Dr. Avradip Pradhan,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

DSE2T (Nuclear and Particle Physics)

Topic – Particle Physics (Part – 1)

Introduction:

It is a little artificial to pinpoint such things, but it is often said that elementary Particle Physics began in 1897, with J. J. Thomson's discovery of the electron. After the discovery of the neutron in 1932 by Chadwick, it was thought that the electron, the proton and the neutron were the *fundamental constituents* of all matter. Subsequent experiments, involving cosmic rays as well as accelerator beams, revealed that there was a bunch of other particles that could be regarded as equally fundamental. We will come across the exitence of leptons, hadrons such as π-mesons (or pions), K-mesons (or kaons), ρ-mesons etc. and their many excited states. All these can be referred to collectively as *elementary particles*. Usually, an elementary particle is thought to be an object without any sub-structure, e.g. a point particle. However, structure can be probed only up to any given scale that is limited by the available energy. Consequently, our definition of an elementary or a fundamental is always tentative and it must rely on experimental verification at ever higher energies. For example, to examine the structure of matter at length scales of $\Delta l \sim 0.1$ fm, it requires transverse-momentum transfers (Δp) at least of the order $\Delta p \approx \frac{\hbar}{\Delta l} = \frac{\hbar c}{\Delta l c} \approx 1977\ \mathrm{MeV}/c$.

Therefore, to be sensitive to small length scales, the energy of the particles used as probes must be very high. Because of this need, the study of elementary particles has also come to be known as High Energy Physics. Whenever a higher-energy accelerator starts operating, we can probe deeper into the structure of matter and find that what was once considered elementary is not really so at present. This has, in fact, been the story of the proton, the neutron, the π-mesons, the K-mesons and so forth. Our current understanding of which particles should be considered as elementary is very different from that of only several decades ago.

The Four Fundamental Forces:

We are quite familiar with the classical *electromagnetic* and *gravitational* forces. We know that every particle, whether with or without rest mass, is subject to gravitational attraction. On the other hand, only particles that carry electric charge can sense the Coulomb field directly. Both the Coulomb and the gravitational forces are long ranged, theoretically upto infinity. The *photon* is the carrier of Coulomb interaction and from the fact that the electromagnetic force has infinite range, we can conclude that the photon must be massless. The carrier of the gravitational interaction is the conjectured *graviton*, which is also believed to be massless. Now, there are two more forces that have importance in the subatomic domain. There is the *strong force*, which is responsible for the binding of nucleons inside a nucleus and the *weak force*, which appears in processes such as nuclear beta (β)-decay.

These forces have no classical analogs and unlike the electromagnetic and the gravitational interactions, are exceedingly short ranged. Thus, it seems that we can point to four fundamental forces in nature as given below along with the type of their ranges

1. Gravitation: Long Range
2. Electromagnetic: Long Range
3. Strong Force: Short Range
4. Weak Force: Short Range

In principle, all the forces can act at the same time, still the forces can be distinguished through the strengths of their interaction. We can estimate the relative magnitudes of these four forces in a heuristic way by considering their effective potentials. We Consider two protons separated by a distance r. The magnitudes of the Coulomb and of the gravitational potential energies for the two particles are given by

$$V_{em}(r) = \frac{e^2}{4\pi\varepsilon_0 r}$$

$$V_{gr}(r) = \frac{G_N m^2}{r}$$

Here m is the mass of a proton and G_N is the gravitational constant. It is more convenient to write the potential energies in the Fourier transformed momentum space. So, except for an overall normalization, they take the form

$$V_{em}(q) = \frac{e^2}{\varepsilon_0 q^2} \text{ and } V_{gr}(q) = \frac{4\pi G_N m^2}{q^2}$$

Here q refers to the magnitude of the momentum transfer that characterizes the interaction. The absolute values of the potential energies for both interactions appear to decrease quadratically with momentum transfer, the ratio of V_{em} and V_{gr} is, in fact, independent of momentum scale and we can evaluate this ratio as

$$\frac{V_{em}}{V_{gr}} = \frac{e^2}{4\pi\varepsilon_0 G_N m^2} \approx 1.2 \times 10^{36}$$

This calculation shows that for charged elementary particles, the gravitational force is inherently much weaker than the electromagnetic force.

Next, let us recall that since both the strong and the weak forces are short-ranged, they can be described phenomenologically by Yukawa potentials of the form

$$V_{str}(r) \sim \frac{{g_s}^2}{4\pi r} e^{-\frac{m_s c r}{\hbar}} \text{ and } V_{wk}(r) \sim \frac{{g_w}^2}{4\pi r} e^{-\frac{m_w c r}{\hbar}}$$

Here g_s and g_w represent the coupling constants (effective charges) for the strong and the weak interactions and and m_s and m_w represent the masses of the force-mediating (or exchanged) particles in the two cases. We can again transform the above potentials to momentum space and except for an overall normalization constant, obtain

$$V_{str}(q) = \frac{{g_s}^2}{q^2 + {m_s}^2 c^2/\hbar^2} \text{ and } V_{wk}(q) = \frac{{g_w}^2}{q^2 + {m_w}^2 c^2/\hbar^2}$$

The values of the coupling constants can be estimated from experiment as

$$\frac{{g_s}^2}{\hbar c} \approx 15 \text{ and } \frac{{g_w}^2}{\hbar c} \approx 4 \times 10^{-3}$$

We also estimate m_s as the mass of π-meson, the mediator of the strong nuclear force as $m_s \approx 140$ MeV/c^2. Again from weak interaction processes at low energies, we can estimate that $m_w \approx 80$ GeV/c^2. Consequently, we can compare the magnitude of the Coulomb potential energy to that for the strong and the weak interactions. However, there appears to be an explicit dependence on momentum scale in the ratio. Since we are considering the interaction of two protons, it is natural to choose the momentum scale to correspond to that of the proton mass. So, we choose $\hbar^2 q^2 = m^2 c^2$ where m is the mass of a proton. So, finally we obtain

$$\frac{V_{str}}{V_{em}} = \frac{{g_s}^2 \varepsilon_0 q^2/e^2}{q^2 + {m_s}^2 c^2/\hbar^2} = \frac{{g_s}^2 \varepsilon_0 m^2/e^2}{m^2 + {m_s}^2} \approx 2 \times 10^3$$

$$\frac{V_{em}}{V_{wk}} = \frac{q^2 + {m_w}^2 c^2/\hbar^2}{{g_w}^2 \varepsilon_0 q^2/e^2} = \frac{m^2 + {m_w}^2}{{g_w}^2 \varepsilon_0 m^2/e^2} \approx 10^4$$

This shows once again that the strong force is stronger than the electromagnetic force, which in turn is stronger than the weak force and that gravitation is the weakest of all the forces. For larger momentum scales of order $\sim m_w c$, the weak and electromagnetic energies and strengths become more comparable, and suggest the interesting possibility for a unification of the two forces at very high energies.

The difference in the forces also manifests itself in the interaction time characterizing a particular process ($\Delta t \sim \hbar/\Delta E$), where $\Delta E \approx V$ is the energy associated with a specific process. Thus, for example, the typical time scale for a strong reaction is about 10^{-24} sec, which is roughly the time it takes a light signal to traverse a proton’s dimension, namely 1 fm. On the other hand, typical electromagnetic reactions of elementary particles occur in time intervals of the order of $10^{-20} - 10^{-16}$ sec, whereas the typical time scales for weak interaction mediated decays are about $10^{-13} - 10^{-6}$ sec.

Elementary Particle Types:

Photon, Lepton, Meson, Baryon. Before it was fully known that quarks were the fundamental constituents of nuclear matter, all the known elementary particles were grouped into four classical categories that depended on the nature of their interactions. Those are photon, lepton(s), meson(s) and baryon(s). Mesons and Baryons are again collectively known as Hadrons. Leptons are the light particles, examples of which are electrons, muons, tauons and their neutrinos (ν).

All particles, including photons and neutrinos, participate in gravitational interactions. The photon can interact electromagnetically with any particle that carries electric charge. All charged leptons participate both in the weak and electromagnetic interactions, and neutral leptons, of course, have no direct electromagnetic coupling. But leptons, on the other hand, do not sense the strong force. All hadrons respond to the strong force and appear to participate in all the interactions.

Boson and Fermion. All the particles in nature can be classified as either bosons or fermions, with the basic difference between them being the statistics that they obey. Bosons obey Bose-Einstein (BE) statistics whereas fermions satisfy Fermi-Dirac (FD) statistics. This is reflected in the structure of their wave functions. For example, the quantum mechanical wave function (ψ_B) for a system of identical bosons is symmetric under the exchange of any pair of particles. Therefore, we write

$$\psi_B(x_1, x_2, x_3, \dots, x_n) = \psi_B(x_2, x_1, x_3, \dots, x_n)$$

where the x_j denote, collectively, space-time coordinates as well as internal quantum numbers of particle j. On the other hand, under similar assumptions, the quantum mechanical wave function (ψ_F) for a system of identical fermions is anti-symmetric under the exchange of any pair of particles, so

$$\psi_F(x_1, x_2, x_3, \dots, x_n) = -\psi_F(x_2, x_1, x_3, \dots, x_n)$$

The Pauli's Exclusion Principle is therefore automatically built into the anti-symmetric fermionic wave function, thereby forbidding a pair of identical fermions to occupy the same quantum state. This follows because, for $x_1 = x_2$ the wave function in the last equation would equal its negative value and therefore gives $\psi_F = 0$. It can be shown from fundamental principles that all bosons have integer values of spin angular momentum, while fermions have half integral spin values. From such information, it has been learnt that the photon and all mesons are bosons, whereas the leptons and all baryons are fermions.

Antiparticle. We will find that every known particle has a corresponding *antiparticle*. The antiparticle is defined as an elementary particle which has the same mass as the original particle, but otherwise opposite quantum numbers. Thus, the positron (e^+) is the antiparticle of the electron (e^-) and it carries a negative lepton number and a positive electronic charge ($e = 1.6 \times 10^{-19}$ C). The antiproton ($\bar{p}$) has one unit of negative charge and one unit of negative baryon number, in contrast to the proton (p) which is positively charged and has a positive baryon or nucleon number. Certain particles cannot be distinguished from their own antiparticles. For example, the photon γ or neutral pion π^0, which has no electric charge, is its own antiparticle. It is clear that for a particle to be its own antiparticle, it has to be, at the very least, electrically neutral. However, not all electrically neutral particles are their own antiparticles. The neutron (n) has no electric charge, yet the antineutron ($\bar{n}$) distinct because of its negative baryon number and the opposite sign of its magnetic moment. Similarly, the K^0 meson, although charge neutral, has a distinct antiparticle. Except where there is a special symbol, antiparticles are denoted by the same symbol as the particles, but with a bar over that symbol.

Quantum Numbers:

The properties of the elementary particles and their interactions are even more mystifying, but there are many elementary particles, and many processes that can be studied. However, to derive any meaningful conclusions from observations, results must be organized in some coherent manner. Here our classical experiences help us. Classically, we know that a process or a reaction can take place if it is allowed kinematically and if it does not violate any recognized conservation law. Thus, for example, we are quite certain that a reaction that violates charge conservation will not take place. This certainty is based upon years of past studies and the development of a reliable theory for electromagnetic interactions. We believe that similar conservation principles hold in the subatomic domain, except that here we do not know all the relevant laws because we do not have a complete theoretical understanding of all the forces. Consequently, to formulate general principles, we must deduce the type of quantum numbers that are conserved and the conservation laws that are appropriate for each of the interactions of the elementary particles from the experimental results. One of the clearest results observed in reactions of elementary particles is that the number of fermions is always conserved (that is, if we count a fermionic antiparticle as a fermion, but with a negative fermion number), whereas the number of photons and mesons is not. This suggests that the conservation of fermion number is a fundamental feature of all interactions, as will be discussed later.

Baryon Number ($\boldsymbol{B}$). From differences in the magnitudes of the observed transition rates or from the absence of kinematically allowed processes, we can often infer the presence of possible conservation laws. For example, let us consider the decay $p \rightarrow e^{+} + \pi^{0}$. Since the proton is far more massive than the sum of the neutral pion and positron masses and since the above decay satisfies the conservation of electric charge, one might expect this process to take place. Nevertheless, proton decay is not observed. In fact, the upper limit on the probability for the previous reaction is a tiny number. This suggests that there is some conservation principle that forbids the proton decay. In fact, we can account for this simply by asserting that baryons carry an additive and conserved quantum number, known as baryon number or nucleon number (B). It is given by

$$B = +1, \text{ for all baryons}$$

$$B = -1, \text{ for all antibaryons}$$

$$B = 0, \text{ for others e.g. leptons, mesons and photon}$$

Consequently, if baryon number is conserved in all elementary physical processes, then the proton must not decay, since it is the lightest among the baryons.

Lepton Number (L). In a similar manner, we can postulate a quantum number for leptons, namely assert that all leptons carry a specific lepton number (L), whereas the photon and hadrons carry no lepton number. It is defined as

$$L = +1, \text{ for all leptons}$$

$$L = -1, \text{ for all antileptons}$$

$$L = 0, \text{ for others e.g. hadrons and photon}$$

The introduction of a lepton quantum number is necessitated by many experimental observations. A few examples are the processes $\mu^- \rightarrow e^- + \gamma$ or $e^- + e^- \rightarrow \pi^- + \pi^-$. At high energies, these reactions are kinematically allowed, and they definitely satisfie charge conservation, but still are not observed. Now we know, lepton number conservation would prevent these processes from taking place.

It is from such experimental findings that we arrive at the conclusion that there must be different kinds of lepton numbers within the family of leptons (see Table 1). Thus, the electron and its neutrino (ν_e) have an electron-lepton number or simply, electron number (denoted as L_e) $L_e = +1$, whereas the other leptons have $L_e = 0$. The muon and its neutrino (ν_μ) have muon-lepton number or muon number (L_μ) as $L_\mu = +1$, whereas the other leptons have $L_\mu = 0$, and similarly for the τ-particle (or tauon) and its neutrino (ν_τ), we got L_τ. The net lepton number of any particle can therefore be expressed as the sum of the electron number, the muon number, and the tauon number.

Leptons can therefore be split into three families, namely, (e^-, ν_e), (μ^-, ν_μ) and (τ^-, ν_τ), with each family number L_e, L_μ and L_τ conserved in all interactions. This would be useful to explain why the muon decays as $\mu^- \rightarrow e^- + \overline{\nu_e} + \nu_\mu$, because here both L_e and L_μ will be conserved. It is also useful to explain the exact nature of pion decay given as $\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$ as well as the beta decay given as $n \rightarrow p + e^- + \overline{\nu_e}$.

Lepton family	L	L_e	L_μ	L_τ
e^-	$+1$	$+1$	0	0
ν_e	$+1$	$+1$	0	0
μ^-	$+1$	0	$+1$	0
ν_μ	$+1$	0	$+1$	0
τ^-	$+1$	0	0	$+1$
ν_τ	$+1$	0	0	$+1$
e^+	-1	-1	0	0
$\overline{\nu_e}$	-1	-1	0	0
μ^+	-1	0	-1	0
$\overline{\nu_\mu}$	-1	0	-1	0
τ^+	-1	0	0	-1
$\overline{\nu_\tau}$	-1	0	0	-1

Table 1

This concludes part 1 of this e-report.

The discussion will be continuing in the part 2 of this e-report.

Reference(s):

Introduction to Elementary Particles, D. J. Griffiths, John Wiley & Sons

Introduction to Nuclear and Particle Physics, A. Das & T. Ferbel, World Scientific

(All the figures have been collected from the above mentioned references)