The Story of Large Electron Positron Collider

1. Fundamental Constituents of Matter

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Keywords
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Introduction

The story of the large electron positron collider, in short LEP, is linked intimately with our understanding of nature's fundamental particles and the forces between them. We begin our story by giving a brief account of three great discoveries that completely changed our thinking and started a new field we now call particle physics. These discoveries took place in less than three years during 1895 to 1897: discovery of X-rays by Wilhelm Roentgen in 1895, discovery of radioactivity by Henri Becquerel in 1896 and the identification of cathode rays as electrons, a fundamental constituent of atom by J J Thomson in 1897. It goes without saying that these discoveries were rewarded by giving Nobel Prizes in 1901, 1903 and 1906, respectively. X-rays have provided one of the most powerful tools for investigating the structure of matter, in particular the study of molecules and crystals; it is also an indispensable tool in medical diagnosis. The discovery of the nucleus of an atom in 1911 by Ernest Rutherford was due to the availability of beam of alpha particles from radioactive decays. The discovery of electron has given us electronics, TV picture tubes, etc., which are now part of our day to day life.

The above three discoveries were matched by two great theories of the early 20th century – quantum mechanics and relativity; the former describes the world within an atom, while the second one deals with objects travelling with speed close to that of light. In 1928, a young and brilliant theoretical physicist named Paul Dirac, working in Cambridge, put together the ideas on quantum theory as developed by Heisenberg and Schrödinger and merged it with Einstein's theory of relativity. The outcome of this marriage was the famous relativistic wave equation for electrons, known also as the Dirac equation. While formulating the relativistic equations for electrons and incorporating the requirements of quantum theory, Dirac ended up with an expression in terms of E^2 for the electron, where E is the energy of the electron. In order to get the expression for E one will have to take a square root of E^2. As is well known, there are two possible solutions, one positive and the other with negative sign (like the square root of 16 is +4 and -4). He identified the positive solution with the familiar negatively charged electron. In general one rejects the negative solution as being unphysical. But Dirac proposed a very strange solution to the problem by conjecturing that the negative solution implies the existence of a new kind of particle called antielectron, or positron as it came to be known later on, with the same mass as that of an electron but with opposite charge and this conjecture seemed at that time like a science fiction. The evidence for the existence of the positron came very soon in 1932 when Carl Anderson, at California Institute of Technology, was studying cosmic rays using a cloud chamber placed in a magnetic field. A cloud chamber is a detector where a charged particle leaves its track which can be photographed and the usage of a magnetic field is to give a curvature to the charged track through which one can identify the positive or negative charge of the particle. Dirac's theory thus led to the concept of antimatter for the first time and it also states that for every particle there exists an antiparticle, which is now an established fact. In this new scenario, the conversion of energy takes place into matter and antimatter in equal amounts, as in the Big Bang cosmological model. As an example, a high energy photon passing through matter gets converted into an electron-positron pair. The reverse scenario that is the annihilation of matter and antimatter, like electrons and positrons, is the subject

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Box 1. Electron-Volt

An electron-volt (eV) is a unit of energy. One also uses a million electron-volt (MeV) and a giga electron-volt (GeV): 1 GeV = 10^3 MeV = 10^9 eV. One electron-volt is defined as the energy gained by a particle carrying one elementary electric charge (like an electron or a proton) while moving through an electric field with a potential difference of one volt. Since the value of an elementary charge is 1.602×10^{-19} Coulomb and a volt is defined as 1 Joule/Coulomb, we can write 1 eV = $1.602 \times 10^{-19} \times 1 = 1.602 \times 10^{-19}$ J, or 1.602×10^{-12} erg. The eV is also used as an unit of mass, since energy and mass are related through $E = mc^2$, where c is the velocity of light. As an example, the mass of an electron is 0.51 MeV/c^2, which on writing MeV in terms of ergs and the value of c as 3×10^{10} cm/sec becomes 9.1×10^{-28} gm $(= 0.51 \times 1.6 \times 10^{-6}/(9 \times 10^{20}))$.

of our present topic that has been the key to LEP.

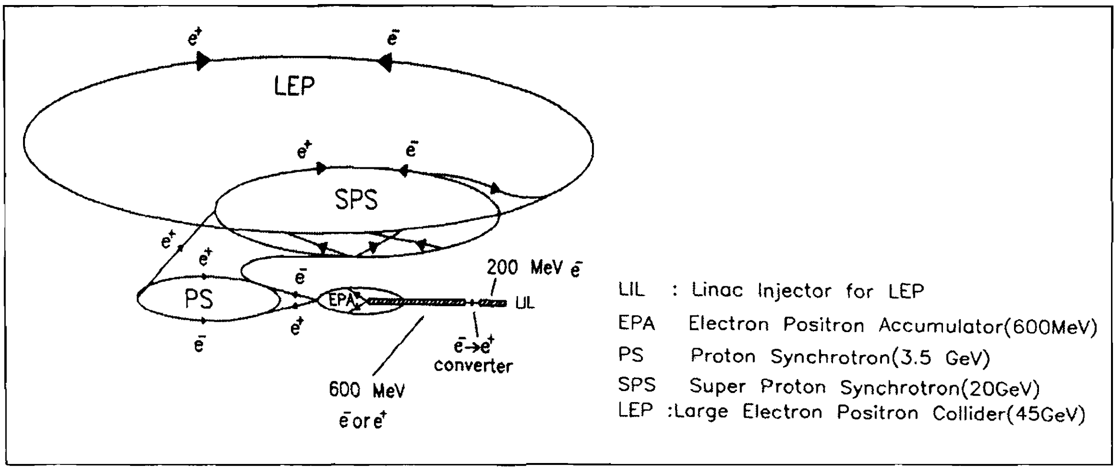
The LEP story started in the late 1970s when the new scenario of the unification of the electromagnetism and weak forces was becoming a reality, although the force carrying particles W and Z for weak forces, responsible for radioactive decays, were not yet discovered. The LEP is a large electron positron collider at CERN, Geneva, which was formally approved by CERN Council in 1981. A few words about CERN are in order. CERN is an European Organization for Nuclear Research, the world's largest particle physics centre; it is also called an European Laboratory for Particle Physics. It was founded in 1954 with its headquarters in Geneva. It started with 28 GeV Proton Synchrotron accelerator (*Box* 1).

In 1971 the first proton-proton collider, called Intersecting Storage Rings ISR, was commissioned. CERN moved on to 450 GeV Super Proton Synchrotron with 6.9 km circumference in 1976. In 1981 this accelerator was used for the first antiproton-proton collider which led to the discovery of W and Z particles two years later. CERN has become a worldwide laboratory. It is a unique centre of excellence in particle physics and a successful model for international collaborations in science and technology. CERN is funded by 20 European countries called CERN's Member States.

The LEP was commissioned on July 14, 1989. The LEP circular tunnel, which is about 50 to 100 metres below the surface of earth, is of 27 kilometre circumference. Electrons were generated by an electron gun and after acceleration to about 200 MeV by a linear accelerator, called linac, they were focused on a tungsten target which led to the production of photons. These photons in turn got converted into electron-positron pairs, which are further accelerated to 600 MeV by a second linac. Before entering the LEP tunnel these beams of electrons and positrons were further accelerated to about 20 GeV, and the final acceleration to desired energies were carried out at the LEP tunnel with beams of electrons and positrons rotating in opposite direction (*Figure* 1). The beams were made to collide at four intersection regions which were surrounded by four giant detectors to carry out experiments by physicists/engineers from all over the world. The four experiments were named: ALEPH, DELPHI, L3 [1] and OPAL. Each of the four experiments consists of about 500 scientists. The general concept of these detectors is very similar. Their basic aims are to detect, to identify and to measure precisely the energy and momentum of all the particles that are emerging from the collisions of electrons and positrons; neutrinos will escape detection in these detectors.

[1] Physicists of Experimental High Energy Physics group of Tata Institute are members of this collaboration.

Figure 1. Acceleration of electrons and positrons for LEP.



The LEP was designed to study the weak force which makes the Sun shine by burning hydrogen and is responsible for radioactive decays. Carriers of the weak force are W and Z particles. In the first phase of the LEP which lasted up to the end of 1995, the collision energy was just right to make Z particles. In its second phase, called LEP 2, the collision energy was upgraded to nearly twice the Z mass to produce W^+ and W^- particles in pairs by incorporating superconducting radio-frequency (RF) accelerating cavities. The final shut down of LEP was in early November 2000 after running successfully for eleven long years. Before discussing some of the precision measurements carried out at LEP, a brief summary of constituents of matter and forces are described below.

Fundamental Constituents of Matter

Matter consists of basic elements ranging from hydrogen to uranium and beyond; the building block of each element is called atom, which is unique to the element. Different atoms can combine to form molecules which can be very complex, like proteins, etc. But atoms are not the simplest building blocks of matter. Most of the mass of an atom resides in a tiny, dense and positively charged nucleus surrounded by almost massless revolving negatively charged electrons (the size of an atom is $\sim 10^{-8}$ cm, while that of a nucleus is $\sim 10^{-13}$ cm). The nucleus, in general, contains two types of particle: positively charged protons and electrically neutral neutrons of almost equal mass. The visible matter that we see around us is formed out of electrons, protons and neutrons. Studies made using high energy cosmic rays and using beams of high energy particles from accelerators led to the observations of many different kinds of particles. They were classified into two categories: (i) strongly interacting particles, collectively called hadrons, like protons (p), neutrons (n), pions (π), kaons (K), lambdas (Λ), sigmas (Σ) etc., and (ii) weakly

Weak force is responsible for radioactive decays.

Box 2. Neutrinos

The first hint for the existence of neutrino came from the radioactive beta decay of nuclei; the beta particle is another name for the electron. Although the beta decay was discovered in 1896, it was only in 1931 that the neutrino was postulated by Pauli to save the energy conservation in beta decay. The first neutrino interaction in the laboratory was observed in 1956 by Cowan and Reines using a nuclear reactor. This was later identified as electron-neutrino (ν_e) associated with the electron, like in beta decay: $n \to p + e^- + \bar{\nu}_e$; it may be noted that an antineutrino ($\bar{\nu}_e$), antiparticle of neutrino, is involved in the beta decay. A second type of neutrino, called muon-neutrino (ν_μ), was discovered in 1960 by Lederman, Schwartz, Steinberger and collaborators at Brookhaven National Laboratories; this neutrino was observed from the decay of a pion: $\pi^+ \to \mu^+ + \nu_\mu$. Experiments at LEP, during early 1990s, determined that there are only three light neutrino species. The third neutrino associated with the tau lepton was observed in 2000 by the DONUT collaboration at Fermilab.

interacting particles, collectively called leptons, like electrons (e), muons (μ), neutrinos (ν)(*Box* 2), etc. Evidence was accumulating that hadrons were not elementary and specifically the experiments with high energy electrons, muons and neutrinos revealed that at very short distances protons and neutrons have structure. As a result we understand now that the fundamental constituents of matter are of two types: quarks and leptons. Out of quarks are formed all the hadrons. Hadrons could be further subdivided into two types: baryons (like p, n, Λ, etc.) and mesons (like π, K, etc.). Basic quark contents of baryons are three quarks and those of mesons are a quark and an antiquark.

What could be responsible for the stability of atoms, movements of planets around the Sun, etc.? As of today we know of four basic forces: gravitational, electromagnetic, weak and strong. In quantum mechanics the forces or interactions between matter particles are due to exchange of force carrying particles. The gravitational force is universal, that is every object experiences the force of gravity; it is the weakest of the four forces and the force carrier is called graviton. It plays a vital role in the formation and sustenanace of stars, galaxies and other objects. The electromagnetic force is experienced

The fundamental constituents of matter are of two types: quarks and leptons.

by all electrically charged particles (quarks and charged leptons), and the force is due to exchange of massless particle, the familiar photon of light. It is responsible for the stability of atoms and molecules. The electromagnetic force between two protons is about 10^{37} times bigger than the gravitational force; as a result one neglects gravitational force in particle interactions. Interactions between particles are dominated by electromagnetic force for distances down to 10^{-13} cm and strong force begins to become important at shorter distances. The strong force, mediated by a particle called gluon, is responsible for the compactness of atomic nuclei and for holding the quarks together in protons and neutrons; leptons are not sensitive to the strong force. The weak force, mediated by W and Z bosons (see later for details), is responsible for the radioactivity and decays of unstable particles like muons; both quarks and leptons experience the weak force. It may be noted that neutrinos are involved only in weak interactions. The energy production in the Sun is dominated by this force via the pp fusion reaction. Forces can be compared by studying interactions between two particles by measuring cross-sections (*Box* 3) of collisions or measuring the lifetimes of particles through their decays. The stronger the force, the larger is the cross-section and shorter the lifetime. This is illustrated by the following examples. (a) Interaction cross-sections at centre of mass collision energy of 10 GeV are: $\pi + \mathrm{p} \rightarrow \pi + \mathrm{p}$ is $\simeq 10$ mb (strong interaction), $\gamma + \mathrm{p} \rightarrow \pi^0 + \mathrm{p}$ is $\simeq 10^{-3}$ mb (electromagnetic) and $\nu + \mathrm{p} \rightarrow \nu + \mathrm{p}$ is $\simeq 10^{-11}$ mb (weak). (b) Lifetimes of some of the unstable particles are: $\Delta^{++} \rightarrow \mathrm{p} + \pi^+$ with lifetime of $\tau \approx 10^{-23}$ sec (strong decays), $\Sigma^0 \rightarrow \Lambda + \gamma$ and $\pi^0 \rightarrow \gamma + \gamma$ with respective lifetimes as $\tau \approx 10^{-19}$ and 10^{-16} sec (electromagnetic decays), and $\Lambda \rightarrow \mathrm{p} + \pi^-$ and $\pi^+ \rightarrow \mu^+ + \nu$ with lifetimes as $\tau \approx 10^{-10}$ and 10^{-8} sec, respectively (weak decays). Relative strengths of these interactions may be gauged from the above observations. The salient

Forces can be compared by measuring cross-sections of collisions.

Box 3. Cross-section

The interaction or collision between two particles is described in terms of what physicists call cross-section and it essentially gives a measure of the probability for a given reaction to occur. It is measured in unit of area, and may be taken in a vague sense as an effective area of the target nucleus seen by an incident projectile. Consider an experiment where a beam of particles, say protons, is directed perpendicularly towards a thin target, say hydrogen, of thickness x cm. Behind the target there is a detector which detects all outgoing particles, say pions, formed in collisions of the incident beam with the target nuclei. Let us assume that a flux F of beam particles per unit area per second is incident on an area A of the target and n is the number of target nuclei per unit volume (in cm^{-3}). Total number of target nuclei seen by the beam is then nAx. The event rate or the number of collisions taking place per second, let us denote it by R, is then proportional to the flux of beam particles and the number of target nuclei. Using the proportionality constant as σ, we can write: $R = \sigma FnAx$. The probability of collision of a single particle is obtained by dividing R by the number of beam particles per second, which is FA. Thus the probability of interaction $= \sigma nx$. The ratio R/σ $(= FAnx)$ is called luminosity and it is in unit of $\text{cm}^{-2}\text{sec}^{-1}$. The dimension of σ is cm^2; one also uses the unit barn: 1 barn $= 10^{-24}$ cm^2, 1 milli-barn (mb) $= 10^{-27}$ cm^2. Let us calculate luminosity for a proton beam of 10^7 sec^{-1} incident on a liquid hydrogen target of length x = 20 cm and density as 0.07 gm/cm^3; the number of target protons is: $\text{n} = 6 \times 10^{23} \times 0.07\ \text{cm}^{-3} = 4 \times 10^{22}$. The luminosity for the collision is thus $10^7 \times 4 \times 10^{22} \times 20 \simeq 10^{31}\ \text{cm}^{-2}\text{sec}^{-1}$.

features of the four basic interactions (*Figure* 2) are summarised in *Table* 1.

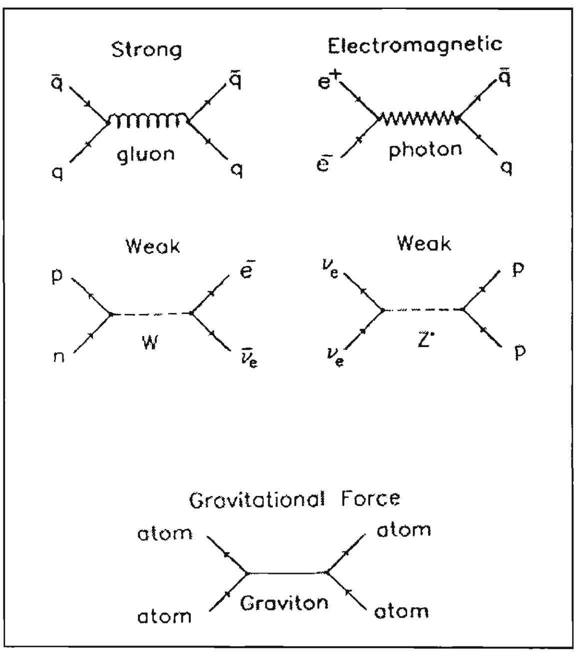


Figure 2. Four basic forces.

Interaction type	Exchanged particle	Mass (GeV/c^2)	Range (m)	Relative strength
Strong	Gluon	0	$\leq 10^{-15}$	1
Electromagnetic	Photon	0	∞	$\sim 10^{-2}$
Weak	$W^{\pm}$, Z	80.4, 91.2	$\leq 10^{-18}$	$\sim 10^{-6}$
Gravity	Graviton	0	∞	$\sim 10^{-39}$

Table 1. Four fundamental interactions.

Matter and force particles are distinguished by an internal property of the particle called spin, which has no classical analogue and it is not exactly a tiny top spinning about an axis. It behaves like a particle possessing an angular momentum, and the spins combine vectorially like angular momenta. Let us only remember that all matter particles like electron, proton, neutrino, quarks, etc. have spin 1/2, while the force particles like photon, W, Z and graviton have integer spins like 0, 1 and 2 (the spin is measured in unit of $\hbar = 6.58 \times 10^{-22}$ MeVsec). Matter particles are collectively called fermions (after Enrico Fermi, an Italian physicist), and force particles as bosons (after S N Bose, an Indian physicist). There is another very important difference between matter particles and force particles – matter particles obey Pauli exclusion principle while force carrying particles do not. Pauli exclusion principle states that two similar particles cannot exist in the same state like having the same position and the same velocity. This is a very important property because it explains why matter particles do not collapse to a state of very high density under the influence of the forces and why well defined separate atoms exist.

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In the late 1960s Steven Weinberg and Abdus Salam gave a unified description of electromagnetism and weak interaction, and together with the work of Sheldon Glashow this came to be known as the electroweak theory.

In this standard electroweak theory there are four vector boson fields. Two of them describe massive charged bosons W^+ and W^- The remaining two are neutral fields which mix in such a way that the physical states are the neutral massive weak boson called Z^0 and the familiar massless photon. The electroweak mixing angle θ_w is generally expressed in terms of $\sin^2\theta_w$. The W boson would mediate weak interactions that violate parity completely (in technical jargon it means that W couples only to left-handed fermions), whereas the Z boson, because of the electroweak mixing, has also a component that describes parity respecting part (in technical jargon it means that Z also has some coupling to right-handed fermions). If the value of $\sin^2\theta_w$ is 0.25, it means that Z will interact electromagnetic like in about 25%. Another consequence of the mixing angle is that the mass of Z and that of the W are not the same.

Electroweak theory predicted a neutral exchange particle in addition to the changed ones.

Prior to 1973 all experimental observations of the weak force revealed that the exchanged particle has electric charge (W^+ or W^-) and hence such weak effects came to be known as charged current interactions. Let us explain by two examples: (a) The decay of neutron can been written as: $n \to p + e^- + \bar{\nu}_e$ (*Figure* 2). We rewrite this in terms of charged current in two steps. Firstly the neutron converts itself into: $n \to p + W^-$ followed by the disintegration of W as: $W^- \to e^- + \bar{\nu}_e$. (b) Let us take the case of neutrino interaction with neutron: $\nu_\mu + n \to \mu^- + p$. This we will write again in two steps. Firstly neutrino converts itself as: $\nu_\mu \to W^+ + \mu^-$ followed by W combining with neutron to become a proton: $W^+ + n \to p$. In both the cases we demonstrated how the charged current (W^+ or W^-) comes into the picture as intermediate step to explain the known weak decays.

The unification of electromagnetism and weak interaction also predicted the existence of a neutral exchanged boson,

As mentioned earlier the unification of electromagnetism and weak interaction also predicted the existence of a neutral exchanged boson, which was called Z^0. In anal-

Neutral current was discovered in 1973.

ogy with the charged current this is called neutral current interaction. An example of a neutral current interaction is: $\nu_e + p \to \nu_e + p$. This can be written in two steps via the exchange of Z^0 as follows: $\nu_e \to \nu_e + Z^0$ followed by the second step as $Z^0 + p \to p$. What is new and exciting is that the neutral current type of weak interaction was not known and not seen experimentally. One of the reasons for not seeing it experimentally was that the neutral current interactions are more difficult to detect than the charged current ones, because the neutral current interactions can be easily confused with the neutron interactions. It is easy to remember that in the charged current case a neutrino gets converted into its corresponding charged lepton ($\nu_e \to e^-$, $\nu_\mu \to \mu^-$), while in the neutral current case a neutrino remains as neutrino ($\nu_e \to \nu_e$, $\nu_\mu \to \nu_\mu$), (*Figure* 2).

The first experimental evidence for the observation of neutral current events came from the Gargamelle bubble chamber at CERN in 1973. The bubble chamber was one of the very important detectors for particle physics experiments during the 1960s and 1970s. The detector consisted of a cryogenic liquid in a magnetic field; a charged particle leaves bubbles along its path which are then photographed by three or more cameras. The discovery of the neutral current interactions in bubble chamber proved to be a keystone in establishing the electroweak theory. The second part of the story of the electroweak theory is the heavy bosons $W^\pm$ and Z^0, which were not yet detected then. As these bosons are heavy, they can be produced only in very high energy interactions. A specially designed antiproton-proton collider was constructed at CERN to look for W and Z bosons. Two independent international collaborations, called UA1 and UA2, carried out the searches at CERN and they discovered the W^+ W^- and Z bosons in 1983. Carlo Rubbia and Simon Van der Meer shared the Nobel Prize in 1984 for this discovery.

Now with the electroweak theory in good shape, another sector dealing with the strong force was getting developed under the name of quantum chromodynamics, QCD in short. This theory postulated the existence of massless particles called gluons by which the quarks are held or glued together. The existence of gluons was confirmed at the DESY laboratory, Germany, in 1979. The gluons as carrier of the inter-quark force plays a role analogous to that of the photon in electromagnetism, but the strong force is very different. Each of the quarks occurs in three varieties and this new variety is due to what is called 'colour' of the quark (this colour has nothing to do with the usual colour we see in nature). Just to distinguish the colours, one normally calls the three colours: red (R), green (G) and blue (B). As an example the up quark (u) is of three types: u(R), u(G) and u(B). The force carrier gluons also possess the novel feature of having colours as one of their intrinsic properties. As a matter of fact, the word chromodynamics stands for the colour of the quarks. The two important features of QCD are: asymptotic freedom and confinement. Asymptotic freedom means that the effective force between two quarks becomes weaker as they approach each other. As a result when the quarks are close enough the force becomes so weak that the quarks can be considered as being free inside a hadron. The property of confinement prevents colour charges from getting separated, such as individual quarks and gluons, because the interaction, in QCD, between colour charges increases with increasing separation; if the force becomes too much the excess energy of the quark is released by emitting a gluon ($q \rightarrow q + g$). As a result quarks cannot be seen in nature as free particles like electrons and protons.

QCD predicts massless particles called gluons by which the quarks are held together.

The two theories, the electroweak theory and the QCD, form two pillars of what we call the Standard Model of elementary particles. This model assumes three generations (or families) of quarks and three generation of lep-

Table 2. Three generation of leptons and quarks.

1st generation	2nd generation	3rd generation	Charge
ν_e	ν_μ	ν_τ	0
e^-	μ^-	τ^-	-1
u (up)	c (charm)	t (top)	+ 2/3
d (down)	s (strange)	b (bottom)	- 1/3

tons, see *Table* 2. Quarks are called (up, down), (charm, strange) and (top, bottom). Leptons are called (electron, electron-neutrino), (muon, muon-neutrino) and (tau, tau-neutrino); all neutrinos are assumed to be massless and neutral. Some examples of quark contents of particles are given in *Table* 3. With increasing generation number the particles become heavier. Among the quarks the heaviest one is the top quark which is nearly two hundred times heavier than the proton, bottom quark is nearly five times the proton, the charm quark is nearly two times heavier than the proton, and the rest of them are lighter ones. Among the charge leptons, tau-lepton is nearly 3500 times heavier than the electron (or two times heavier than the proton), and the muon is nearly two hundred times heavier than the electron.

How do these particles and the force carriers W and Z acquire their masses? Newton gave us the relation between mass and the weight and Einstein taught us the equivalence between energy and mass, but nobody explained to us how anything acquires mass in this mysterious universe. The Standard Model has tried to give

Table 3. Examples of quark contents of particles.

Particles	Quark contents	Particles	Quark contents
proton	uud	K^+	$u\bar{s}$
neutron	udd	K^0	$d\bar{s}$
π^+	$u\bar{d}$	K^-	$\bar{u}s$
π^-	$\bar{u}d$	$\bar{K}^0$	$\bar{d}s$

Box 4. CP violation

Neutral kaons were known in early 1950s to decay into two pions, $K^0 \to \pi^+ + \pi^-$, with short decay lifetime of $\approx 10^{-10}$ sec. They are produced via strong interaction, a typical example of the reaction is: $\bar{p} + p \to K^0(S = +1) + \bar{K}^0(S = -1)$, where S is the strangeness quantum number (all particles containing a strange quark have strangeness quantum number with value +1 or -1), which is conserved in strong interactions. The weak interaction was known not to conserve the strangeness quantum number, as is seen from K^0 decay, where the two pions have a total strangeness as zero, while the neutral kaon has +1. However, it was believed that CP was a good quantum number. Based on this, Gellmann and Pais in 1955 constructed two eigenstates with opposite CP from neutral kaons:

$$\begin{aligned} K_1 &= (K^0 + \bar{K}^0)/\sqrt{2}, \ (\mathrm{CP} = +1) \\ K_2 &= (K^0 - \bar{K}^0)/\sqrt{2}, \ (\mathrm{CP} = -1). \end{aligned}$$

They argued that CP of $(\pi^+\pi^-)$ in neutral kaon decay is even, that is +1, and hence K_1 can decay into two pions, while K_2 will not. But K_2 can decay into three body final states: $K_2 \to \pi^+\pi^-\pi^0$, $\pi^- e^+ \nu_e$, etc. They further argued that the decay lifetime of K_2 particle will be much longer than K_1 because of restricted phase space available for the K_2, and hence a prediction was made for the existence of a longer lived component of neutral kaons. A search was made for the K_2 particle by a number of groups and within a year one could identify it with a lifetime about 580 times longer than the K_1. Following the discovery of parity violation in 1957, it was believed that the CP operation may still be valid in weak interactions. However in 1964, an experiment conducted by Christenson, Cronin, Fitch and Turlay demonstrated that the long-lived neutral kaons also decays to two pion mode in one out of 500 decays. Thus the CP violation was discovered. J W Cronin and V L Fitch were awarded Nobel Prize in 1980 for this discovery.

mass to particles via what is called the Higgs mechanism. The Higgs mechanism is due to Peter Higgs and others who predicted that the Universe is permeated by an undetected form of field carrying energy, which on interaction with massless elementary particles gives masses to them. The field is called Higgs field and the particle corresponding to the field is a neutral particle named as Higgs particle. The hunt is on for the Higgs.

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Why three generations of quarks and leptons in the Standard Model? It is needed, as proposed by Kobayashi and Maskawa in 1973, to accommodate the anomalous decays of neutral particle called kaon. These neutral kaons (K^0) and its antiparticle ($\bar{K}^0$), when they decay, were found to violate a symmetry principle called CP in 1964; here C stands for charge conjugation, which exchanges particles and antiparticles, and P stands for parity that is viewing the scene in a mirror (*Box* 4). In passing it is worth noting that this violation of CP led Andrei Sakharov in 1967 to propose a possible linkage of the CP violation to the matter dominance of our universe, that is to explain the non-observation of any antimatter in the universe (matter and antimatter are supposed to have been created with equal amount in the Big Bang theory of the expanding universe).

Conclusion

In this first part of the article on LEP detector, we have described in brief the standard model for the fundamental constituents of matter. We have also described the experimental supports for the electroweak theory and quantum chromodynamics, which are the two pillars of the standard model. In the next part of the article, we will focus on the LEP detector and the measurements that have been carried out with it.

Suggested Reading

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