Chapter 12 Nuclear and Particle Physics

Learning Objectives

After studying this chapter, 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 (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 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.]

We believe that all atoms are made up of neutrons, protons, and electrons. The antiparticles of these three particles are also known. The positron (a positive electron), the neutrino, and the photon are also known. By the end of 1960s, many new types of particles similar to the neutron and the proton were discovered. These were called *mesons* whose masses were mostly less than nucleon masses but more than the electron mass. Afterwards, other mesons were also found that have masses greater than nucleons. Physicists started to look for more fundamental particles which must have even smaller constituents which was later confirmed by experiments. These were named as *quarks*. We will discuss in this chapter, the basic building blocks of matter.

12.1 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, whose existence was pointed out in 1932 by James Chadwick, is electrically neutral as its name suggested and its mass is nearly the same as that of proton. Now we can say that 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** represented by the symbol Z. The total number of nucleons, the sum of neutrons and protons, is represented by the symbol A and is called the **atomic mass number**, or simply **mass number**. It is written as

$$A = N + Z \quad \text{..............} \quad (12.1)$$

where N represents the neutron number.

In order to specify the given nuclei, the symbol X is commonly used as $^{A}_{Z}X$, 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 twelveth the mass of carbon-12 atom ($1u = 1.6606 \times 10^{-27}$ kg = 931 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 $^{12}_{6}C$, $^{13}_{6}C$, and $^{14}_{6}C$, amongst them $^{12}_{6}C$ and $^{13}_{6}C$ are stable but $^{14}_{6}C$ is unstable and decays into nitrogen along with the emission of β and neutrino

12.2 FUNDAMENTAL FORCES OF NATURE

To understand the structure of the nucleus, it is important to know the nature of the forces that bind the nucleon together. But before that, we should know the basic forces in nature. Despite the apparent complexity within the universe, all interactions in the universe are governed by the four basic forces, known as fundamental forces. These forces control how objects move, interact and behave at different scales from nucleons in the atom to massive galaxies. The four fundamental forces are gravity, electromagnetism, weak nuclear force, and strong nuclear 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.

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. **James Clerk Maxwell** (1861) formulated a set of four fundamental equations named as "Maxwell's equations" that unified electricity and magnetism into **electromagnetism.** These equations describe how electric and magnetic fields interact and how electromagnetic waves propagate. These equations showed that electric and magnetic fields are not separate forces but are two aspects of a single **electromagnetic force.**

Out of the four fundamental 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. **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

Table 12.1
Relative strength and range of four fundamental forces

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

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 above four forces are given in Table 12.1.

12.3 MATTER AND ANTI-MATTER

It was predicted by Paul Dirac in 1928 that the 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 by Anderson in 1932 in a cloud chamber experiment. This was first experimental discovery of an 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.

Interesting information

For their work on this discovery, Dirac and Anderson received the Nobel Prize in Physics-Dirac in 1933, and Anderson in 1936. In 1955, Segre and Chamberlain discovered anti-proton using a particle accelerator and were awarded the Nobel Prize in physics in 1959 for their discovery of anti-proton.

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.

Pair Production

Pair production occurs when a γ-ray (high energy photon) passes nearby an atomic nucleus. As a result, an electron-positron pair is emitted as shown in Fig. 12.1. 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 $2m_oc^2$ = 1.02 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.

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

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.

Annihilation of Matter

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 as shown in Fig. 12.2. The reaction can be written as

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

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. $E=m_oc^2$. 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.

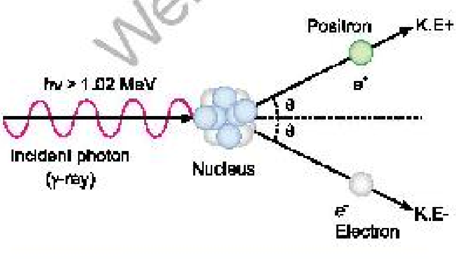


Fig. 12.1: A high energetic photon (γ-ray) interacting with a nucleus and results into an electron and a positron pair.

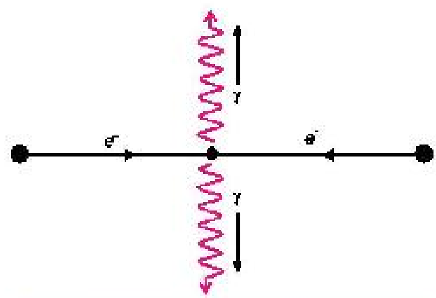


Fig. 12.2: Annihilation of matter

A particle accelerator, named as Large Hadron Collider (LHC) at CERN have revealed that some mass of colliding particles is changed to electromagnetic radiation according to Einstein's equation and left over mass appears in the form of new sub-atomic particles (Fig. 12.3).

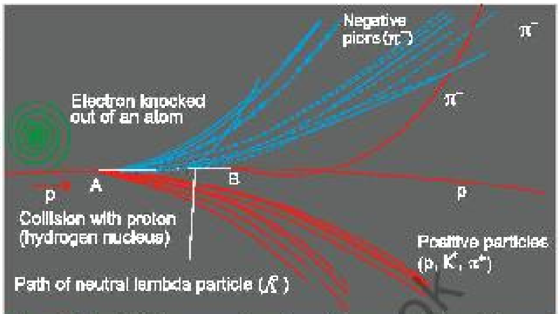


Fig. 12.3: A high energetic $p\bar{p}$ collision producing 18 new particles.

12.4 RADIOACTIVITY

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 radiation. This is called artificial radioactivity and radioactive isotopes are named **radioisotopes** or **radionuclides.**

The α-particles, β-particles and γ-radiations are traversed differently when passed through the electric field as shown in Fig.12.4. It is seen that α-particles deflect towards the negative terminal of the electric field, showing that they have a positive charge. The α-particles are emitted at high speeds, typically a few percent of the speed of light. However, α-particles can travel only several centimetres in the air due to their large mass. The β-particles deflect towards the positive terminal of the electric field, showing

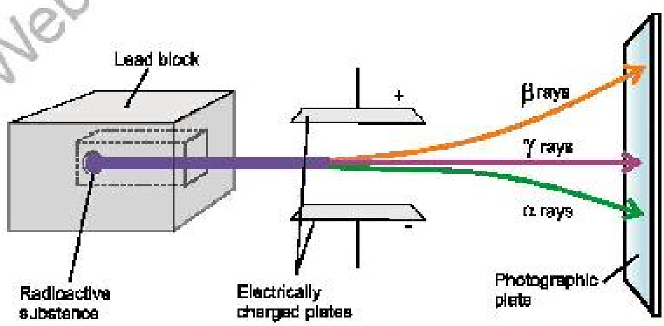


Fig. 12.4: The three radioactive radiations, namely alpha, beta and gamma rays

they have a negative 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 passed through the electric field without deflection, showing that they have no charge. The γ-radiations are electromagnetic radiations which consist of photons. They move with the speed of light with the highest penetrating power but the lowest ionization power.

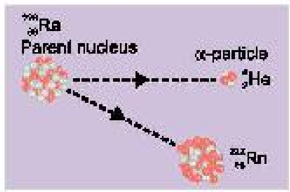
The process of emitting α-particles, β-particles and γ-radiations from the nucleus is called α-decay, β-decay and γ-decay, respectively, and are discussed below.

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:

$$^{A}_{Z}X \rightarrow \, ^{A-4}_{Z-2}X + \, ^{4}_{2}He \quad \text{.................} \quad (12.2)$$

Here $^{A}_{Z}X$ is the parent nucleus which decays into the daughter nucleus $^{A-4}_{Z-2}X$ and $^{4}_{2}He$ 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 ($^{226}_{88}Ra$) emits an alpha particle and decays into a daughter nucleus radon-222 ($^{222}_{86}Rn$).

$$^{226}_{88}Ra \rightarrow \, ^{222}_{86}Rn + \, ^{4}_{2}He \quad \text{.................} \quad (12.3)$$

In the above nuclear reaction, the **daughter** nucleus ($^{222}_{86}Rn$) is different from the **parent** nucleus ($^{226}_{88}Ra$). 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.

β-Decay

There are two types of β-decay; β^--decay and β^+-decay.

(i) 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 a Greek symbol ν (nu) and anti-neutrino is denoted by a bar over the $\bar{\nu}$. The decay process is given by the following relation:

$${}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + \bar{\nu}$$

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:

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X + {}^{0}_{-1}e + \bar{\nu}$$

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.

From the above 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:

$${}^{A}_{Z}Th \rightarrow {}^{239}_{91}Pa + {}^{0}_{-1}e + \bar{\nu}$$

(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:

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}X + {}^{0}_{+1}e + \nu$$

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

$${}^{19}_{10}Ne \rightarrow {}^{19}_{9}F + {}^{0}_{+1}e + \nu$$

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 as shown in Fig. 12.5. This demonstrates that **α-particles have discrete energies.**

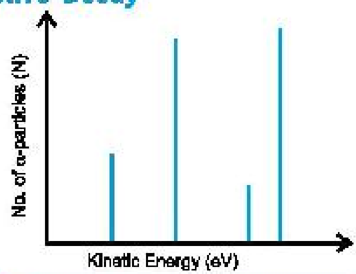


Fig. 12.5: Discrete energy values of α-particles

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 as shown in Fig. 12.6. 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.

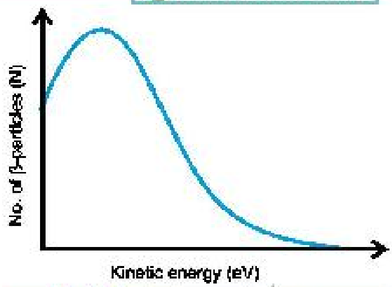


Fig. 12.6: Continuos spectrum of β-particles

(iii) γ-Radiation

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

$$^{A}_{Z}X^{*} \rightarrow \, ^{A}_{Z}X + \gamma$$

where $^{A}_{Z}X^{*}$ represents an excited nucleus while $^{A}_{Z}X$ shows ground state of the nucleus.

Table 12.2: The summary of nature of alpha, beta and gamma radiations

Characteristics	α-particles	β-particles	γ-rays
1. Nature	Helium nuclei of charge 2e	Electrons or positrons from the nucleus of charge ±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 10^2	About 1
4. Range in air	Several centimetres	Several metres	Obeys inverse square law
6. 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	$\sim 10^7\ m\ s^{-1}$	$\sim 1 \times 10^8\ m\ s^{-1}$	$\sim 3 \times 10^8\ m\ s^{-1}$

12.5 FUNDAMENTAL PARTICLES

By the term **fundamental particle**, we mean a particle that has no internal structure, which means that it is indivisible. Presently, the fundamental constituents of matter are considered to be **quarks** (protons, neutrons and mesons are made up of quarks) and **leptons** (including electrons, positrons, and neutrinos). They are considered the basic building blocks of matter.

When a nucleus is smashed in an ultra high energy particle accelerator, or two high energy particles are collided, entirely new types of particles are created which apparently do not exist within the atoms of the ordinary matter. They are the outcome of the violent collisions needed to probe the basic structure of matter. More than a hundred new particles have been identified to be classified into families with similar properties. Many of these were accounted well with the scheme of theoretical physicist while the rest were named "strange particle". They are always created in pairs, e.g., when a pion (π^-) collides with a proton, two strange particles k^0 (Kaon), and Λ^0 (Lamda) are created. The nuclear reaction is:

$$\pi^- + p \rightarrow k^0 + \Lambda^0$$

All particles spin on their axes and the spin of charged particles makes them tiny magnets. The characteristic spin of electrons, protons, neutrons is 1/2 and the spin of photon is 1 and of pions is taken as zero. Half spin particles obey the Pauli's exclusion principle which says that only one particle of a kind occupies a given quantum state. These particles are called **"fermions"**. The particles with zero or whole number spin do not obey this principle. They are called **"bosons"** as they obey Bose-Einstein statistics. Further major classifications are:

1. The nucleons and the heavier particles such as Λ^0 and k^0 which decay to nucleons are called **"baryons"** (heavy).
2. The particles that do not interact strongly with nucleons, and are called **leptons** (small) along with the electrons, tau and neutrino.

Both of the β-decay (beta-minus and beta-plus) processes provide evidence that the protons and neutrons are not the fundamental particles. By the 1960s many new types of particles similar to the neutron and proton were discovered, as well as many "midsized" particles called *mesons* whose masses were mostly less than nucleon masses but more than the electron mass (other mesons, found later, have masses greater than nucleons). The strongly attractive particles are called π meson or pions while the weakly interacting particles were named μ mesons or muons.

This discovery led to the conclusion that these particles could not be fundamental particles, and must be made up of even smaller constituents, which were given the name *quarks*.

Hadrons and Leptons

Particles can also be classified based on the four fundamental forces that act on them. While 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 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).

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 ½, so they all are fermions. The **six known leptons** are grouped as three pairs of particles as shown in Table 12.3. 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 12.3: The lepton family

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

12.6 QUARKS

In 1964, M. Gell-Mann and George Zweig proposed that none of the hadrons, not even the proton and neutron, are truly fundamental, but instead are made up of combinations of three more fundamental entities called **quarks** or **quark flavours**. Quarks are considered to be truly fundamental particles, like leptons. Three quarks originally proposed were named **up**, **down**, and **strange**, with abbreviations **u, d and s**, respectively. Presently, we are aware of six quarks, just as there are six leptons-based on a presumed *symmetry* in nature. The other three quarks are called **charm**, **bottom**, and **top (c, b, t)**. These new quarks can be distinguished from the 3 original quarks (Table 12.4). All quarks have a spin and an electric charge (a fraction of the previously thought smallest charge *e* on an electron). Quarks are invisible. They never appear on their own.

All hadrons are considered to be made up of combinations of quarks (plus the gluons that hold them together), 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 ud combination. A π^0 can be made of $u\bar{u}$).

Each baryon, on the other hand, consists of three quarks, such as:

The proton has a quark composition of uud and so its charge quantum number is:

$$q(\text{uud}) = \frac{2}{3} + \frac{2}{3} + \left(-\frac{1}{3}\right) = +1$$

Neutron has a quark composition of udd and its charge quantum number is:

$$q(\text{udd}) = \frac{2}{3} + \left(-\frac{1}{3}\right) + \left(-\frac{1}{3}\right) = 0$$

Table 12.4: Quark flavours

Particles	Symbol	Charge (q)	Mass (MeV/c^2)	Anti - Particle	Charge (q)
Up	u	$+\frac{2}{3}$	5	$\overline{m}$	$-\frac{2}{3}$
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	$\bar{b}$	$+\frac{1}{3}$

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 +2/3 and that of the antidown quark is +1/3. This adds nicely to a charge quantum number of +1 for the π^+ meson; that is, q(u) = 2/3 + 1/3 = +1.

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

Fig. 12.7 (a): Colourless baryons: blue + red + green = white

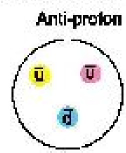


Fig. 12.7 (b): A colourless anti-baryons: anti-blue + anti-red + anti-green = white

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.

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:

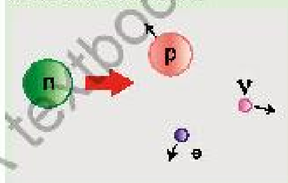
$$^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + \bar{\nu}$$

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:

$$d \rightarrow u + {}^{0}_{-1}e + \bar{\nu}$$

Do you know?

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



Thus, as our understanding of the fundamental nature of matter deepens, we can analyze familiar processes at increasingly intricate levels. The quark model not only enhances our comprehension of particle structures but also provides insight into their interactions.

12.7 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 a special particle discovered in 2012 at large hadron collider at CERN. It 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. 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.

12.8 CONSERVATION LAWS

All nuclear processess such as nuclear reactions and nuclear decays obey conservation laws such as:

1. conservation of energy, momentum and charge. It includes the nucleon number N and charge number Z.
2. baryon number
3. lepton number

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

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

Many observations show that 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

Our universe is more vast than our thinking, because we still know about its 5% part but we still do not know about its remaining 95% part. For example, 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

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.

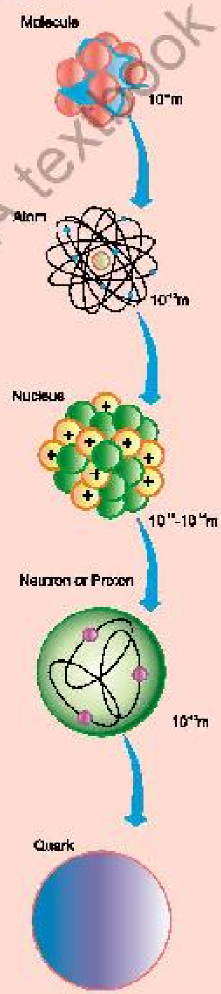
1. The Quantum Field Theory

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 ($W^{\pm}$ and Z) and the gravitational forces is mediated by field particles called gravitons.

2. 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

For your Information



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

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 are shown in Fig. 12.8. 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 Higg's boson provides an explanation for how the other particles get mass.

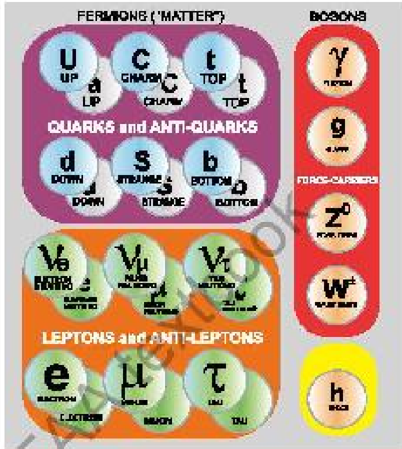


Fig. 12.8: Elementary particles in the standard model

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).

QUESTIONS

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 radiation/particles has the highest penetrating power?
(a) α (b) β^+ (c) β^- (d) γ

12.13 A change occurs in atomic member 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?

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

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

12.4 Fill in the missing particle or nucleus:

(a) $^{45}_{20}Ca \rightarrow ? + e^- + \bar{\nu}$

(b) $^{56}_{29}Cu^* \rightarrow ? + \gamma$

12.5 Why neutrino must be released in the positron emission?

12.6 Distinguish between fermions and bosons.

12.7 How does strong force hold the nucleus?

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

12.9 What is the difference between beta particle and electron?

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

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

12.12 Differentiate between hadron and leptons with examples.

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

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

12.15 What are Mesons? Give examples.

Constructed Response Questions

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

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

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

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

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

Comprehensive Questions

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

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

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

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

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

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

12.7 Describe four fundamental forces in nature.

12.8 Describe the classification of elementary particles.

Numerical Problems

12.1 Uranium-238 is an alpha emitter. In the process, it is transmutated into a daughter nucleus. What is the mass number A and charge number Z of the daughter nucleus? What is its chemical symbol? [Ans: A=234, Z=90, Thorium(Th)]

12.2 Polonium $^{218}_{84}Po$ is a beta minus emitter. What will be the mass number A and charge number Z of the daughter nucleus? (Ans: A = 218, Z = 85)

12.3 Nitrogen $^{14}_{7}N$ bombarded by alpha particle results into $^{17}_{8}O$. What is the product particle in this nuclear reaction? (Ans: $^{1}_{1}H$ proton)

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

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

(Ans: 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:

$^{14}_{7}N = 14.007515\,u$, $^{4}_{2}He = 4.003837\,u$, $^{17}_{8}O = 17.004533\,u$ and $^{1}_{1}H = 1.008142\,u$

(Ans: -1.23 MeV)