 keV? Explain briefly.

Ans. No, pair production cannot occur for photons with energy of 20 keV.

Reasons:

- (i) Pair production is the process when a photon transforms into a particle-antiparticle pair, typically an electron and a positron.
- (ii) To create an electron-positron pair, the photon must have at least enough energy to account for the rest-mass energy of both particles.
- (iii) The rest-mass energy of one electron (or positron) is about 0.51 MeV, so for both it is:
 $2 \times 0.51 \text{ MeV} = 1.02 \text{ MeV}$

Therefore, the minimum energy required for pair production is 1.02 MeV, much higher than 20 keV.

20 keV is only 0.02 MeV, which is far too small to create an electron-positron pair.

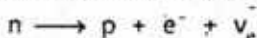
Conclusion: Photons with 20 keV energy do not have enough energy to cause pair production.

12.9 What is the difference between beta particle and electron?

- Ans.** (i) An electron is a fundamental sub-atomic particle with a negative electric charge. It is a basic building block of atoms, found in the "cloud" around the nucleus.
- (ii) A beta particle is usually an electron (or sometimes a positron) that is emitted from a nucleus during beta-decay, which is a type of radioactive decay.
- (iii) In beta-minus decay, a neutron turns into a proton and emits an electron and an anti-neutrino.
- (iv) In beta-plus decay, a proton turns into a neutron and emits a positron and a neutrino.

12.10 How do a proton and a neutron convert to each other?

- Ans.** (i) A neutron can turn into a proton by beta-minus decay. It emits an electron and an anti-neutrino:



(This happens because a down quark inside the neutron changes into an up quark).

- (ii) A proton can turn into a neutron by beta-plus decay or electron capture.

In beta-plus decay (in unstable nuclei), the proton emits a positron and a neutrino:



- (iii) In electron capture, the proton absorbs an electron and becomes a neutron, emitting a neutrino:



In all cases, it is the weak nuclear force—one of the four fundamental forces that causes the change.

12.11 Why does beta-decay have a continuous energy spectrum and alpha-decay have a discrete energy spectrum?

- Ans. Beta-decay:** In beta-decay a neutron (or proton) decays into three particles – an electron (or positron) a neutrino (or anti-neutrino) and a proton (or neutron). Since there are three particles in the final state, energy and momentum must be conserved, but the energy can be shared in many different ways between the electron and the neutrino. The electron does not always take the same amount of energy because the neutrino can take varying amounts.

Result: The electron's energy spectrum is continuous, it can have a range of energies up to a maximum value.

Alpha-decay: In alpha-decay, a parent nucleus decays into a daughter nucleus plus an alpha particle (which is two protons and two neutrons). Now there are only two particles involved. Energy and momentum conservation in two body decays completely fix the energies of the products.

Result: The alpha particle always comes out with a specific, discrete energy.

12.12 Differentiate between hadron and leptons with examples.

- Ans.** Hadrons and Leptons are both sub-atomic particles, but they differ in their composition, properties and behaviour.

Composition: Hadrons are made of quarks, while leptons are elementary particles and are not made of small components.

Interactions: Hadrons interact through the strong force, while leptons interact via the weak force and electromagnetic force (if charged).

Examples: Hadrons include protons, neutrons, and pions. Leptons include electrons, muons, tau particles, and neutrinos.

12.13 Why electron-positron pair cannot decay into a single photon?

- Ans.** An electron – positron pair cannot decay into a single photon, because of the conservation laws, specifically the conservation of both energy and momentum. Let us understand, why.

1. Energy and Momentum Conservation

For an electron and positron to annihilate into a photon, the total energy and momentum before and after the annihilation must be conserved.

- The electron and positron have both rest-mass and kinetic energy, and their total energy and momentum are determined by their respective energies and momenta.
- A single photon, however, has energy but no rest mass, and its momentum is directly related to its energy ($E = pc$).

2. Violation of Momentum Conservation

- In the centre of mass, frame of the electron positron system, the total momentum is zero before annihilation.
- After annihilation, for a single photon, the momentum would not be zero (since, it has non-zero momentum). To conserve both energy and momentum, at least two photons are needed. The two photons can travel in opposite directions, ensuring that the total momentum is zero and the energy is conserved.

12.14 State the role of Higgs Boson in the generation of mass in modern physics theories.

Ans. In modern physics, particularly in the Standard Model of Particle Physics, the Higgs boson plays a crucial role in explaining how particles acquire mass. The Higgs mechanism, named after Physicist Peter Higgs, describes how particles interact with the Higgs field that permeates all of space.

In essence, the Higgs boson and the associated Higgs field are key elements in the Standard Model's explanation of why elementary particles, such as quarks and leptons have mass. Without the Higgs mechanism, these particles would be massless, and the universe would look very different, with no stable atoms or complex structures like stars and planets.

12.15 What are Mesons? Give examples.

Ans. Mesons are a type of sub-atomic particles that are composed of one quark and one anti-quark. They are part of the Haden family, which includes particles made up of quarks. Unlike baryons (such as protons and neutrons), which consist of three quarks, mesons are typically unstable and play a significant role in mediating the strong nuclear force between nucleons (protons and neutrons) in atomic nuclei.

Examples of Mesons:

Pion (π meson), Kaon (K meson), Eta meson (η), Rho meson (ρ meson).

CONSTRUCTED RESPONSE QUESTIONS

12.1 Is meson, a boson or fermion? Give reason.

Ans. Mesons and bosons are not fermions. That is why:

- Fermions are particles that have half-integer spin (like $\frac{1}{2}$, $\frac{3}{2}$, etc.)
- Bosons are particles that have integer spin (like 0, 1, 2, etc.)
- Now mesons are made of a quark and an anti-quark, and their total spin is always an integer (usually 0 or 1), so mesons are bosons.
- Bosons, by definition, have integer spin, so they are bosons, not fermions.

Reason: Spin determines if a particle is a fermion or boson. Half-integer spin $\rightarrow$ fermion, integer spin $\rightarrow$ boson.

12.2 Why does an alpha emitter emit alpha particles instead of four separate nucleons?

Ans. An alpha emitter releases an alpha particle, which is a tightly bound group of two protons and two neutrons (basically a helium-4 nucleus).

The alpha particle is extremely stable and tightly bound. The binding energy per nucleon in an alpha particle is very high (about 7 MeV per nucleon). That means; the two protons and two neutrons prefer to stick together because they are in a lower-energy, more stable configuration than they would be if were separated.

If a nucleus tried to emit single protons and neutrons one at a time:

- it would cost more energy.
- it must not even be possible unless there is enough energy available to overcome the binding energy that holds the nucleons inside the nucleus.
- emitting an alpha particle, on the other hand, releases energy and makes the parent nucleus more stable.

12.3 Which is more energetic alpha decay or beta decay? Justify your answer.

Ans. Alpha decay is generally more energetic than beta decay. That is why;

- In alpha decay, a heavy nucleus (like uranium or radium) emits an alpha particle (which is 2 protons and 2 neutrons, basically, a helium nucleus). The mass of the alpha particle is significant, and the binding energy released when it escapes is large, of several MeV, typically between 4-8 MeV or even more.
- In beta decay, a nucleus emits a beta particle (an electron or positron) and a neutrino. The mass difference between the parent and daughter nuclei is much smaller, and the energy released is shared between the beta particle and the neutrino. Typical beta decay energies are around a few hundred keV to 1 MeV (much less than alpha decay).

Justification: Alpha particles are much heavier and carry away more energy because the change in mass during alpha decay is bigger. Also alpha decay happens in heavy nuclei where the binding energy differences are large, leading to higher energy releases.

12.4 A nucleus undergoes gamma decay, emitting gamma ray photon with energy 1.5 MeV. Calculate.

- (i) frequency of gamma ray (ii) wavelength of gamma ray
(iii) momentum of gamma ray

Ans. Energy of a gamma ray photon is:

$$E = 1.5 \text{ MeV} = 1.5 \times 10^6 \text{ eV}$$

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

$$\text{So } E = 1.5 \times 10^6 (1.6 \times 10^{-19}) \text{ J}$$

$$E = 2.4 \times 10^{-13} \text{ J}$$

Now

(i) **Frequency (f) of the gamma ray:**

$$E = hf \text{ where } h = 6.63 \times 10^{-34} \text{ Js}$$

$$f = \frac{E}{h} = \frac{2.4 \times 10^{-13} \text{ J}}{6.63 \times 10^{-34} \text{ Js}}$$

$$f = 3.63 \times 10^{20} \text{ Hz}$$

(ii) **Wavelength of the gamma ray:**

$$\text{As } c = f\lambda \text{ where } c = 3 \times 10^8 \text{ ms}^{-1}$$

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8 \text{ ms}^{-1}}{3.63 \times 10^{20} \text{ Hz}}$$

$$\lambda = 8.27 \times 10^{-13} \text{ m}$$

(iii) **Momentum of the gamma ray:**

$$\text{As } p = \frac{E}{c}, \text{ so}$$

$$p = \frac{2.4 \times 10^{-13} \text{ J}}{3 \times 10^8 \text{ ms}^{-1}} = 8.01 \times 10^{-22} \text{ kg ms}^{-1}$$

12.5 Why does the α -particles not make physical contact with the nucleus when headed directly towards it?

Ans. When an alpha particle (which is positively charged) is fired directly at an atomic nucleus (also positively charged), they do not actually make physical contact in most cases because of the electrostatic repulsion.

At very high energies (like a nuclear fusion), particles can get close enough for the strong nuclear force to take over and allow fusion but under normal conditions like in Rutherford's gold foil experiment, alpha particles just bounce off or are deflected.

COMPREHENSIVE QUESTIONS

12.1 What is meant by radioactivity? Compare the properties and behaviour of three types of radiations.

Ans. See Q. 7

12.2 Elaborate the phenomenon of beta-positive decay and beta-negative decay with examples.

Ans. See Q. 8

12.3 What is the difference between matter and anti-matter? Discuss reasons why our universe is almost entirely composed of matter.

Ans. See Q. 4

12.4 Explain the phenomenon of pair annihilation with an example. Explain the utility of its principle in the medical field.

Ans. See Q. 6

12.5 Explain the law of conservation of energy and momentum in electron-positron pair annihilation.

Ans. See Q. 15

12.6 Describe protons and neutrons in terms of their quark composition.

Ans. See Q. 14

12.7 Describe four fundamental forces in nature.

Ans. See Q. 2

12.8 Describe the classification of elementary particles.

Ans. See Q. 12

NUMERICAL PROBLEMS

12.1 Uranium-238 is an alpha emitter. In the process, it is transmuted into a daughter nucleus. What is the mass number A and charge number Z of the daughter nucleus? What is its chemical symbol?

Solution:

When U-238 undergoes alpha decay, it emits an alpha particle, which is essentially a helium-4 nucleus. An alpha particle has:

$$\text{Mass number} = A = 4$$

$$\text{Charge number} = Z = 2$$

So, during alpha-decay

- the mass number A of the daughter nucleus = $238 - 4 = 234$

- the charge number Z = $92 - 2 = 90$

An element with atomic number or charge number 90 is thorium (Th).

12.2 Polonium $^{218}_{84}\text{Po}$ is a beta minus emitter. What will be the mass number A and charge number Z of the daughter nucleus?

Solution:

Polonium-218 ($^{218}_{84}\text{Po}$) undergoes beta-minus (β^-) decay. In beta-minus decay:

- a neutron is converted into a proton, emitting an electron (β^-) and an anti-neutrino.
- As a result, the charge number Z increases by 1, but the mass number A remains the same.

As the parent nucleus has mass number A, 218 which remains unchanged and the charge number Z becomes $84 + 1 = 85$.

So, the daughter nucleus is $^{218}_{85}\text{At}$, which is Astatine-218.

12.3 Nitrogen $^{14}_7\text{N}$ bombarded by alpha particle results into $^{17}_8\text{O}$. What is the product particle in

this nuclear reaction?

Solution:

We are given a nuclear reaction, where:

- a nitrogen nucleus with charge number 7 and mass number 14 ($^{14}_7\text{N}$) is bombarded by an alpha particle (^4_2He).

- This results in an oxygen nucleus with charge number 8 and mass number 17 ($^{17}_8\text{O}$).

We have to determine the product particle. Let us write the nuclear reaction in symbolic form:



Now conserve both mass number A and charge number Z.

Mass Number:

$$14\text{N} + 4\text{H} = 17\text{(O)} + A\text{(X)}$$

$$\longrightarrow AX = 1$$

Charge number:

$$7\text{(N)} + 2\text{(He)} = 8\text{(O)} + Z\text{(X)}$$

$$\longrightarrow Z\text{(X)} = 1$$

So, the unknown product particle X has:

$$\text{Mass number} = A = 1$$

$$\text{Charge number} = Z = 1$$

That means, X is a proton (^1_1H).

12.4 Show that nucleon number N and charge number Z are conserved in the numerical question 12.3.

Solution:

Given data:

Nitrogen nucleus: $^{14}_7\text{N}$ (Charge number Z = 7, Mass number A = 14)

Alpha particle: ^4_2He (Charge number Z = 2, mass number A = 4)

Product nucleus: $^{17}_8\text{O}$ (Charge number Z = 8, mass

number $A = 17$)

Let us write the equation:



Now calculate totals:

Left side:

- Total charge number = $Z = 7 + 2 = 9$
- Total mass number = $A = 14 + 4 = 18$

Right side:

Oxygen has mass number = 17, $Z = 8$

To conserve both mass number A and charge number Z , the remaining particle X must have:

$$\text{Mass number} = A = 18 - 17 = 1$$

$$\text{Charge number} = Z = 9 - 8 = 1$$

So, particle X must be a proton ${}^1_1\text{H}$.

Final reaction:



Therefore, total mass number A is:

$$14 + 4 = 17 + 1 = 18$$

And total charge number Z is:

$$7 + 2 = 8 + 1 = 9$$

Conclusion: Mass number and charge number are both conserved.

12.5 Determine the rest-mass energy of electron in eV. Its rest-mass is 0.000555 u?

Solution:

To find the rest-mass energy of the electron in MeV, we use Einstein's mass-energy equation:

$$E = mc^2 \quad \dots\dots (i)$$

The rest mass of electron is equal to 0.000555 u, where u is the atomic mass unit (a.m.u).

$$1 \text{ u} = 931.5 \text{ MeV}/c^2$$

$$\text{Thus } m = 0.000555 \times 931.5 \text{ MeV}/c^2$$

$$\approx 0.517 \text{ MeV}/c^2$$

Since $E = mc^2$, the rest-mass energy of the electron is:

$$E \approx 0.517 \text{ MeV}/c^2 \times c^2$$

$$E \approx 0.517 \text{ MeV}$$

So, the rest-mass energy of the electron is approximately 0.517 MeV.

12.6 Calculate the Q -value for the reaction taking place in Rutherford's experiment on artificial disintegration of nitrogen by bombardment with alpha particles. Relative masses are:

$${}^{14}_7\text{N} = 14.007515 \text{ u}, {}^4_2\text{He} = 4.003837 \text{ u},$$

$${}^{17}_8\text{O} = 17.004533 \text{ u} \text{ and } {}^1_1\text{H} = 1.008142 \text{ u}$$

Solution:

The nuclear reaction is given by



Mass of reactants:

$$m_{\text{reactants}} = 14.007515 \text{ u} + 4.003837 \text{ u}$$

$$= 18.011352 \text{ u}$$

Mass of products:

$$m_{\text{products}} = 17.004533 \text{ u} + 1.008142 \text{ u}$$

$$= 18.012675 \text{ u}$$

$$\text{Mass difference } \Delta m = m_{\text{reactants}} - m_{\text{products}}$$

$$= 18.011352 \text{ u} - 18.012675 \text{ u}$$

$$= -0.001323 \text{ u}$$

$$Q\text{-value} = \Delta m \cdot 931.5 \text{ MeV}$$

$$= -0.001323 \text{ u} \cdot 931.5 \text{ MeV}$$

$$Q \approx -1.23 \text{ MeV}$$

The negative sign indicates that the reaction is endothermic. It means that energy is absorbed.