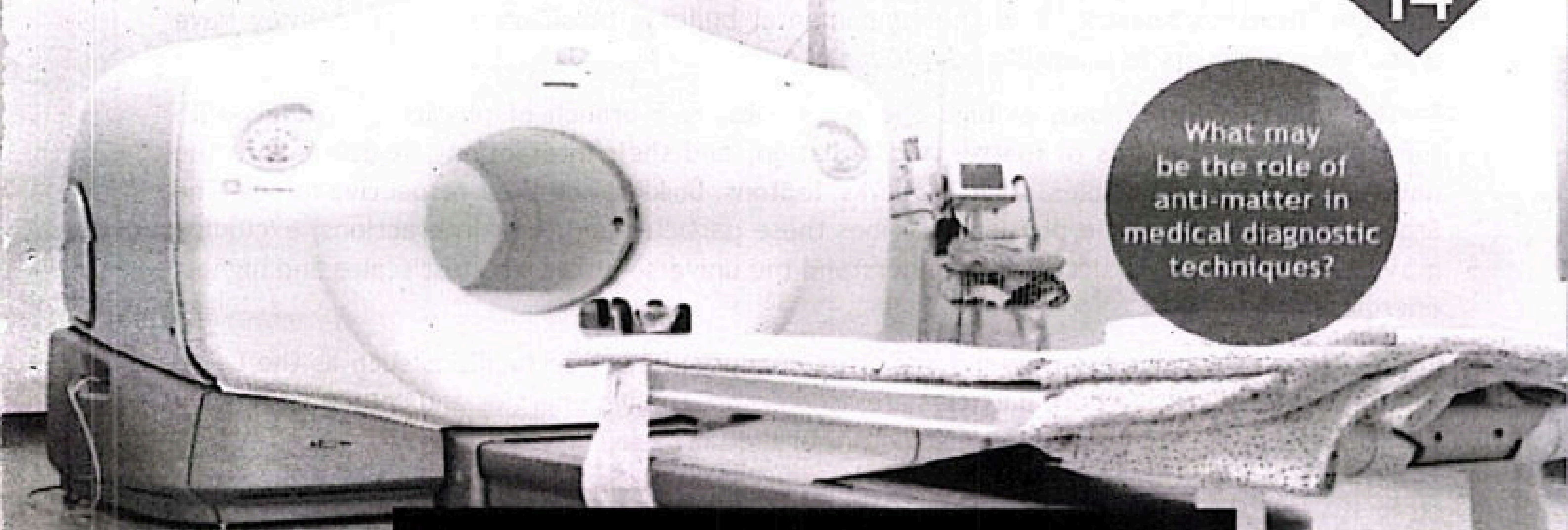
PARTICLE PHYSICS

UNIT 14



What may be the role of anti-matter in medical diagnostic techniques?

Student Learning Outcomes (SLOs)

The students will:

- State that nucleon number and charge are conserved in nuclear processes.
- Describe the composition, mass and charge of alpha, beta and gamma radiations [both β^- (electron) and β^+ (positron) are included].
- Explain that an antiparticle 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-antineutrinos 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 are fundamental particles [including that there are six flavors (types) 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 anti-quark).
- 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 that 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 a same mass as a given particle but opposite electric or magnetic properties according to the Standard Model of Particle Physics].
- Describe protons and neutrons in terms of their quark composition.
- State that a hadron may be either a baryon or meson.
- 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 multidimensional 'strings' that vibrate in higher dimensions to give rise to particles].
- Explain the working principle of particle accelerators and also their uses.
- Explain that anti-matter is the counter part of matter [e.g. a positron is the anti-matter counterpart to an electron].
- Illustrate that the anti-particles usually have the same weight, but opposite charge, compared to their matter counter parts.
- 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 unresolved mystery.
- Describe annihilation reactions [a particle meets its corresponding anti-particle, they undergo annihilation reaction in which either all the mass is converted to heat and light energy, or some mass is left over in the form of new subatomic particles].

From the beginning of time, humans have had an innate urge to discover the mysteries of the universe. In other quest to find the fundamental building block of the cosmos, they have unlocked many doors to scientific knowledge.

Particle physics, also known as high-energy physics, is a branch of physics that deals with fundamental constituents of matter and radiation, and their interactions. It delves into the nature of subatomic particles, such as quarks, leptons, bosons, and their respective forces. The Standard Model of particle physics describes these particles and their interactions, excluding gravity. This field of physics aims to understand the universe at the smallest scales and highest energies.

Today, particle physics experiments are often conducted at large facilities such as the Large Hadron Collider (LHC), where particles are accelerated to high energies and collided, allowing physicists to probe the fundamental structure of the universe.

14.1 CONSERVATION LAWS IN NUCLEAR REACTIONS

Charge and nucleon conservation are fundamental principles in nuclear processes, deeply rooted in the laws of physics and the interactions among subatomic particles. These conservation laws play a crucial role in maintaining the integrity of atomic nuclei and ensuring that the fundamental properties of matter are preserved during nuclear reactions and decays.

14.1.1 Conservation of Charge

The conservation of charge is a fundamental property of particle interactions. In any closed system, the total charge before and after an interaction or decay must remain the same. Consider the example of α-decay:

$$_{88}Ra^{226} \longrightarrow {}_{86}Rn^{222} + {}_{2}He^{4} + Q$$

Here in this reaction, total charge on L.H.S is equal to the total charge on R.H.S. This is because charge is a conserved quantity i.e. it cannot be created or destroyed. It can only be transferred from one particle to another. In nuclear processes, the charges of the particles involved (such as protons, electrons, positrons) are carefully balanced to maintain overall charge neutrality.

14.1.2 Conservation of Nucleons

Nucleons, comprising both protons and neutrons, are the building blocks of atomic nuclei. The conservation of nucleons refers to the principle that the total number of nucleons remains constant before and after a nuclear reaction or decay. Consider the following nuclear reaction

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

The number of nucleons on the L.H.S = 14 + 4 = 18

The number of nucleons on the R.H.S = 17 + 1 = 18

Hence, total number of nucleons on both the sides are same, i.e., 18. This conservation law is a consequence of the strong nuclear force, that binds nucleons together in the nucleus. The strong force is a short-range force that acts between quarks (the constituents of protons and neutrons), ensuring that the nucleons are not spontaneously created or destroyed during nuclear processes.

The conservation of charge and nucleons is upheld in various nuclear reactions, such as alpha decay, beta decay, and fusion reactions. These laws have been extensively tested and confirmed through experiments and observations in particle physics and nuclear science. They provide a deep insight into the underlying symmetries and interactions within the subatomic world and have far-reaching implications for understanding the behavior of matter at the smallest scales.

Alpha particles, beta particles, and gamma rays are three types of radiation commonly associated with radioactive decay processes. These particles and rays have distinct properties regarding mass and charge:

1) Alpha Particle:

Composition: An alpha particle consists of two protons and two neutrons, which are bound together as a single entity.

Mass: The total mass of an alpha particle is approximately 4 atomic mass units (u) or unified atomic mass units (u), equivalent to about 6.64×10^{-27} kilograms.

Charge: Alpha particles carry a positive charge of +2e, where "e" represents the elementary charge. This charge corresponds to twice the charge of a single proton.

2) Beta Particle:

Composition: Beta particles are high-energy electrons (β^-) or positrons (beta-plus) emitted during certain types of radioactive decay.

Mass: β-particles have a much smaller mass than α-particles. Electrons have a mass of approximately 9.11×10^{-31} kg, while positrons have the same mass but with a positive charge.

Charge: β^- particles (electrons) carry a negative charge of -1e. β^+ particles (positrons) carry a positive charge of +1e, where $e = 1.6\times10^{-19}$ C.

3) Gamma Ray:

Composition: Gamma rays are electromagnetic waves, similar to X-rays. They do not consist of particles in the traditional sense.

Mass: Gamma rays have no mass because they are composed of photons, which are massless particles.

Charge: Gamma rays are electrically neutral, meaning they carry no electric charge.

These differences in mass and charge are essential for understanding their behavior, interactions, and effects in various contexts, including radioactivity and radiation protection.

14.2 PARTICLE'S DECAYS

Antiparticles are a unique concept in particle physics, representing the counterparts to regular particles. They share the same mass as their corresponding particles but have opposite electric charges. This phenomenon is a consequence of the symmetries in the fundamental laws of physics. Here are a couple of examples to illustrate this concept:

Electron-Positron:

Electron: An electron is a subatomic particle with a negative electric charge of -1e and a mass of approximately 9.11×10^{-31} kg.

Positron: The positron is the antiparticle counterpart of the electron. It has the same mass as an electron (approximately 9.11×10^{-31} kg) but carries a positive electric charge of +1e. This pairing of electron and positron is an example of matter-antimatter annihilation. When an electron and a positron collide, they annihilate each other, converting their masses into energy in the form of gamma rays. This process is known as matter-antimatter annihilation.

Proton-Antiproton:

Proton: A proton is a subatomic particle found in the nucleus of an atom. It carries a positive electric charge of +1e and has a mass of approximately 1.67×10^{-27} kg.

Antiproton: The antiproton is the antiparticle counterpart of the proton. It shares the same mass as a proton (approximately 1.67×10^{-27} kg) but carries a negative electric charge of -1e. Antiprotons can be produced artificially in high-energy particle accelerators and are used in scientific experiments to study the fundamental properties of matter.

These examples highlight the principle of charge conservation in particle-antiparticle pairs, where the total charge remains conserved while exhibiting opposite signs. Additionally, the conservation of mass is also evident as the masses of particles and their corresponding antiparticles are identical.

14.2.1 Alpha Decays

In **alpha decay,** atomic number of the parent nucleus reduces by 2 and the mass number reduces by 4 units. The decay product is called the daughter nucleus. The daughter nucleus may also remain unstable and undergo further disintegration till it attains stability. Alpha decay of ${}_{88}Ra^{226}$ is shown below:

$${}_{88}Ra^{226} \longrightarrow {}_{86}Rn^{222} + {}_{2}He^{4} + Q$$

Q is the disintegration energy, which is always positive (as the process is spontaneous).

14.2.2 Beta Decays

Beta-minus (β-) decay and beta-plus (β+) decay are two types of radioactive decay processes involving the emission of beta particles. These processes occur in atomic nuclei to achieve a more stable nuclear configuration. Here's how each process works:

In **beta-minus decay,** a neutron (n) within the nucleus is transformed into a proton (p), an electron (beta-minus particle β^-), and an antineutrino ($\bar{\nu}_e$). The antineutrino is a nearly massless, electrically neutral particle that carries away some of the energy released during the decay. The emitted beta-minus particle is an electron. The process can be summarized as follows:

$$n = p^+ + \beta^- + \bar{\nu}_e \quad \text{\_\_\_\_\_} \quad (14.1)$$

The newly formed proton remains in the nucleus, increasing the atomic number by 1, while beta-minus particle and antineutrino are emitted from the nucleus.

In **beta-plus decay**, a proton within the nucleus is transformed into a neutron (n), a positron (beta-plus particle β^+), and a neutrino (ν_e). The emitted beta-plus particle is a positron, which is the antiparticle of an electron. The process can be summarized as follows:

$$p^+ = n + \beta^+ + \nu_e \quad \text{\_\_\_\_\_\_} \quad (14.2)$$

The newly formed neutron remains in the nucleus, reducing the atomic number by 1, while beta-plus particle and neutrino are emitted from the nucleus. Both beta minus and beta plus decay processes are governed by the weak nuclear force, one of the fundamental forces in nature responsible for mediating certain types of particle interactions. These processes play a crucial role in the overall stability and transformation of atomic nuclei, allowing them to achieve more balanced configurations and release excess energy.

14.2.3 Energies for Alpha and Beta Decay

Alpha and beta particles are products of radioactive decay processes, and they carry different amounts of energy due to their distinct properties and mechanisms of emission.

Alpha particles have discrete energies in nuclear processes due to the specific nature of the quantum mechanical interactions within atomic nuclei. These energies are determined by the energy levels and quantum states of the particles within the nucleus, as well as the binding forces that hold the nucleus together. Inside a nucleus, protons and neutrons are arranged in energy levels or shells, similar to how electrons are arranged in energy levels around an atom's nucleus. These energy levels are quantized, meaning they can only take a certain discrete value. When an alpha particle is formed during radioactive decay, it involves the rearrangement of nucleons within the nucleus, which results in specific energy changes.

Quantization of Energy Levels: Just as electrons in an atom can only exist only at certain discrete energy levels, nucleons within a nucleus also occupy quantized energy levels. When nucleons rearrange themselves to form an alpha particle, the energy change corresponds to the difference between the initial and final energy states.

Binding Energies: The formation of an alpha particle involves the strong nuclear force, which binds nucleons together in the nucleus. As nucleons combine to form an alpha particle, changes occur in the binding energies of the particles involved. These changes result in the release of energy, which is carried away by the alpha particle.

Conservation of Energy: The conservation of energy is a principle in all physical processes. The total energy of the system before and after the alpha particle emission must be conserved. This conservation leads to the emission of alpha particles with specific, well-defined energies. Consequently, the energies of alpha particles emitted in nuclear processes are quantized and discrete. These specific energy levels of alpha particles provide valuable information about the structure of atomic nuclei, the binding forces involved, and the dynamics of nuclear reactions.

Energy of beta particles: The continuous energies spectrum of beta particles in nuclear processes can be attributed to the probabilistic nature of quantum mechanics, along with the conservation of energy and momentum. Unlike alpha particles, which have discrete energies, the energies of beta particles are spread out over a range of values. This continuous energy spectrum arises from several factors:

i) Quantum Uncertainty: In quantum mechanics, particles are described by wave functions that exhibit inherent uncertainty in certain properties, including energy. This uncertainty allows for a range of possible energies for a given particle. When a beta particle is emitted during a nuclear decay, its specific energy is not predetermined but subject to quantum uncertainty.

ii) Neutrinos in Beta Decay: In beta decay processes, such as beta-minus (ß-) and beta-plus (ß+) decay, an additional particle is involved: the neutrino or antineutrino. These particles are extremely lightweight and have negligible mass, which means they carry away some of the energy released during the decay. This leads to a spread of energies in the emitted beta particles, as the neutrinos can take varying amounts of energy, leaving less for the beta particles.

iii) Conservation Laws: While the total energy before and after beta decay must be conserved, there is flexibility in how that energy is distributed between the emitted beta particle and the accompanying neutrino. This flexibility results in a continuum of possible energy values for the beta particles.

iv) Final State Interactions: In some cases, the emitted beta particles can interact with other particles or fields as they travel through matter. These interactions can affect the energy and momentum of the beta particles, contributing to the continuous energy spectrum observed in experiments.

14.3 MATTER AND ANTI-MATTER

In 1928, a British physicist Paul Dirac, while studying the behavior of electrons at very high speeds (speeds comparable to light) derived an equation for the energy of an electron by combining special relativity and quantum theory. Generally, the relationship for the energy and momentum of a particle can be expressed as:

$$E = \frac{p^2}{2m} \quad \text{\_\_\_\_\_ (14.2)}$$

Solving this relation for relativistic speed by using special relativity and quantum theory, he derived an equation which can be given as:

$$E = \pm\sqrt{m^2c^4 + p^2c^2} \quad \text{\_\_\_\_\_ (14.4)}$$

Here 'E' is the energy of the particle, 'm' is the mass, 'p' is the momentum and 'c' is the speed of light. Positive and negative solutions for energy give a striking idea for anti-particles.

If positive solution of the Dirac's equation is for electron (the particle) then negative solution for energy must be for a particle which should have mass and momentum equal to that of electron but of opposite charge and magnetic moment. Dirac said this energy solution is for positron (the anti-particle of electron). The energy cones for electron and positron are shown in Fig. 14.1. Soon after the prediction of Dirac on solving his equation for the existence of anti-particles, James Anderson discovered the positron. In 1932, while studying the tracks of cosmic ray particles in a cloud chamber at California institute of technology, he discovered a particle which has the mass equal to the mass of an electron but has the opposite charge to that of electron i.e. the positive charged particle. This was the first experimental discovery of an anti-particle. After that a lot of anti-particles were discovered. Electron, proton and neutron along with their respective anti-particles are listed here in table 14.1.

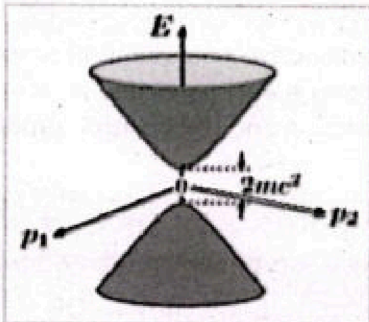


Figure 14.1: Electron-positron energy.

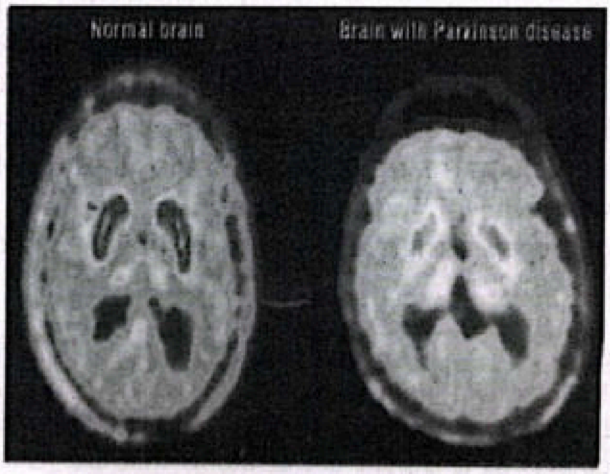
Table 14.1 (Particles and anti-particles)

Property	Electron	Positron	Proton	Anti-proton	Neutron	Anti-neutron
Mass (kg)	9.1×10^{-31}	9.1×10^{-31}	1.67×10^{-27}	1.67×10^{-27}	1.67×10^{-27}	1.67×10^{-27}
Mass (MeV/c^2)	0.51	0.51	938.28	938.28	939.57	939.57
Charge	-1e	+1e	+1e	-1e	0	0
Spin	1/2	1/2	1/2	1/2	-1/2	-1/2
Family	fermion	fermion	fermion	fermion	fermion	Fermion

Particles are divided into two groups depending upon their spins. Particles with integer spins (0, 1, 2 ...) are called 'boson' and the particles with half integer spin (1/2 etc.) are called 'fermions'.

Anti-matter and Medical Technology

Antimatter is used in the medical technology, for example, anti-protons are used to treat some types of cancers, positrons are used in positron emission topography (PET scan) to create images of internal body part. In this process positrons are emitted by the decay of radio nuclei. Photons are produced when positrons collide with electrons, converting the electron-positron pair into energy. Scanner detects the annihilated photons at an angle of 180° apart from each other. Using these photons an image of the internal body is obtained. PET scan is used to evaluate organs like the heart and brain and are also used for detection and evaluation of cancers.



For Your Information

Radioactive potassium-40 present in bananas, Brazil nuts and even human body produce anti-particles. It releases positrons in beta decay. The amount of such reaction and the positron production is so small that it has no health threats.

Example 14.1: The energy of a particle system is 2 MeV moving with relativistic speed, approach each other. If their masses are 0.511 MeV/c² find their momentum. Also justify why momentum has two values i.e. positive and negative.

Given: $E = 2\ MeV$ OR $E = (2\times10^{6}\times1.6\times10^{-19})J = 3.2\times10^{-13}J$

$m = 0.511\ MeV/c^{2}$ OR $m = (\frac{0.511\times10^{6}\times1.6\times10^{-19}}{9\times10^{16}})kg = 9.11\times10^{-31}kg$

To Find: Momentum: p = ?

Solution: To find momentum of the system we use equation 14.4.

$$E = \pm\sqrt{m^{2}c^{4}+p^{2}c^{2}}$$

Squaring on both sides, we get: $$E^{2} = m^{2}c^{4}+p^{2}c^{2}$$

Re-arranging the above: $$p^{2} = \frac{E^{2}-m^{2}c^{4}}{c^{2}}$$

Using values: $$p = \sqrt{\frac{(3.2\times10^{-13}J)^{2}-(9.11\times10^{-31}kg)^{2}(3\times10^{8}ms^{-1})^{4}}{(3\times10^{8}ms^{-1})^{2}}}$$

$$p = \pm1.03\times10^{-21}kg\ ms^{-1}$$

There are two values of momentum i.e. positive and negative, corresponding to particle and anti-particle.

Assignment 14.1

Find the momentum of a positron, moving with relativistic speed. The energy of the positron is 0.47 MeV.

Physicists at the Relativistic Heavy Ion Collider (RHIC) in New-York created the anti-nuclei of helium-4. Anti-helium-4 is the heaviest anti-particle produced. Scientists at CERN (the European research laboratory for particle physics), artificially created an atom of anti-matter, which has opened the doors of further research in the field of anti-matter. Hydrogen along with its anti-hydrogen is shown here in the Fig. 14.2.

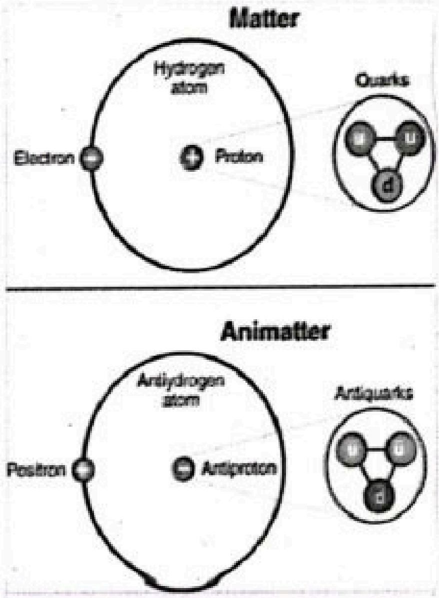


Figure 14.2: Hydrogen and anti-hydrogen.

For Your Information

The cost of 1 gram of anti-matter is 62.5 trillion dollars, making it the most expensive material on Earth. Anti-matter can create objects as it is built out of atoms that are '*charge conjugate*' of ordinary atoms, i.e., the anti-atom.

14.3.1 Asymmetry of Matter and Anti-matter

Particle and anti-particles mirror each other almost perfectly; for every particle in the universe, there ought to be a particle of anti-matter. Our Earth, the Sun and the dust between the galaxies are made up of normal matter. It looks like the whole universe is made up of matter, so when we look around, we don't see any anti-matter, why? The asymmetry in the universe is essential for the existence of stars and even life itself. Hence asymmetry is good thing in itself.

A particle and anti-particle are charge conjugate of each other (i.e., a positive and negative pair), hence whenever in any reaction, a pair of particle and anti-particle is made law of conservation of charge requires this conjugation, which is known as C-symmetry. Also, the particle and anti-particle are like '*mirrors*' to each other, as the inversion of nuclear spatial coordinates; the state of being equal with reference to some coordinate is called 'parity' (the space inversion). Collectively, charge conjugation and parity are called CP-symmetry. A simple depiction of charge symmetry and parity is shown in Fig. 14.3.

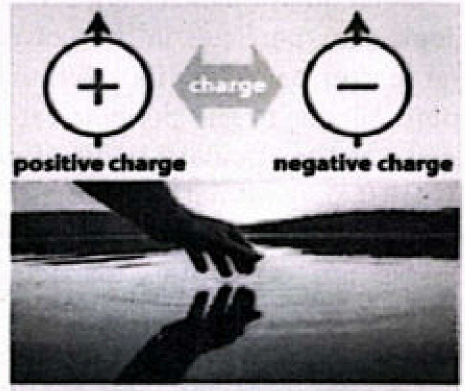


Figure 14.3: A simple depiction of C-symmetry and P-symmetry

Then why the anti-matter is so rare if the matter and anti-matter are perfectly balanced. What happened to the anti-matter stuff? The answer lies to the early universe.

The most accepted theory about the creation of universe is the big bang theory. According to this theory, about 13.7 billion years ago an explosion took place with creation of matter and antimatter in perfectly equal amount with CP-symmetry. But with this symmetry all the matter would annihilate leaving behind an empty universe. But the real universe has the excess matter which formed by surviving this annihilation, is due to CP-violation.

> CP-violation is a phenomenon where the same decay process has a different probability for a particle than for an anti-particle.

In particle physics, it is the violation of the combined conservation laws i.e. charge conjugation and parity by the weak force. The CP-violation seems to be the main cause of this asymmetry in the universe. In early universe, equal amount of matter and anti-matter were produced, but after first second when nuclei formed the matter started dominating. As in the nucleus two forces are prominent the strong nuclear force which binds the nucleus and the weak force responsible for the nuclear decays, both violate the CP. Evidences in early universe for strong force's CP-violation are less as compare to the weak force.

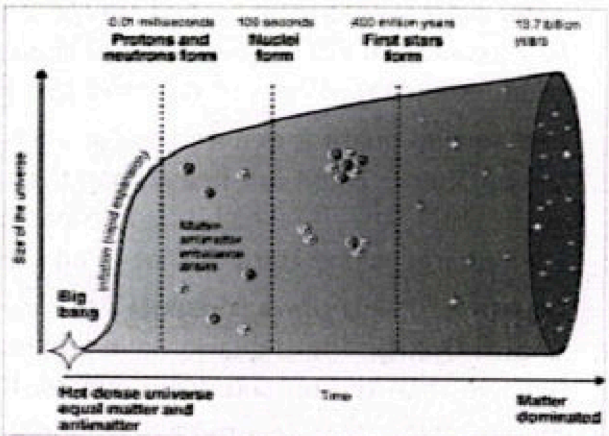


Figure 14.4: The timeline of universe.

14.4 QUARKS

In the early 20th century, protons and neutrons were considered as elementary particles. However, in 1964 Murray Gell-Mann and George Zweig independently proposed the quark theory, which described the protons and neutrons as being composed of quarks. The existence of quark was first confirmed in a deep inelastic scattering experiment at the Stanford Linear Accelerator Center (SLAC) in 1968.

Elementary particles are those particles which are not composed of the other particles.

Elementary particles in the universe can be broadly categorized mainly into two groups i.e., the matter particles (fermions with half integer spin) and force carriers (bosons with integer spin). Similar to the periodic table of elements, elementary particles are arranged in a table known as the Standard Model of elementary particles, as shown in Fig. 14.5.

The first part of matter particles in the table is quarks, which have a size of roughly 10^{-18} m. Quarks are elementary particles and basic building blocks of meson and baryons, the main constituent of all the matter. Each quark has a corresponding anti-quark with same properties but opposite charge. These quarks combine to form composite particles called hadrons. Quarks can be divided into six flavors (flavors are some properties of the particles) i.e. up, down, charm, strange, top and bottom. All the quarks have half spin (1/2).

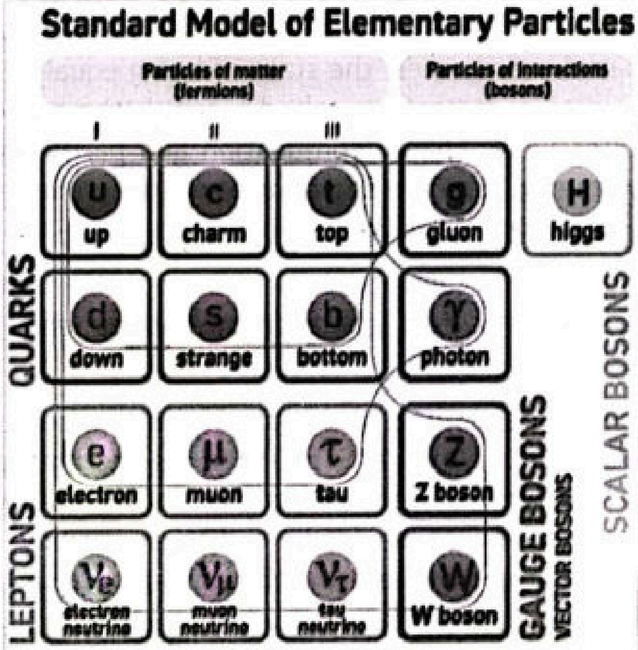


Figure 14.5: The standard model of particles.

1. **Up Quark:** These are the lightest among all the quarks that is why they are the most stable among all the six quark flavors. Their mass ranges from 1.7-3.1 MeV/c^2 and has a charge of +2/3e (two-third of charge of an electron). They are denoted by 'u' and anti-up quark is denoted by '$\bar{u}$'. It is first generation quark.
2. **Down Quark:** These are heavy than the up quark but lighter than rest of all quarks. Due to small mass, they are highly stable particles. Their mass ranges from 4.1-5.7 MeV/c^2 and their charge is one-third of that of an electron (-1/3 e). They are denoted by 'd' and their counterpart anti-down is denoted by '$\bar{d}$'. It is first generation quark.
3. **Charm Quark:** These quarks have a mass about 1280 MeV/c^2. It is hundreds of times more massive than the up and down quarks. It is the second generation of quarks. They have a charge +2/3e. It is denoted by 'c' and its anti-charm quark is denoted by '$\bar{c}$'.
4. **Strange Quark:** These quarks have a mass about 96 MeV/c^2. It is the second generation of quarks. They have a charge -1/3e. It is denoted by 's' and its anti-strange quark is denoted

by '$\bar{s}$'. They have very long life even they can live 100,000 times longer than the similar particles.

5. **Top Quark:** These quarks are the heaviest among all the quarks and have a mass about 173.1 GeV/c^2. It is the third generation of quarks. They have a charge +2/3e. It is denoted by 't' and its anti-top quark is denoted by '$\bar{t}$'. It is not a stable particle even it decays before it has an opportunity to form hadronic bound states.
6. **Bottom Quark:** These quarks have a mass about 4.18 GeV/c^2. It is the third generation of quarks. They have a charge -1/3e. It is denoted by 'b' and its anti-bottom quark is denoted by '$\bar{b}$'. Bottom quark decays mostly into a charm quark but rarely into an up quark.

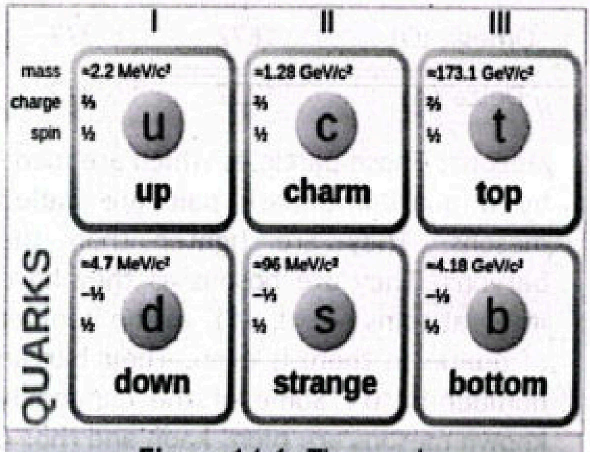


Figure 14.6: The quarks.

The quarks are shown in figure 14.6. Another property of quarks and gluons is the color charge, which is related to particle's strong interaction in the theory of quantum chromo dynamics (QCD). Quantum chromo dynamics is the model which governs the behavior of quarks. This color property is totally different from common meanings of color in everyday life. Quarks can be found in three color charges i.e. the red, the blue and the green along with the three anti color quarks i.e. the anti-red, the anti-blue and the anti-green.

14.4.1 Hadrons:

The subatomic particles which are made up of quarks and anti-quarks held together by the strong force with the help of gluons are called hadrons. They are the heaviest particles. As we studied that quarks have fractional charges, but hadrons which are made up of quarks have integer charges.

Some examples of hadrons include kaons, protons, neutrons, anti-protons and anti-neutrons. Hadrons experience strong nuclear force. Properties of hadrons are as follow:

- They carry no net color charge, although their constituent particles quarks to carry colour charge.
- Hadrons are unstable particles and they can decay. Only hadron which is stable even in free-state is the proton while the neutron is stable only within the nucleus.

Due to participating quarks, hadrons are mainly divided into two groups i.e. baryons and mesons.

1. **Baryons:** Those particles which are approximately equal in mass to that of a proton or greater are called baryon. These hadrons are made up of three quarks and are classified as fermions, as they have half integer spin due to the odd number of quarks. Proton and neutron are well known baryons. A quantum number which is equal to the number of baryons minus the number of anti-baryons in a system of subatomic particles is called 'baryon

number'. Baryons have a baryon number +1 while anti-baryons have a baryon number of −1. Some baryons along with their properties are listed in the Table 14.2.

Table 14.2: Some baryons with their properties.

Particle	Rest Mass (GeV/C^2)	spin	Electric charge	Quarks Composition	Baryon Number	Lepton Number
Proton (p)	938.3	1/2	+1	$u\ u\ d$	+1	0
Neutron (n)	939.6	1/2	0	$d\ d\ u$	+1	0
Omega (Ω)	1672	3/2	-1	$s\ s\ s$	+1	0
Delta (Δ)	1232	3/2	+2	$u\ u\ u$	+1	0

2. **Mesons:** Those particles which are made by a quark-antiquark pair are called mesons. They are lighter than the baryons. They are bosons as they have integral spins (-1, 0, +1), as the number of quarks in them is even. Their baryon number is '0'. Some of the commonly known mesons are pion, kaon and rho. A typical Baryon and a meson are shown in Fig. 14.7. Some of mesons along with their properties are listed in the Table 14.3.

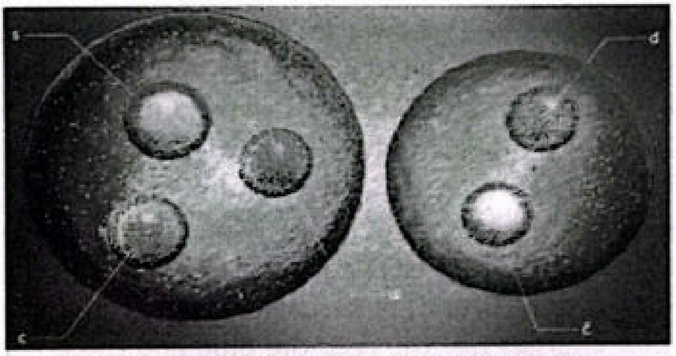


Figure 14.7: Left (Baryon), right (Meson).

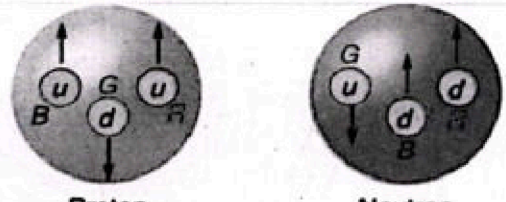
Table 14.3: Some mesons with their properties.

Particle	Rest Mass (GeV/C^2)	spin	Electric charge	Quarks Composition	Baryon Number	Lepton Number
Pion$^+$ (π^+)	0.140	0	+1	$u\ \bar{d}$	0	0
Kaon$^-$ (K^+)	0.494	0	-1	$s\ \bar{u}$	0	0
Kaon^0 (K^0)	0.498	0	0	$d\ \bar{s}$	0	0
Rho$^+$ (ρ^+)	0.770	1	+1	$u\ \bar{d}$	0	0

14.4.2 Composition of Proton and Neutron

Protons and neutrons are made up of quarks. A proton is made up of two up quarks and one down quark. As we know that up quark has a charge of (+2/3)e and down quark has a charge of (-1/3)e. By adding the charge of these three quarks we get +1e charge for a proton, i.e., (+2/3 +2/3-1/3 = +1). Similarly, the anti-proton consists of the anti-quarks of the same type. A proton in terms of color charge consists of a blue-up, a red-up and a green-down quark. The composition of both proton and the neutron along with type and color charge is shown in Fig. 14.8.

Similarly, a neutron is made up of two down quarks and one up quark. Both down quarks have a charge of (-1/3)e and one up quark have a charge of (+2/3)e. By adding the charge of these three quarks we get '0' charge for a neutron, i.e. (+2/3 -1/3 - 1/3 = 0). Similarly, the anti-neutron consists of the anti-quarks of the same type. A neutron in terms of color charge consists of a blue-down, a red-down and a green-up quark. The composition of both the proton and the neutron, along with their counter anti-particles i.e., the anti-proton and the anti-neutron is shown in Fig. 14.9.



	Proton	Neutron
Spin	$\frac{1}{2}+\frac{1}{2}-\frac{1}{2}=\frac{1}{2}$	$-\frac{1}{2}+\frac{1}{2}+\frac{1}{2}=\frac{1}{2}$
Charge	$+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=1$	$+\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$

Figure 14.8: Composition of proton and neutron.

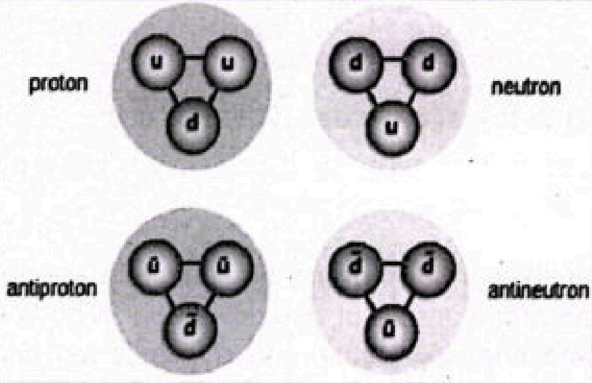


Figure 14.9: Composition of the anti-proton and the anti-neutron.

For Your Information

In electromagnetic force, charge is the basic property that allows a particle to experience this force. Neutral particles cannot experience the electromagnetic force. Similarly, in the strong interactions of the strong nuclear force (color force), color is the basic property of a particle to experience this force. A colorless particle cannot feel the strong nuclear force. This property is sometime referred as 'color charge'. There are three color charges i.e. red, blue and green and three anti-color charges i.e. anti-red, anti-blue and anti-green.

14.4.3 Change in Quarks during Beta Decays

As we have studied in topic 14.2.1 that whenever a proton decays into a neutron or a neutron decay into a proton, these processes are called beta decay. We now need to study how quarks change their types during these decays.

1) Beta-positive Decay: In this decay, a proton is converted into a neutron, a positron (β^+) and a neutrino. This decay can be represented by equation 14.2, as:

$$p^+ = n + e^+ + \nu_e$$

In above relation, only two particles are made up of quarks i.e. the proton and the neutron. A proton consists of two up-quarks and one down-quark, while a neutron consists of two down-quarks and one up-quark. So, in this reaction one of the up-quark turns into a down-quark with production of weak boson W^+, which is very short lived and soon decays into a positron and a neutrino due to the weak interaction. Beta positive decay, when an up-quark turns into a down-quark is shown in Fig. 14.10.

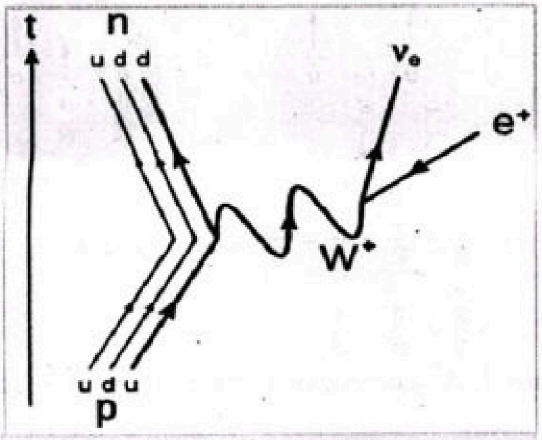


Figure 14.10: Beta-positive decay.

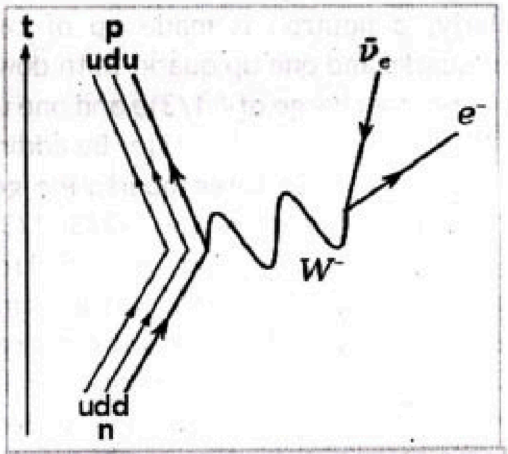


Figure 14.11: Beta-negative decay.

2) Beta-negative decay: In this decay, a neutron is converted into a proton, an electron (β^-), and an anti-neutrino. This decay is given by equation 14.1, as:

$$n = p^+ + e^- + \bar{\nu}_e$$

In above relation, only two particles are made up of quarks i.e., the proton and the neutron. A neutron consists of two down-quarks and one up-quark, while proton consists of two up-quarks and one down-quark. In this reaction one of the down-quark turns into an up-quark with production of a weak boson W⁻, which is very short-lived and soon decays into an electron and an anti-neutrino due to the weak interaction. Beta negative decay, where a down-quark turns into an up-quark, is shown in Fig. 14.11.

14.5 LEPTONS

In the standard model of particle physics, the second group of matter particles is lepton. Leptons are also elementary particles; they are not composed of other particles. Leptons can have a unit positive, unit negative electric charge or may be neutral. The smallest lepton is the electron, which is most stable among all leptons. Other leptons, such as muon and tau exist only at high energy collisions and lasts for a very short period.

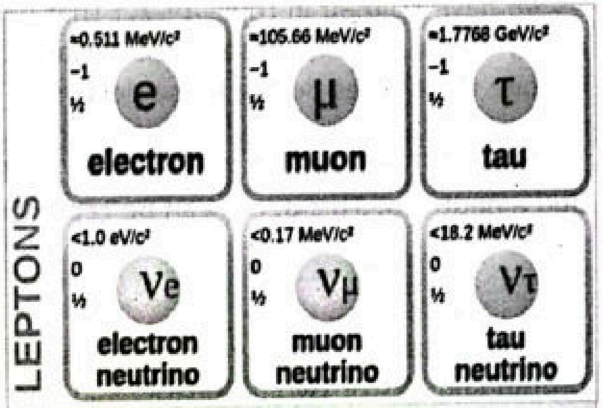


Figure 14.12: Leptons.

Leptons have spin ½ and do not take part in strong interactions. The strong nuclear force is blind for leptons. Leptons cannot be found within nucleus or nucleons; rather if they produced in nucleus, they escape with large kinetic energies. Just like baryon number, the lepton number is also a concept in particle physics. A lepton number is a conserved quantum number. For leptons this number is '+1' while for anti-leptons its value is '-1'. For any reaction, this number can be calculated as difference between the number of leptons and the number of anti-leptons. Some leptons and their properties are given in the Table 14.4.

Table 14.4: Leptons with their properties.

Particle	Rest Mass (MeV/C^2)	spin	Electric charge	Baryon Number	Lepton Number
Electron) e^-	0.511	1/2	-1	0	+1
Muon (μ)	105.66	1/2	-1	0	+1
Tau (τ)	1776.8	1/2	-1	0	+1
Electron neutrino (ν_e)	<1.0 (eV/C^2)	1/2	0	0	+1
Muon neutrino (ν_μ)	<0.17	1/2	0	0	+1
Tau neutrino (ν_τ)	<18.2	1/2	0	0	+1

14.5.1 Conservation Laws of Lepton and Baryon

Like conservation laws of mass, energy, momentum and charge in physics, we need some other conservation laws like the lepton-number conservation and the baryon-number conservation. Every particle interaction should necessary be according to these laws of conservations. The interaction which is not satisfying any of these laws cannot take place in real world. The law of conservation of lepton-number says that

The lepton-number of reaction on both sides should essentially be same.

Similarly, the law of conservation of baryon-number says that

The baryon-number of reaction on both sides should essentially be same.

Example 14.2: Show that the beta-positive decay and the beta negative decay satisfy the laws of conservation of charge, lepton-number and baryon-number.

Given: Beta negative decay: $n = p^+ + e^- + \overline{\nu}_e$ Beta positive decay: $p^+ = n + e^+ + \nu_e$

To Find: charge , lepton-number and baryon-number are same on both sides.

Solution:

For law of conservation of charge: As we know that charge on each particle is.

$n = \nu_e = \overline{\nu}_e = 0$ $p = e^+ = +1$ $e^- = -1$

Beta negative decay: $0 = (+1) + (-1) + (0)$ $\Rightarrow$ $0 = 0$ Satisfied.

Beta positive decay: $+1 = (0) + (+1) + (0)$ $\Rightarrow$ $+1 = +1$ Satisfied.

For law of conservation of lepton-number: As we know that lepton number of each particle is. $n = p = 0$ $e^+ = \overline{\nu}_e = -1$ $e^- = \nu_e = +1$

Beta negative decay: $0 = (0) + (+1) + (-1)$ $\Rightarrow$ $0 = 0$ Satisfied.

Beta positive decay: $0 = (0) + (-1) + (+1)$ $\Rightarrow$ $+1 = +1$ Satisfied.

For law of conservation of baryon-number: As we know that baryon number of each particle is. $n = p = +1$ $e^+ = \overline{\nu}_e = e^- = \nu_e = 0$

Beta negative decay: $+1=(+1)+(0)+(0) \Rightarrow +1=+1$ **Satisfied.**

Beta positive decay: $+1=(+1)+(0)+(0) \Rightarrow +1=+1$ **Satisfied.**

As all the basic conservation laws of particals are satisfied, hence beta-positive and beta-negative decays are real.

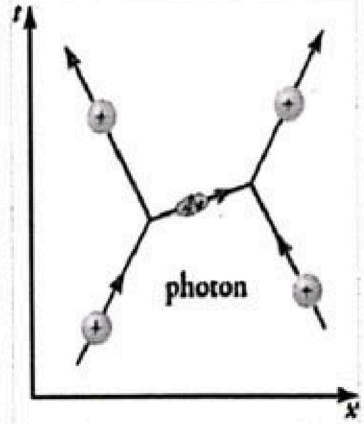
Assignment 14.2

Show that the particle reactions given below satisfy the laws of conservation of energy, charge, lepton- number and baryon-number.

i) $\pi^- + p = \pi^0 + n + \pi^- + \pi^+$ ii) $\mu^+ = e^+ + \nu_e + \overline{\nu_\mu}$

Point To Ponder

Hideki Yukawa introduced the quantum idea of fields (which is studied in quantum field theory QFT). He proposed that the nuclear forces are transmitted by the exchange of particles called "mediators or carrier particles". Later, we found carrier particles for all natural forces. A fermion (matter particle) produces a boson (force carrier) which is absorbed by another fermion to exert force on each other. The interaction between two approaching protons' repulsion by exchanging a photon (force carrier for electromagnetic interaction) is shown here by the Feynman diagram.



14.6 FORCE CARRIERS

In standard model of particle, there is a group of particles which do not make the matter but they are responsible for binding matter together. The interactions between matter-particles are mainly due to four types of fundamental forces i.e. the strong nuclear force, the weak nuclear force, the electromagnetic force and the gravitational force. Each force interacts through the exchange of particles called 'force carriers' or 'mediators'. The force carriers, are shown in Fig. 14.13, and are given in detailed below.

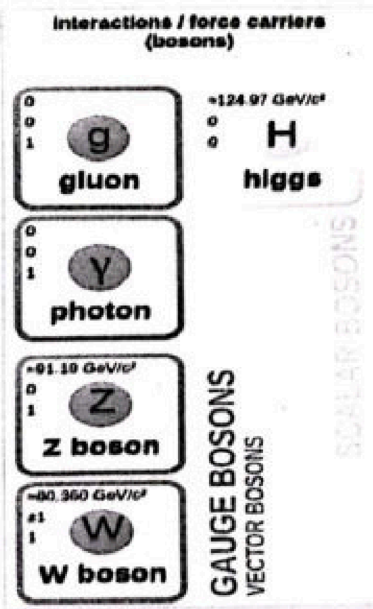


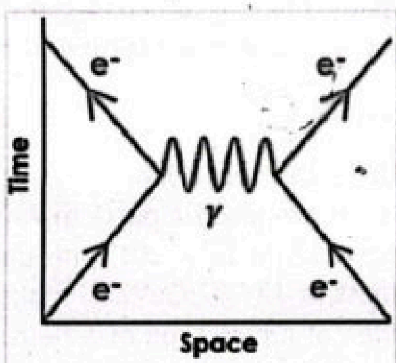
Figure 14.13: Force carriers.

14.6.1 The Photon

In interactions involving electromagnetic force, the exchange particle is photon. A photon is the smallest quantum of electromagnetic radiation and is the basic unit of light. Photons can travel through vacuum with a speed of $3\times10^8\ m\ s^{-1}$. According to Max Planck, the energy of photon is the product of its oscillation frequency and the Planck's constant, expressed as:

$$E = hf \quad (14.5)$$

Photons have zero rest mass energy; they exist only as moving particles. They are neutral and stable particles. They have a spin of '1' hence belong to the boson family. They are also elementary particles which have energy, momentum and frequency of oscillations. According to quantum field theory, they are exchanged between the charged particles when they exert electromagnetic force on each other. Hence, they are the mediators of electromagnetic force, as shown in Fig. 14.14, where two approaching electrons (shown in blue color) repel each other (shown in red color) by exchanging a photon. During electromagnetic interactions every photon is emitted by one charged particle and absorbed by the another, so photon carries the electromagnetic force in this context.



$e^- + e^- \rightarrow e^- + e^-$

Figure 14.14: Photons mediators of electromagnetic force.

14.6.2 The Gluon

A particle that is exchanged between quarks to bind them together to form particles like protons and neutrons is called gluon.

Gluons are massless particles, travel at the speed of light and are vector boson, meaning they have a spin of 1. They are the exchange particles for the color force (the strong nuclear force). Like quarks, gluons also exhibit the property of color. During strong interactions, one quark or anti-quark emits a gluon and other anti-quark or quark absorbs the gluon; hence they are called the quanta of strong force. The gluons are capable of exchanging color for conservation of color charge. They have no electric charge. The exchange of a gluon between two quarks is shown in Fig. 14.15.

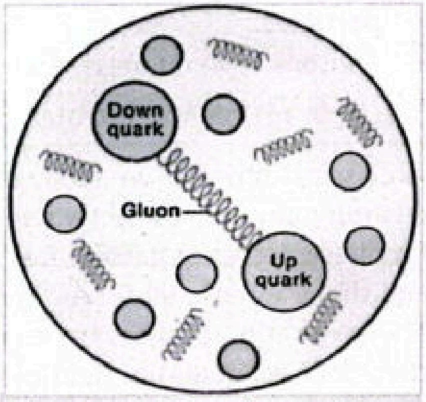


Figure 14.15: exchange of gluon between two quarks.

14.6.3 The Z-Boson

Z-boson was discovered in 1983 at CERN. Z-boson is electrically neutral and has its own anti-particle. It has a mass of 91.19 GeV/c^2, which is nearly hundred times that of the proton, making it one of the heaviest elementary particles. Bosons are very short-lived particles, with a lifetime of order of 10^{-25} seconds. It is the carrier of the weak nuclear force and is a partner to W^+ and W^- bosons, that mediate radioactive decay processes. In weak interactions, W and Z bosons interact with each other as well as with quarks and leptons.

14.6.4 The W-Boson

W-bosons found in two different charge compositions i.e. W^+ and W^-. They can have both positive and negative electric charges. W and Z are gauge bosons that mediate the weak nuclear force. They have a mass of 80.360 GeV/c^2 and 91.2 GeV/c^2 and spin 1. They are responsible for many nuclear processes such as the reactions that power stars. They are very short-lived particles, with a lifetime of order of $3x10^{-25}$ seconds. They do not have their anti-particles.

14.6.5 The Higgs Boson

Up to the year 1964, the mass of a particle was considered as intrinsic property. In 1964, Peters Higgs proposed a particle which is responsible for the mass of matter, which he called it Higgs particle. In July, 2012 this particle was experimentally confirmed at CERN. Higgs particle has a mass of 124.97 GeV/c^2, making it 130 times more massive than a proton. Peter Higgs gave the idea of a new type of a field, called the Higgs field that fills the universe and gives mass to all elementary particles. It is a scalar field and the Higgs boson is a wave in that field. It has a zero spin, zero electrical charge and no strong force interactions.

All the above four particles were gauge bosons that is a form of force carrier, while Higgs boson is an elementary particle which is produced due to quantum excitation of Higgs field.

- Quarks interact strongly with the Higgs field, gaining relatively large mass.
- Electrons (lepton) interact only slightly with the Higgs field, making them extremely light particles.
- Photons have no mass, and hence do not interact with the Higgs field.

14.6.6 Theories about Generation of Force and Mass

In classical physics, we study only the macroscopic concepts of mass and forces. However, in quantum physics, these two entities have very different meanings. As we know that there are four basic forces of nature, i.e. strong nuclear force, weak nuclear force, electromagnetic force and the gravitational force. Two main theories about the force generation are discussed here. The generation of mass, as explained above involves Higgs field. For force we have two main theories i.e., quantum field theory and the string theory.

Quantum Field Theory (QFT):

Quantum field theory is a set of physical principles that combine the elements of quantum mechanics with the theory of relativity to explain the behavior of sub atomic particles and their interactions due to a variety of force fields. Three different quantum field theories address three of the four fundamental forces in nature. Matter interacts through these forces. Electromagnetism explains how atoms hold together, strong nuclear force explains the stability of nucleus and the weak nuclear force explains why some atoms undergo radioactive decay. QFT describes the particles as excited states of quantum fields, which are more fundamental than particles themselves. Interaction between the particles is basically an interaction between the fields. Each interaction can be represented by a Feynman diagram. Similarly, according to QFT, mass is not the strength of attraction of two bodies or the quantity of matter; rather, it is the tendency of an object to resist changes in its speed and position. In precise, at the smallest level, everything is made up of some entities or fluid-like substance call quantum field. This field sometimes behaves like particles, sometimes like waves, and they can even interact with each other.

String Theory:

String theory suggest that, the whole universe is made up of tiny vibrating strings. These strings are smaller than the smallest particles. These strings can twist, vibrate and fold. By twisting, folding and vibrating they create matter, energy and forces. Phenomenon such as electromagnetism and gravity arise from these strings. This theory replaces point-like particles to one dimensional string. According to this theory strings have characteristics like charge and mass and the characteristics of strings are controlled by their vibrations. According to string theory, the matter composition is shown in Fig. 14.16.

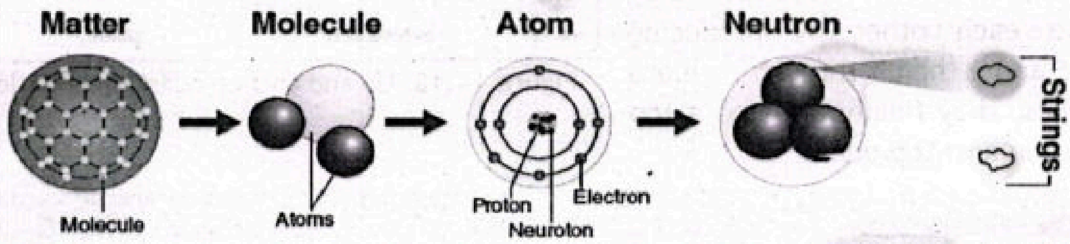


Figure 14.16: Composition of matter according to string theory.

14.7 PARTICLE ANNIHILATION

Einstein's famous mass-energy equation indicates that mass can be converted into energy and vice versa. As we studied earlier, that soon after Big Bang matter and anti-matter were formed. What will happen if matter comes close to its anti-matter? They annihilate each other and convert their mass into energy in accordance with Einstein's mass-energy equation. A particle and its anti-particle cannot exist in the same place, because when they come close to each other, they annihilate each other. After annihilation process, the product is the energy in the form of gamma ray photons. If an electron and a positron come in a close proximity, they annihilate each other and forms two gamma ray photons.

$$e^- + e^+ \rightarrow \gamma + \gamma$$

Production of two photons is necessary in this reaction to conserve the momentum of the system. The annihilation of electron-positron is shown in Fig. 14.17. The above reaction of annihilation is that in which the product is energy, but this energy can further be converted into matter particles, in Large Hadron Collider at CERN and Tevatron at Fermi-Lab, the energy from such annihilations has been converted into matter particles which were previously undiscovered.

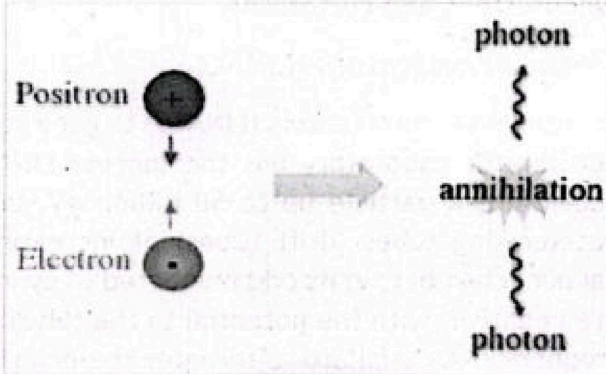


Figure 14.17: Electron-positron annihilation.

14.7.1 Annihilation of Matter into Matter

Annihilation not only gives us energy by totally destroying the particles, but it can also produce some new particles. If quarks with their own flavored anti-quark come close to each other, they annihilate each other, producing energy and a new pair of quark and anti-quark. The annihilation of an up quark and an anti-up quark is shown in Fig. 14.18, in which at first, they annihilate each other by producing energy, and then through gluons interactions, they finally produce a top quark and an anti-top quark.

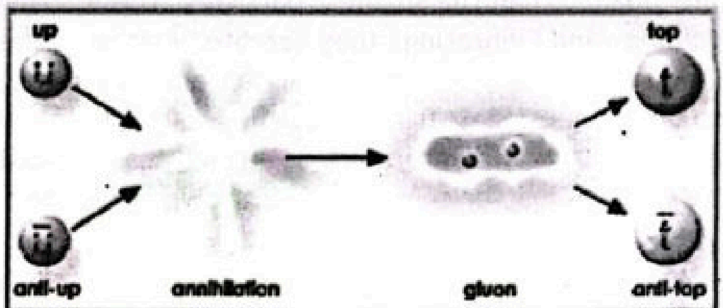


Figure 14.18: Up and anti-up quark annihilation.

For Your Information

Resistive plate chamber (RPC) is a particle detector widely used in high energy physics for muon's detection. It is relatively new and has become standard technology. It is known for very high detection efficiency (>95%), excellent sub-nanosecond time resolution, high counting rates and relatively low cost. This detector is easy to build, covers large areas and is extensively used in nuclear facilities like BESIII, ALICE and CMS at CERN. It operates on the principle of ionizing a gas when particles traverse through it.

14.8 PARTICLE ACCELERATORS

In High Energy Physics (Particle Physics), we need to accelerate particles to very high speeds to study their behavior at high energies. We use to collide these high energy particles to produce new particles. For such high energies to achieve, we need projectiles that can accelerate the particles to higher velocities. The instruments used to accelerate the particles up to a desired speed and energy are called accelerators. There are two basic types of particle accelerators i.e. linear accelerators and circular accelerators, including synchrotrons and cyclotrons.

Linear Accelerators (LINACS)

We use linear accelerators (LINACS) to get a steady, intense beam of particle. The SLAC National Accelerator Laboratory has the longest LINAC in the world, which is 2 miles long and can accelerate a particle up to 50 billion eV. Linear accelerators consist of a set of cylindrical accelerating tubes (drift tubes) of increasing length which are connected alternately in a vacuum chamber. In its odd numbered of cylinders are positive and even numbered of cylinders are negative, with the potential to the tubes reversing periodically according to the oscillating frequency. An oscillator alternates the polarity of the tubes. An ion source is used to produce ions which are to be accelerated. An accelerated beam of charge particles leaves the drift tubes and moves towards the target. A schematic diagram of a linear accelerator is shown in Fig. 14.19.

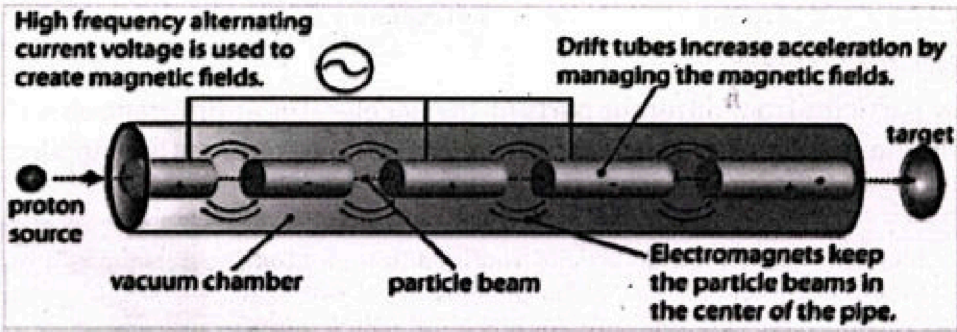


Figure 14.19: Linear accelerator.

Synchrotron Accelerators

Synchrotron accelerators, also called the 'heavy lifters', are circular accelerators. These are the highest energy accelerators in the world. These accelerators have a closed pathway that moves particles in a ring.

When a particle enters the accelerator it moves repeatedly in the circular path, which is enclosed in a vacuum pipe. Radiofrequency cavities at intervals around the ring increase their speeds. Several magnets create electromagnetic fields to bend the particles' path. The maximum energy obtained by the synchrotron accelerator is 13.6 TeV which was produced during the proton collision in the Large Hadron Collider (LHC) at CERN.

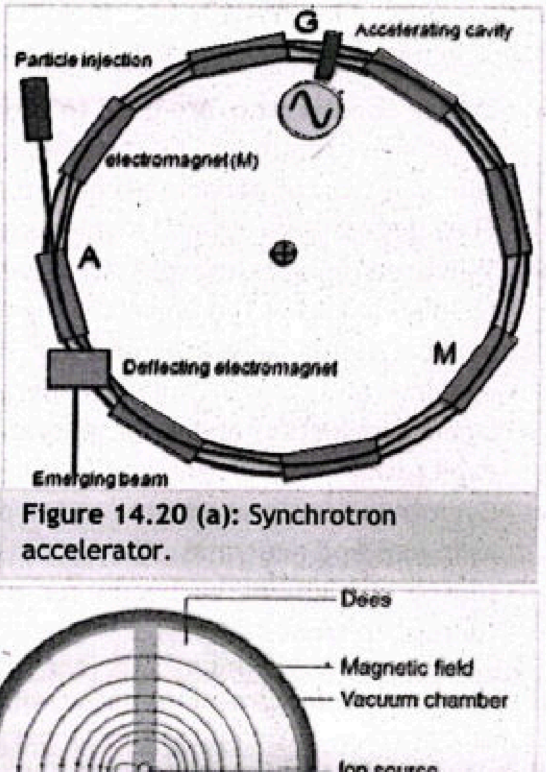


Figure 14.20 (a): Synchrotron accelerator.

Researchers send different beams to collide at required energy at fixed points, where particle detectors (like Compact Muon Solenoid CMS) are positioned to detect the particles produced by these collisions. Synchrotron accelerators are used to study the basic building blocks of the universe. Synchrotron accelerators like LHC can accelerate heavy ions and nuclei like lead. At RHIC accelerator in USA, the heavy ions like uranium and gold to create quark-gluon plasma. A schematic diagram of a synchrotron accelerator is shown in Fig. 14.20 (a).

Cyclotron Accelerators

Cyclotron accelerators, accelerate the particles in a spiral pattern, starting from the center of spiral. They use one large electromagnet to bend the path of particles. To move particles in increasing larger circles, they use metal electrodes. Cyclotrons can accelerate particles to 520 million eV. Cyclotron accelerators consist of two circular metal boxes called 'dees', which are separated from each other

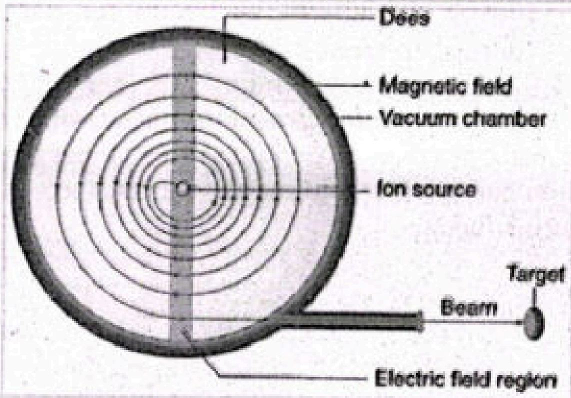


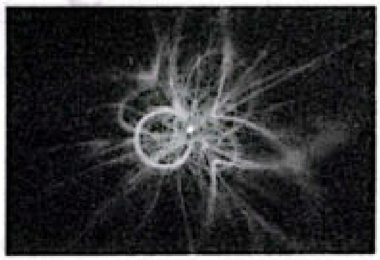
Figure 14.20 (b): Cyclotron accelerator.

and connected to a radiofrequency oscillator of frequency 10^7 Hz, and alternating potential of 10 kV is applied between dees.

They can draw particles from different parts of the accelerator at different energies. Source of ion is placed in the middle from which ions move outward in spiral path in applied electric and magnetic fields.

Particle Physics and Early Universe

Just like at very high energies, electrons are not confined to their atoms i.e., electrons and ions are found in plasma state. Similarly, at very high energies, the baryonic matter gets the same plasma state called quark-gluon plasma, the high temperature soup that made up the universe just after the Big Bang. In this state of baryonic matter, quarks and gluons are no longer confined to each other by the strong force. Instead, they become free from their mutual attraction.



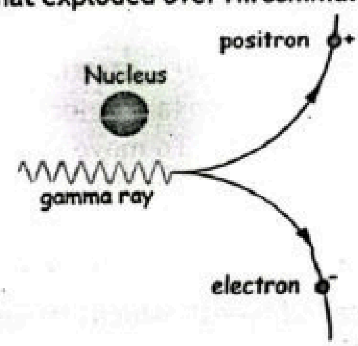
14.8.1 Uses of Particle Accelerators

Particle accelerators are not only used for scientific research but they can also be used in various other field of daily life, including medical field. Some uses of particle accelerators are listed below:

- **Linear accelerators** are used to produce medical isotopes, and create beams of radiations for cancer treatment. Electron linear accelerator (LINACS) for cancer therapy is the most common type of particle accelerator. It serves as injectors for higher energy accelerators. They generate x-rays and high energy electrons for radiation therapy.
- **Synchrotron accelerators** are used to produce high energy environment to study the building blocks of the universe. Higgs boson was discovered using these accelerators. In the medical field, they are used for studying cell biology, crystallography, high resolution imaging, and cancer radiation therapy. In environmental sciences they use in toxicology, clean combustion and atmospheric research. They are also used in agriculture, mineral exploration, engineering and forensics.
- **Cyclotron accelerators** are used to produce large number of certain types of particles, such as muons and neutrinos. They are also used to produce medical isotopes. They are the best source of high-energy beams for particle physics experimentation. They use in particle therapy to treat cancer.

For Your Information

If 1 kg of anti-matter came into contact with 1 kg of matter, the resulting explosion would be equivalent to 43 megatons of TNT or about 3,000 times more powerful than the bomb that exploded over Hiroshima. Even one gram of anti-matter can produce an explosion of the size of a nuclear bomb.



Example 14.3: A 3.0 MeV photon interacts with a lead nucleus and creates an electron-positron pair. The pair moves perpendicular to the initial direction of travel of the photon. (a) Find the kinetic energies of the electron and positron, assuming the nucleus is at rest after the collision. (b) Find the kinetic energy of lead nucleus to ensure momentum conservation. Would

this amount of K.E greatly affect the results in part (a)? The mass of lead atom is 193007 MeV.

Given: $E_{photon} = 3\ MeV \qquad m_{Lead} = 193007\ MeV$

To Find: (a) Kinetic energy of electron: $E_{electron} = ?$

Kinetic energy of positron: $E_{positron} = ?$

(b) Kinetic energy of lead nucleus: $E_{nucleus} = ?$

Solution: (a) According to law of conservation of energy (ignoring energy of nucleus):

$$E_{photon} = E_{electron} + E_{positron}$$

$$3\ MeV = E_{electron} + E_{positron} \quad \text{-------(1)}$$

Now the y-component of momentum (ignoring nucleus):

$$0 = -pc_{electron} + pc_{positron} \qquad \text{or} \qquad pc_{electron} = pc_{positron}$$

As the pair have equal momentum, they must have equal energy. Hence equation (1) gets the form:

$$E_{electron} = E_{positron} = E$$

$$3\ MeV = 2E$$

Energy of either of the pair is: $\qquad E = \frac{3}{2} MeV = 1.5 MeV$

The rest mass energy of each particle is 0.511 MeV, hence:

$$K.E = (1.5 - 0.511)\ MeV$$

$$K.E_{electron} = K.E_{positron} = 0.989\ MeV$$

(b) To ensure x-component of momentum to be conserved (as positron and electron are moving in y-direction):

$$pc_{photon} = pc_{nucleus}$$

$$3MeV = pc_{nucleus}$$

Using: $\qquad E_{nucleus} = \sqrt{(pc)^2 + (mc^2)^2}$

Putting values: $\qquad E_{nucleus} = \sqrt{(3MeV)^2 + (193007MeV)^2}$

$$E_{nucleus} = 193007MeV\sqrt{1 + \frac{9}{(193007)^2}}$$

Using the binomial expansion, we get:

$$E_{nucleus} = 193007MeV\left(1 + \frac{1}{2}\frac{9}{(193007)^2}\right)$$

$$E_{nucleus} = 2.33 \times 10^{-5} MeV \qquad \text{or} \qquad E_{nucleus} = 2.3.3\ eV$$

As the nuclear energy has a very small value, the nucleus can preserve momentum conservation while taking a very small portion of the total energy available. So we can ignore the presence of nucleus while dividing the energy of incoming photon between electron and positron.

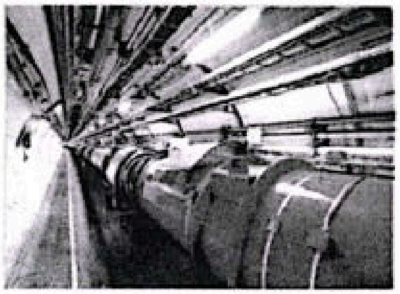
Assignment 14.3

A gamma-ray photon produces an electron-positron pair. If the rest mass energy of electron is 0.51 MeV and the total K.E of the pair is 0.78 MeV, then find the energy of gamma-ray photon in MeV.

PARTICLE PHYSICS

For Your Information

The Large Hadron Collider (LHC) at CERN is the most powerful synchrotron accelerator in the world. It moves the particles like protons and other matter at extremely high-speed close to the speed of light, before colliding them. These collisions produce massive particles like the Higgs boson and the top quark. It has the ability to accelerate particles to energy of 6.5 trillion eV.



SUMMARY

- **Nuclear radiation** includes three types of particles: alpha particle with double positive charge and heaviest among all, beta particle with negative charge and medium mass and the gamma photon which is neutral and massless.
- **Conservation laws** are the universal principles which must be followed during every interaction and decay of particles.
- **Matter and anti-matter** are the two distinct forms of particles, identical in all respects except charge and magnetic moment.
- **Quarks** are the elementary particles which make up all matter in the universe, these are of six types.
- **Hadrons** are the particles which are made up of quarks.
- **Baryons** are the particles which are made up of three quarks, proton and neutron are baryons.
- **Mesons** are the particles which are made up of a quark and an anti-quark, pions are the examples of mesons.
- **Beta positive decay** is the process in which proton converts into a neutron by changing one of its up quarks into down quark, producing a positron and an electron neutrino through the emission of W-boson.
- **Beta negative decay** is the process in which neutron converts into a proton by changing one of its down quarks into up quark, by producing an electron and an anti-neutrino through W-boson.
- **Leptons** are the lightest particles among the fermions; electron and muon are examples of the leptons.
- **Photon, gluon, W and Z bosons** are the force carriers responsible for the exchange of electromagnetic, strong and weak force respectively.
- **Higgs boson** is the particle associated with the Higgs fields which particle interact with to acquire masses.
- **Particle and anti -particle** whenever come close to each other, they annihilate each other by releasing energy or by forming a set of another particle and anti-particle pair.
- **Particle accelerators** are instruments used for accelerating the particle up to very high speed and high energies for research and technology.

EXERCISE

Multiple Choice Questions

Encircle the correct option.

1) Which fundamental conservation principle states that the total number of nucleons (protons and neutrons) remains constant in a closed system?

A. charge B. energy C. nucleon D. momentum

2) According to the principle of charge conservation, in any physical process, the total electric charge before and after the process must?

A. decreases B. increases C. become zero D. becomes neutral

3) In a nuclear reaction, if a nucleus emits an alpha particle (helium nucleus), what happens to the nucleon number (A) of the original nucleus:

A. decreases by 1 B. decreases by 2 C. remains same D. increases by 1

4) During beta-minus (ß-) decay, a neutron is transformed into a proton, emitting an electron (beta particle) in the process. What happens to the total charge during this decay, the total charge:

A. increases B. decreases C. remains same D. becomes neutral

5) Positrons in our atmosphere can be produced during the natural process of:

A. spinning of Earth B. lightning C. Earth's magnetic field D. winds

6) Which type of carrier particle has not been found yet?

A. W-boson B. Z-boson C. pion D. graviton

7) What type of hadron is always constructed partially of an anti-quark?

A. baryon B. lepton C. meson D. photon

8) Analysis of which particles resulted into the search of Higgs boson?

A. W and Z boson B. up and down quark
C. mesons and baryons D. neutrinos and photons

9) Which device is used for proton decay?

A. Cyclotron B. Synchrotron C. super-kamiokande D. Large Hadron Collider

10) Lepton number for 'delta' particle is:

A. -1 B. 0 C. +1/2 D. +1

11) Which particle has a baryon number of +1?

A. muon B. tau C. kaon D. omega

12) The particle which has the color property is:

A. pion B. kaon C. gluon D. proton

Short Questions

Give short answers of the following questions.

14.1 Why does beta-minus (ß-) decay lead to an increase in the atomic number of the nucleus, while beta-plus (ß+) decay results in a decrease in the atomic number?

14.2 Explain how the mass-energy equivalence principle, as expressed by Einstein's famous equation $E=mc^2$, is relevant to understanding the energy release in nuclear processes such as alpha decay.

14.3 How do the principles of nucleon conservation and charge conservation in nuclear reactions reflect deeper symmetries and conservation laws present in the fundamental interactions of subatomic particles?

14.4 Can anti-matter burn? Explain.

14.5 List at least three applications of anti-matter.

14.6 Why are gluons short range exchange particles? Explain.

14.7 Why do gluons interact only with particles in the first two rows of the standard model?

14.8 What are the Feynman diagrams? What information about particles these diagrams give?

14.9 What are the differences between quarks and leptons?

14.10 What advantages do circular particle accelerators have over the linear particle accelerators?

14.11 What is the difference between quantum field theory and the string theory?

14.12 How do we determine if a particle reaction or decay occurs?

Comprehensive Questions

Answer the following questions in detail.

14.1 Explain how the principles of nucleon conservation and charge conservation play a fundamental role in understanding nuclear processes. Provide examples to illustrate the application of these conservation laws in nuclear reactions.

14.2 Describe the process of beta-minus (β^-) decay and beta-plus (β^+) decay. How do these decay processes violate the conservation of nucleon number within a nucleus while still respecting the conservation of charge? How is the energy released during these processes related to the mass difference between the initial and final particles?

14.3 Discuss the nature of gamma radiation in the context of nuclear decay. How is gamma radiation different from alpha and beta particles? Explain how the emission of gamma rays is related to the de-excitation of an excited nucleus and the transition to a lower energy state.

14.4 Discuss the fundamental differences between alpha, beta, and gamma radiation in terms of their origins, properties, interactions with matter, and potential biological hazards. How do these types of radiation impact various applications, such as medical imaging and nuclear energy production?

14.5 What is matter and anti-matter? How did Dirac propose the existence of anti-matter?

14.6 Why is there asymmetry between matter and anti-matter in the known universe?

14.7 Explain the quark family of particles.

14.8 What are hadrons, baryons, mesons and leptons?

14.9 What are the force carriers? Explain.

14.10 What is particle annihilation? Discuss its two cases.

14.11 Explain the particle accelerators. Also, give working of its three types.

14.12 Give in detail the uses of linear and circular particle accelerators.

Numerical Problems

14.1 A uranium-238 nucleus undergoes alpha decay, emitting an alpha particle (helium nucleus) with a mass of 4.00151 atomic mass units (u). Calculate the energy released in this alpha decay process. The speed of light (c) is approximately 3.00×10^8 meters per second, and 1 atomic mass unit (u) is approximately equal to 931.5 MeV/c^2. **(Ans: 4.25 MeV)**

14.2 A carbon-14 nucleus undergoes beta-minus (β-) decay, emitting a beta particle (electron) with a negligible mass. Calculate the energy released in this beta-minus decay process. The speed of light (c) is approximately 3.00×10^8 meters per second. **(Ans: 0.17MeV)**

14.3 A nucleus undergoes a gamma decay, emitting a gamma ray photon with energy of 2.00 MeV. Calculate the frequency and wavelength of this gamma ray.

(Ans: 3.02×10^{20} Hz, 9.94×10^{-13} m)

14.4 If the negative solution of Dirac equation is for electron, then prove that the positive solution for same equation is not for a proton of the same momentum.

14.5 Show that the following particle reactions satisfy the laws of conservation of charge, lepton-number and baryon-number.

i) $\pi^- + p = K^+ + K^- + n$ ii) $\pi^+ = \mu^+ + \nu_\mu$

Glossary

Accuracy	The closeness of a measured value to a standard or true value.
Addition Of Vectors	Vectors are added by the head to tail rule, rather than simple algebraic addition.
Adiabatic Process	A thermodynamics process in which no heat enters or leaves the system.
Amorphous Solids	Solids in which constituent particles are arranged in a random manner i.e. irregular structures.
Amps	unit of electric current.
Angular Acceleration	The time rate of change of angular velocity is called angular acceleration.
Angular Displacement	It is the angle of the movement of a body in a circular path.
Angular Momentum	The cross product of position vector and linear momentum.
Angular Velocity	The rate of change of angular displacement.
Antinode	The point of maximum displacement on a Stationary wave.
Artificial Gravity	The rotation of a spaceship about its own axis to produce gravity like effect produced in orbiting space ship to overcome weightlessness.
Atom	The smallest unit of matter.
Average Velocity	The average velocity of an object is its total displacement divided by the total time taken
Baryons	Are the particles which are made up of three quarks like proton and neutron.
Base Quantities	Seven physical quantities such as length, mass, time, electric current, temperature, amount of substance and intensity of light.
Battery	A group of connected electric cells.
Boyle's Law	The volume of a given amount of gas in inversely proportional to the pressure of the gas while temperature is kept constant.
Brittle Materials	Materials which break after the elastic limit and do not go into the plastic region.
Carnot's Theorem	No heat engine can be more efficient than a Carnot's engine operating between the same two temperatures.
Centre of Mass	The point at which all the mass of the body is assumed to be concentrated.
Centripetal Force	The force which bends the straight path of a body into a circular path.
Charles's Law	The volume of a given amount of gas in directly proportional to the temperature of the gas while pressure is kept constant.
Circuit	In electronics, a circuit is a complete circular path that electricity flows through.
Compression	The region of a longitudinal wave where particles are closer than the average.
Conductor	A substance or material that allows electrons, or electrical current, to flow through it.
Conservation Laws	In all natural phenomenon some basic laws are to be conserved like charge, mass-energy, momentum etc.
Conservative Field	The field in which work done along a closed path is zero.
CP-Violation	It is a phenomenon of violation of combined conservation laws of charge and parity by the weak force.
Crest	The portion of a transverse wave above the mean level.
Crystal Lattice	It is the repetition of unit cells in a crystal.
Crystalline Solids	Solids which have three dimensional regular patterns throughout their body.
Current	The movement or flow of electricity through a conductor.
Cyclic Process	A process which come back to initial state after succession of events.
Cyclotron	A cyclotron is a machine that accelerates charged particles or ions to high energies

Cyclotron Accelerators	These are devices to accelerate the atomic sized particles in spiral path.
Damping	A process whereby energy is dissipated from the oscillatory system.
Deformation	The change in shape, length or volume of a body subjected to a force is called deformation.
Denser Medium	The medium which has greater density, like solids.
Derived Quantities	The physical quantities defined in terms of base quantities.
Destructive Interference	The interference between two waves when they are out of phase i.e. 180 degree phase difference.
Diffraction	Bending of light around obstacles.
Dimension	A measurable extent of a particular kind, such as length, breadth, depth, or height.
Displacement	The Directed change in the position of a body from its initial position to its final position.
Doppler Shift	The apparent change in the frequency of a wave due to relative motion of source and observer.
Drag Force	A retarding force experienced by an object moving through a fluid.
Drift Velocity	The average velocity with which free electrons drift towards the positive end of the wire in the presence of external electric field is known as drift velocity.
Ductile Materials	Materials which goes into plastic region before breakage.
Elastic Collision	The interaction of two or more bodies in which both momentum and kinetic energy conserve.
Electric Potential	Electric potential is the work done per unit charge to bring the charge from infinity to a point in an electric field.
Electricity	The flow of electrons.
Electron	A negatively charged particle that orbits the nucleus of an atom. The flow of electrons produce electricity.
Energy	The ability to do work.
Entropy	It is the measure of disorder of the system.
Entropy	A thermodynamic quantity representing the unavailability of a system's thermal energy for conversion into mechanical work, often interpreted as the degree of disorder or randomness in the system.
Equilibrium	The condition of a system when neither its state of motion nor its internal energy state tends to change with time.
First Condition of Equilibrium	When the body has zero linear acceleration.
First Law of Thermodynamics	When heat (Q) is added to the system it increases the internal energy (U) of the system plus work (W) is done by the system.
Force Carriers	These are the particles which carry anyone of the natural forces.
Forced Oscillations	The oscillations of a body subjected to an external force.
Free Oscillations	The oscillation of a body or system with its own natural frequency and under no external influence other than the impulse that initiated the motion.
Freely Falling Body	A body moving under the action of gravity only.
Gay Lussac's Law	The pressure of a given amount of gas in directly proportional to the temperature of the gas while volume is kept constant.
Geo-Stationary Satellite	The satellite whose orbital motion is synchronized with the rotation of the Earth.
Gluon	It is the mediator for strong nuclear force.
Hadrons	The subatomic particles which are made up of quarks.
Harmonics	An overtone accompanying a fundamental tone at a fixed interval, produced by vibration of a string, column of air, etc.
Heat	The amount of thermal energy in a system.

Heat Engine	It is a device which converts heat energy into the mechanical energy.
Higgs Particle	It is a vector boson which has the field called Higgs's field, particles acquire their mass by the interaction with this field.
Ideal Fluid	An ideal fluid is a fluid that is incompressible and no internal resistance to flow (zero viscosity).
Impulse	The product of force and time for which it acts on a body.
Inelastic Collision	The interaction in which kinetic energy does not conserve, however total energy and momentum remains conserved.
Instantaneous Acceleration	The acceleration of a body at a particular instant of time.
Instantaneous Velocity	The velocity of a body at a particular instant of time.
Insulator	Any material that will not allow electricity to easily flow through.
Internal Energy	The energy possessed by the molecules of a body.
Irreversible Process	A process which cannot be retraced in backward direction without bringing change in its surroundings.
Isobaric Process	A thermodynamic process in which the pressure of the system remains constant.
Isochoric Process	A thermodynamic process in which the volume of the system remains constant.
Isothermal Process	A thermodynamic process in which the temperature of the system remains constant.
Kilowatt	A unit for measuring electrical energy.
Kilowatt Hour (Kwh)	One kilowatt of electrical energy produced or used in one hour.
Kinetic Energy	Energy possessed by a body due to its motion.
Laminar Flow	The type of fluid flow in which the fluid travels smoothly or in regular paths.
Leptons	Particles which are light in mass and do not feel the strong nuclear force, like electron and neutrinos.
Linear Accelerators	These are devices to accelerate the atomic sized particles in straight lines for different experiments.
Longitudinal Wave	The wave in which the particles of the medium vibrate parallel to the propagation of the wave.
Magnetic Field	The region around a magnet or region around the current carrying conductor in which magnetic force acts on magnetic material.
Magnetic Flux	The magnetic lines of force passing through area held perpendicular to field lines.
Magnetic Flux Density	The magnetic lines of force passing through a unit area
Magnetic Flux Linkage	It is the product of magnetic flux and number of turns of coil.
Mesons	Particles which are made up of two quarks i.e. a quark and an anti-quark.
Modulus Of Elasticity	The ratio of stress to strain in a body.
Molar Specific Heat at Constant Pressure	Amount of heat required to raise the temperature of one mole of a gas through 1 K keeping the pressure of the system constant.
Molar Specific Heat at Constant Volume	Amount of heat required to raise the temperature of one mole of a gas through 1K keeping the volume of the system constant.
Moment Arm	Perpendicular distance between the axis of rotation and line of action of the force.
Moment of Inertia	A quantity expressing a body's tendency to resist angular acceleration.
Momentum	The product of mass and velocity of an abject.
Node	The point on a stationary wave having zero displacement.
Null Vector	A vector having zero magnitude and arbitrary direction.

Orbital Velocity	The tangential velocity to put a satellite in orbit around the Earth.
Oscillatory Motion	The to and fro motion of an object from its mean position.
Pair Annihilation	Particle and anti-particle when come close to each other annihilate each other by producing energy.
Particle Accelerators	These are devices to accelerate the atomic sized particles.
Periodic Motion	The motion repeated in equal intervals of time.
Permeability	It is the measure of the ability of a material to support the formation of a magnetic field within the material
Phase	A quantity which indicates the state and direction of motion of a vibrating particle.
Photon	It is the mediator for electromagnetic force.
Physical Quantity	The quantity which can be measured.
Physics	The branch of science that describes the motion, energy and their mutual relationship.
Pitch	The quality of a sound governed by the rate of vibrations producing it. The degree of highness or lowness of a tone.
Plane Wave Front	When the small part of the spherical or cylindrical wave front originates from a distant source, then the wave front which is obtained is known as a plane wave front.
Polarization	The orientation of vibration along a particular direction.
Polycrystalline Solids	Solids that have intermediate structure between crystalline and amorphous.
Position Vector	A vector that describes the location of a point.
Potential Difference	It is the difference between the potentials between two points in the electric field.
Potential Energy	Energy possessed by a body due to change in its position in some force field.
Power	The ability or capacity of a body to do work.
Precision	The closeness of measured values to each other.
Progressive Wave	The wave which transfers energy away from the source.
Projectile	An object thrown into the space or air and allowed to move free under the influence of gravity and air resistance.
Quarks	The elementary particles which are the basic building blocks of all the matter.
Radian	The angle subtended at the centre of the circle by an arc length equal to the radius of the circle
Random Error	An error in measurement caused by factors which vary from one measurement to another.
Range of a Projectile	The horizontal distance covered by the projectile from the point where it is launched to the point where it hits the ground at same level.
Rarer Medium	A medium in which speed of light is more and has less density is known as rarer medium.
Rays	Radial lines leaving the point source in all directions.
Rectangular Components	The components of a vector which are mutually perpendicular.
Refrigerator	A device which extract heat from colder body and rejects it into hotter body.
Resistance	The opposition to flow of electricity through a material.
Restoring Force	The force that brings the body back to its equilibrium position.
Resultant Vector	A single vector which has the same effect as all individual vectors may have.
Reversible Process	A process which can be retraced back under same conditions.
Rotational Equilibrium	If a body rotating with constant angular velocity, it has zero angular acceleration and said to be in rotational equilibrium.
Scalar Product	The product of two vectors which gives, as a result a scalar quantity.

Scalar Quantity	A physical quantity that has magnitude only.
Second Condition of Equilibrium	The condition in which a body has zero angular acceleration.
Second Law of Thermodynamics	To extract work from a system two reservoirs at different temperatures are necessary so that heat can flow between them.
Significant Figures	The number of accurately known digits and first doubtful digit are called significant figures.
Simple Harmonic Motion	A motion of a body in which acceleration is directly proportional to displacement from mean position and is always directed towards the mean position.
Solenoid	A solenoid is a coil of insulated or enameled wire.
Spherical Wave Front	When the disturbance is propagated in all directions from a point source.
Static Electricity	An electrical charge built up due to friction between two dissimilar materials.
Stationary Wave	The superposition of two waves of same frequency but moving in opposite direction.
Steradian	The solid angle subtended at the centre of a sphere by an area of its surface equal to the square of the radius of the sphere
Strain	The quantitative measure of deformation in a body.
Strain Energy	The area under the force-extension graph represents the strain energy in the deformed material.
Stress	It is the applied force per unit area of the solid.
Switch	An electrical component used for connecting, breaking, or changing the connections in an electrical circuit.
Synchrotron Accelerators	These are devices to accelerate the atomic sized particles in circular path.
System	A thermodynamic system is the portion of universe under study.
System International	The international agreed system of units used almost over.
Systematic Error	Systematic error is associated with faulty equipment or a flawed experiment design.
Terminal Velocity	Maximum constant velocity of an object falling vertically downward.
Tesla	It is SI unit of magnetic flux density.
Thermal Energy	The energy of a system possessed due average kinetic energy of its molecules.
Thermal Equilibrium	When two systems are at same temperature they are called in thermal equilibrium with each other.
Thermal Equilibrium	The state in which net flow of heat is zero.
Thermodynamic Work	In thermodynamics when gas is the working substance the work is equal to the product of pressure and the change in volume of the system.
Thermodynamics	The study of transfer of heat energy.
Torque	Torque is the twisting force that tends to cause rotation.
Total Internal Reflection	When the angle of incidence increases by the critical angle, then the incident light in spite of leaving the medium is reflected back in the same medium.
Trajectory	The path followed by a projectile.
Translational Equilibrium	A body moving with uniform velocity, hence moving with zero linear acceleration.
Transverse Wave	The wave in which the particles of the medium vibrate perpendicular to the propagation of wave.
Trough	The portion of a transverse wave where the particles are below mean position.
Turbulent Flow	Disorderly and changing flow pattern of fluids.
Uncertainty	The range of possible values within which the true value of the measurement lies

Unit Cell	It is the basic unit of a crystalline solid which has all the properties of the entire crystal.
Unit Vector	A vector of zero magnitude used for the direction.
Vector Product	The product of two vectors that result into a vector quantity.
Vector Quantity	A physical quantity which requires both magnitude and direction for its complete discerption.
Velocity Selector	Velocity selector is a device with a perpendicular arrangement of electric and magnetic fields which is used as a velocity filter for charged particles.
Volt	The unit of measurement of force used to produce an electric current.
W And Z Bosons	They are the mediator for weak nuclear force.
Watt	A unit for measuring electric power.
Wave-Front	A surface over which the phase of the wave is constant.
Wavelength	The distance between successive crests of a transverse wave.
Weber	It is SI unit of magnetic flux.
Work	Work is the energy transferred to or from an object via the application of force along a displacement.

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ABOUT THE AUTHORS

Mr. Naeem Nazeer (Managing Author): Mr. Naeem Nazeer belongs to Jhangar, Mansehra. He has completed M.Phil degree in Physics from FUUAST, Islamabad and M.Ed from AIOU, Islamabad. His specialization is in Medical Physics and Biophotonics, from PIEAS and NILOP Islamabad. He has vast teaching experience at school, college and university level. He is currently teaching at IMCB, I-10/1, Islamabad. He is author and reviewer of many textbooks and helping books. **(For feedback and comments, please feel free to contact at: naeem.alsufa@gmail.com)**

Mr Ajaz Ahmad: He graduated in M.Sc Physics from PU, Lahore. He is an Assistant Professor in Physics at Punjab Group of Colleges. He is author and editor of many Physics books.

Dr. Ejaz Ahmed: Dr. Ejaz Ahmed presently working as Associate Professor/ Head of the Physics department at IMCB, F-8/4 Islamabad. He is Ph.D (Physics) and NBF Author of Physics Textbooks Class 9th & 10th and General Science Textbook for class VI.

Mr. Aamir Ullah Khan: Mr. Aamir Ullah Khan has obtained M.Phil degree in Physics and is currently working as Vice Principal / Associate Professor / Head, Department of Physics at F. G. Degree College (for Men), Peshawar. He is the co-author of physics textbooks for grade 9 to 12 and general science grade 6 to 8.

Mr. Nazir Ahmed Malik: Mr. Nazir Yousaf is from Anga, Soon Valley, Khushab. He is a PhD scholar and previously did M.Phil in Physics from FUUAST, Islamabad. His specialization is in Experimental High Energy Physics from the National Centre for Physics (NCP), Islamabad. He is currently teaching at Fazaia Inter College, Jinnah Camp, PAF Nur Khan Rawalpindi. He is an author of books of Physics, Statistics and General Science. He is reviewer of books of Physics and General Science.

Mr. Ghulam Murtaza Siddiqui: Ghulam Murtaza Siddiqui belongs to Hyderabad, Sindh. He has completed his Master and M.Phil Degree in Physics from QAU, Islamabad. He is currentiy teaching as Associate Professor at IMCB F-10/3, Islamabad.

Dr Humaira Anwar: Dr Humaira Anwar Associate Professor of Physics with 25 years of teaching experience in the field of physics. She did PhD in Material Sciences from NUST and have more than 20 publications in ISI indexed peer-reviewed journals. She has also research experience at Ohio State University (USA). She is recently serving in the education department under FDE Islamabad.