Fundamental Particles

Mahatsab Mandal
Government General Degree College at Kalna-I, Purba Bardhaman
email: mahatsab@gmail.com

PACS numbers:
Keywords: elementary particle, lepton, quark

I. INTRODUCTION

Elementary Particle Physics deals with the search and the study of the fundamental constituents of matter and the interactions between them. The ancient Greek philosopher Democritus first introduce that everything is composed of indivisible particles called atoms (from Greek $\alpha\tau o\mu o\nu$, atomon, i.e. "uncuttable"), or ancient Indian philosopher Kanada came up with the idea of "anu" in a similar concept. After the birth of modern science, the idea of atoms came to be used as the smallest building blocks of the matter. Issac Newton explained the expansion of gas in terms of the flow of their atoms in empty space. In the early nineteenth century John Dalton introduced the atomic theory in chemistry and it explain atoms of different elements combine in fixed ratios to form compounds.

II. THE ELECTRON AND THE NUCLEUS

Particle physics in a recognizable modern sense begins with the discovery of the negatively charged electron by J. J. Thomson in 1897. Electron was the first of the modern elementary particle to be discovered. He evaluated the ratio of the charge to the mass of the electron (e/m). Subsequently, Millikan's oil drop experiment allowed one to determine the electronic charge and its value is $e = 1.6 \times 10^{-19}$C. By combining the value of e and e/m_e, we get the mass of the electron $m = 0.511$ MeV$/c^2$. It may also be noted here that the electron carries spin which is an intrinsic property of elementary particles and has a value that is denoted by $\frac{\hbar}{2}$. Electrons are examples of fermions, and they obey Fermi-Dirac statistics.

In 1991, Rutherford explain the Geiger-Marsden experiment that the atom was largely empty by shooting α particles at a thin gold foil. These relatively heavy particles ignored the very light electron and they scattered only on the nucleus which indicated the presence of positively changed protons inside the nucleus. The proton has an electric charge +1 (in unit where the charge of electron is -1). Atoms are electrically neutral because the number of electrons in an atom equals to the number of protons in the nucleus. Finally, Niels Bohr, in 1913 proposed the atomic model, containing a nucleus orbited by electrons. The discovery of neutron, a neutral particle was made in 1932 by James Chadwick which was another constituent of nuclei. Nuclei can now be understood as composed of protons and neutrons. These also each carry spin of $\frac{\hbar}{2}$. In the 1920s the quantum mechanics was developed to explain the structure of the atom.

III. THE PHOTON

The next elementary particle was discovered entirely theoretical aspect. An ideal blackbody at thermal equilibrium emits radiation in all frequency range, and radiates more energy as frequency is increased. By calculating the total amount of radiated energy, it can be shown that blackbody would released an infinite amount of energy, and contradicting the principle of conservation of energy which is known as ultraviolet catastrophe. In 1900, Max Plank was the first to explain the blackbody spectrum for the electromagnetic radiation emitted by a hot object. He assume that electromagnetic radiation is quantized, coming in little packages of energy

$$E = h\nu \tag{1}$$

where ν is the frequency of their radiation. Plank din not go so far to say that light is quantized. Einstein, in 1905, adopted Plank's idea, and electromagnetic radiation is quantized and appear only in precisely defined energy packets called photons. It explain the photoelectric effect. Einstein suggested that an incoming light quantum hits an electron in the metal surface, and transfer the whole energy, the excited electron then brakes through the metal surface, losing in the process an energy W. Thus the maximum kinetic energy of the emitted photoelectrons is given by

$$\frac{1}{2}mv_m^2 = h\nu - W \tag{2}$$

The maximum electron energy of the emitted photoelectrons depends only on its frequency and not on the intensity of the incident light. The existence of photons was verified experimentally by the result of Millikan's studied of the photoelectric effect in 1914-16. Photon have zero rest mass and zero electric charge and always travel at the speed of light within a vacuum, so they cannot be contained inside atoms.

IV. ANTIPARTICLES

In 1928, Paul Dirac succeeded in combining quantum mechanics and theory of relativity to describe the electron [2]. It shows that for every positive-energy solution correspond to a particle with momentum $\mathbf{p}$ and energy $E = \sqrt{p^2c^2 + m^2c^4}$, whereas the negative-energy solution correspond to a particle momentum $-\mathbf{p}$ and energy $-E = -\sqrt{p^2c^2 + m^2c^4}$ and predicts that for every particle there is an antiparticle, which is like the particle in every respect, except that its electronic charge is on the opposite sign. Dirac at first hoped that the negative energy solution might be protons, but it was soon apparent that they had to carry the same mass as the electron itself 2000 times too light to be a proton. No such particle was known at the time, and Dirac's theory appeared to be in trouble. This prediction was unexpectedly verified in 1932 when Carl Anderson tracts of cosmic-ray particles that curved in a magnetic field about as much as electron track, but in the opposite direction. These particles are called positron.

V. NEUTRINOS

Both the electrons and positrons are emitted spontaneously from radioactive nuclei. This phenomenon is called beta-decay. Chadwick observed that the electron emitted in the beta-decay of radioactive nucleus does not emerge with the definite kinetic energy. The spread of these energies of beta particles is called beta-spectrum of the given nuclei. This was a most disturbing result, because one would have excepted the energy of the electron is equal to the difference in energies between final and initial nuclei, and it is fixed for each specified radioactive elements [1]. It thus appears to violet the principle of conservation of energy. Wolfgang Pauli proposed that another particle was emitted with the electron in beta-decay and shares the missing energy. It had to be electrically neutral but is so highly penetrating that its energy is not converted into heat. Fermi called it the neutrino or "little neutral one". The neutrino was incorporated in Fermi's 1933 theory of beta decay, the fundamental process was one in which neutron inside a nucleus spontaneously turns into a proton, an electron and an antineutrino. The fundamental beta decay process is

$$n = p^{+1} + e^{-1} + \bar{\nu} \tag{3}$$

At that time it has been realized an unfamiliar force of nature must be responsible for this and was so 'weak' that a neutrino with energy typical of those production in beta-decay would be able to penetrate light year of lead before absorbed and this force is known as *weak force* which seems to play only at sub-atomic distance scale. The neutrino mass is no grater than about 10^{-4} electron masses and it is a spin $\frac{1}{2}$ particle.

VI. MESONS

The binding of the nucleus could not understood by the electromagnetic force. The positive charge proton should repel each other. In 1935 Hideki Yukawa tries to describe that the proton and neutron are attracted each other by an exchange of new particles and the mass of the particle whose exchange produces the force [1]. There is a characteristic distance beyond which the force drops rapidly to zero, and this distance is inversely proportional to the mass of the exchange particle. In electromagnetic theory the exchange particle is photon, which is zero mass, so the range of force is infinite. If the exchange particle is electron, the range of force is about hundred times larger than the nuclei. The short range of the force indicated that the mediator would be rather heavy, Yukawa proposed a new kind of particle, with a mass hundreds of times larger than that of the electron. Yukawa's particle came to be known as the meson because its predicted mass was between that of the electron and that of the proton. Just two year latter, in 1937, a particle with a mass about 200 electron was found in cosmic-rays by S. H. Neddermeyer and C. D. Anderson and by C. E. Stevenson and J. C. Street. It was widely assume at the time that this was Yukawa's meson. In 1945, M. Conversi, E. Pancini and O. Piccioni shows that mesons that predominate in cosmic rays interacted very weakly with atomic nuclei, and could not provided the mechanism for nuclear force. The puzzle was finally resolved in 1947, when Powell and his co-workers discovered that there are two actually two different kind of mesons, with slightly different masses, which they called π (or pion) and μ (or muon). The true Yukawa meson is the pion.

VII. STRANGE PARTICLES

Nonetheless, in 1947, in the interactions of cosmic rays in a cloud chamber with magnetic field, particles with a particularly strange behavior were discovered. Unlike pions they were always produce in pair. They were thus named strange particles. Detailed analysis shows that these charged particles are in fact a π^+ and a π^-. Hence, there was a new neutral particle with at least twice the mass of the pion, we call it the K^0 (Kaon):

$$K^0 = \pi^+ + \pi^- \tag{4}$$

In 1952 the first of the modern particle accelerators (the Brookhaven Cosmotron) began operating, and soon it was possible to produce strange particles in the laboratory. The garden which seemed so tidy in 1947 had grown into a jungle by 1960, and hadron physics could only be described as chaos [2]. In 1960 the elementary particles awaited their own "Periodic Table".

VIII. THE STANDARD MODEL

With the advance of accelerator physics, discovery of many new particles was made possible; most of them are subject to the strong interaction and are named hadrons. The fermionic particles that do not strongly interact were named leptons. In 1964, Gell-Mann and Zweig independently proposed that all hadrons are in fact composed of even more elementary constituents, which Gell-Mann called quarks [3]. All matter is made out of three kinds of elementary particles: leptons, quarks, and mediators.

There are six type of leptons, grouped in three generations. These are electron, muons, tauons and three neutrino: electron-neutrino, muon-neutrino and tau-neutrino. They are classified according to their charges (Q), electron number (L_e), muon number (L_μ) and tau number (L_τ).

Lepton Classification					
	l	Q	L_e	L_μ	L_τ
First generation	e	-1	1	0	0
	ν_e	0	1	0	0
Second generation	μ	-1	0	1	0
	ν_μ	0	0	1	0
Third generation	τ	-1	0	0	1
	ν_τ	0	0	0	1

There are also six antileptons, with all the signs reversed. So there are 12 leptons. All leptons have spin $\frac{1}{2}$.

Quarks never directly observed or found in nature. There are six flavors of quarks (q), named up (u), down (d), strange (s), charm (c), bottom (b), and top (t). Antiparticles of quarks are called antiquarks ($\bar{q}$). The are classified according to charge (Q), strangeness (S),charm (C), beauty (B),and truth (T).

Quark Classification						
	q	Q	S	C	B	T
First	d	$-\frac{1}{3}$	0	0	0	0
generation	u	$\frac{2}{3}$	0	0	0	0
Second	s	$-\frac{1}{3}$	-1	0	0	0
generation	c	$\frac{2}{3}$	0	1	0	0
Third	b	$-\frac{1}{3}$	0	0	-1	0
generation	t	$\frac{2}{3}$	0	0	0	1

Again, all signs would be reversed on the table of antiquarks. Meanwhile, each quark and antiquark comes in three colors, so there are 36 of them in all. All quarks have spin $\frac{1}{2}$.

The baryons are bound state of three quarks, and every mesons are composed of a quark and an antiquark. The up quark and down quark are the constituents of the proton and neutron: the proton contains two up quarks and one down quark, the neutron one up quark and two down quarks. The down is more massive than the up quark, and for this reason the down quark can decay into an up quark plus an electron and an antineutrino. The π^+-meson is a $u\bar{d}$ state; it is a meson, in the sense $B = L = 0$, and its charge in indeed $+1$. It is true that the qqq, $\bar{q}\bar{q}\bar{q}$ and

$q\bar{q}$ state reproduce sequence of baryons, anti-baryons and mesons state, but all other possibilities such as qq, $\bar{q}\bar{q}$, $\cdots$, single quark never observed. Both the problem can be resolved by introducing a new property or quantum number for quarks: “color”. We suppose that the quarks comes in three primary colors: red (R), blue (B), green (G). All the particle state observed in nature are colorless.

Gluons are particles of mass zero that interact with the quarks, they are somewhat like photons with respect to electrons. The gluons are responsible for the force between the quarks, like photon is responsible for the electric force between electrons. Gluons carry color charge, in fact they carry one color and one anti-color charge. Gluons couple only to colored particles.

Every interaction has its mediators: the photon for the electromagnetic force, two W's ($W^{\pm}$)and a Z^0 for the weak force. 8 gluons for strong force.

[1] Steven Weinberg, The Discovery of Subatomic Particles, Scientific American Library, ISBN-0-7167-1488-4.

[2] David Griffiths, Introduction to Elementary Particles, 2004 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, ISBN-13: 978-0-471-60386-3.

[3] Sylvie Braibant, Giorgio Giacomelli and Maurizio Spurio, Particles and Fundamental Interactions, Springer, ISBN 978-94-007-2463-1