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Building Blocks of the Universe-Discoveries in 20th Century

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ABSTRACT

The revelation of the substructure of matter in 20th century is reviewed. Since the beginning of the century three layers of matter, atoms to nucleons to quarks have been uncovered. At present, the leptons and quarks are considered as the fundamental building blocks of the universe, which are interacting via exchange of gauge bosons, namely, photons, W and Z bosons and gluons.

1. INTRODUCTION

The building blocks of the universe can be identified in various forms. The most fundamental form of the building block can be considered as block of matter that cannot be divided into substructures. Here we consider most elementary structure, which is indivisible, as the building block. In other words one can consider most elementary or fundamental particles as the building blocks of the universe. What are the building blocks of the universe? Have we discovered them experimentally? In this article, the discoveries of building blocks of the universe during the 20th century are reviewed.

The physicists in the 20th century have been very successful in revealing the structure of matter. Three successive layers of matter have been revealed during this period. At the dawn of the century, in 1879, Crookes suggested that the cathode rays observed within Crookes tube (or cathode ray tube) consist of streams of negatively "charged molecules". In 1897, the English physicist Joseph John Thomson later confirmed that the rays consisted of charged particles of matter. The discovery of these charged particles is generally attributed to Thomson and the particle is called electron. The American physicist Robert A. Millikan reported an accurate measurement of the electron's charge. Electrons are the lightest particles that have an electric charge. The electron is not known to have substructures, hence considered as a fundamental particle.

At the beginning of the 20th century, in 1905, Albert Einstein proposed the existence of "energy packets" or quanta of light in explaining the photoelectric effect. These quanta are

named as photons or γ -particles. Photons are now believed to be the mediator of interaction between electrically charged particles like electrons.

2. THE STRUCTURE OF THE ATOM

Immediately after the discovery of the electron, Thomson realized that the electrons must be a part of the atom. He proposed a model, the plumb-pudding model of the atom, in which negatively charged electrons were embedded in a positively charged sphere. Although Thomson's description was far from correct, his view suggested that the atom could no longer be considered as a fundamental building block. His work encouraged other scientists to investigate the structure of the atom.

In 1911, the British physicist Ernest Rutherford, a former student of Thomson's bombarded thin sheets of gold with alpha (α) particles from radioactive materials. Most of the particles passed through the sheets, except for few particles that bounced back as if they had hit something hard. Based on the result of the experiment Rutherford concluded that these particles had been reflected by a strong force from a small, but a heavy object, which is considered as the nucleus of the atom. Rutherford declared that nearly all the mass of an atom is concentrated in the nucleus. He also stated that electrons are traveling at very high speeds through the atom's outer regions that surround the nucleus. However, Rutherford's theory did not explain the arrangement of electrons in atoms.

In 1913, Niels Bohr, a Danish physicist, first proposed a description of the electronic structure of the atom. He proposed that electrons could exist only in a certain set of orbits around the nucleus. Although many ideas behind his model were correct, Bohr's simple picture of the atom was inadequate. A French physicist, Louis De Broglie proposed the concept of wave-particle duality, namely, the wave nature of electrons, in 1924. The correct description on the electronic distribution of the atom was established in 1928, after the development of quantum mechanics. A several physicists, especially Erwin Schrödinger and Wolfgang Pauli of Austria and Max Born and Werner Heisenberg of Germany, have made significant contribution in understanding the electronic distribution of the atom. The complete description of the structure of the atom in terms of the nucleus and electrons can be considered as the revelation of the first layer of matter during the first three decades of the 20th century.

3. THE STRUCTURE OF THE NUCLEUS

Although the proton had been found in 1902 and Rutherford had proposed in 1914 that they must form part of the nucleus, the structure of the nucleus was not known until 1919. In 1919, Rutherford produced the first artificial transmutation by bombarding nitrogen with alpha particles and the particle emitted was called proton. He proposed that the proton must be a part of the nucleus. However, by this time, scientists suspected that the nucleus could not consist of only protons. James Chadwick, a British physicist, in a study of reactions induced in boron by α particles, discovered the neutral partner of the proton, the neutron, in 1932. The discovery of the neutron immediately provided a firm foundation for the explanation of the nuclear structure. However, unlike the proton, a free neutron, a neutron outside the nucleus, is not stable but undergoes β decay into a proton with a half-life of 12 min.

The studies of properties of radioactive nuclei, namely, the β decay ($Z \rightarrow Z-1 + e^-$) processes led to the discovery of a new particle. It was found that the energies and momenta of daughter nucleus and the electron did not add up to those quantities of the parent nucleus. These results suggested that energy and momentum might not be conserved in β decay process, although they appear to be conserved in every other type of processes. The Austrian-Swiss theoretical physicist Wolfgang Pauli suggested an explanation of β decay that is consistent with the conservation law of energy and momentum in 1930. Pauli pointed out that the energy and momentum could be conserved in the process if the excess energy and momentum were carried off by a particle of very small mass that did not possess an electric charge and hence that would be difficult to detect. The Italian-American Physicist Enrico Fermi, who gave the name neutrino, meaning little neutral one, to the missing particle, developed Pauli's suggestion further. He, also, formulated a theory of nuclear β decay in terms of point interaction between neutron, proton, electron and neutrino (ν). These neutrino particles interact very weakly with matter. After a long delay, in 1956, the American physicists Frederick Reines and Clyde L. Cowan, Jr. detected a neutrino beam came from a nuclear reactor.

4. PARTICLE ACCELERATORS

After the Rutherford experiment scientists had realized the need of high-energy beams of particles for the revelation of the structure of matter. Higher the energy of the particle the

lower the associated wavelength and hence the fine details of the target can be uncovered. These needs have forced scientists to the construction of particle accelerators.

The particle accelerators are devices that produce beams of subatomic particles of extremely high energies. Physicists John D. Cockcroft of Britain and Ernest T. S. Walton of Ireland invented the first accelerator in 1929. The Cockcroft-Walton accelerator, a linear machine, was the first accelerator to break up atomic nuclei. In 1932, they used it to accelerate protons to 500 keV and break up nuclei. Today's machines speed up protons, antiprotons, electrons, positrons and ions.

A Cockcroft-Walton accelerator has a long pipe with an electrode (electric terminal) at one end. This electrode receives a high voltage of the same kind--positive or negative--as the particles to be accelerated. At the other end is an electrode whose voltage is zero. This electrode has a hole through its center and is connected to the first electrode by a tube that carries the beam. Most of them later have served as beam sources for more powerful accelerators.

1931 United States physicist Robert J. Van de Graaff built his first high-energy accelerator. The Van de Graaff generator can accelerate protons, electrons, and ions to about 15 MeV. Hundreds of such accelerators have been built, more than all other types combined.

The pioneers of nuclear physics did not expect that they would soon see a practical use for their knowledge. In 1938, however, researchers discovered that bombarding the nucleus of a uranium atom with a neutron caused the nucleus to split into two parts and release energy. They called the process nuclear fission. The discovery came a few months before the start of World War II in 1939, and fission was used in atomic bombs that helped end the war in 1945.

The technology of particle accelerators was developed rapidly during the period of 1960s to 1980s from linear accelerators, proton synchrotrons to collider beams. The longest linear accelerator in the world was built at Stanford Linear Accelerator Center (SLAC) in Palo Alto, California, which is a 3.2 kilometers long traveling-wave device. This machine was operational since 1966 and could accelerate electrons up to 25GeV. A circular structure was added to one end of this machine in 1989 so that a beam of electrons and a beam of positrons, each with energy up to 50 GeV, could accelerate in opposite directions. The collider beam experiments are more advantages in the discovery of heavy particles due to higher available energy for particle production.

An American physicist Ernest O. Lawrence invented the cyclotron, the simplest circular accelerator, in 1930 and received the 1939 Nobel Prize for physics for this achievement. The diameter of the magnet and the strength of the magnetic field limit the energy of a particle in a cyclotron. The largest cyclotron ever built could accelerate protons to 720 MeV.

The synchrotron built at Fermi National Accelerator Laboratory (FNAL or Fermilab) near Batavia, Illinois, is the most powerful (highest beam energy) accelerator in the world to date. This machine, which lies in a tunnel of 6.3 kilometers in circumference, accelerated protons to 400 GeV in 1972. This machine was converted to a collider, in 1987, by mounting superconducting electromagnets in the tunnel so that beams of protons could collide with beams of antiprotons, which are accelerating in opposite direction, each with energy up to 900 GeV. Fermilab has undergone a major five-year upgrade since 1996 and back in operation from 2001. The new machine can speed up protons and antiprotons to 980 GeV with a collision rate (luminosity) boosted by twenty-fold. This machine is expected to run until 2007, with interruptions only for maintenance and upgrades, and scientists are optimistic to make major discoveries in the upgraded machine.

The world's largest (27 km circumference) accelerator is the LEP (Large Electron-Positron) synchrotron at the CERN research center near Geneva, Switzerland. LEP had energies of about 45 GeV per electron and positron beam when it began operations in 1989. CERN scientists changed the name in 1996 to reflect a major increase in beam energy. LEP2 could collide electrons and positrons at energies of 87 GeV per beam in 1996. With the incorporation of superconducting cavities providing higher accelerating fields the machine has delivered 100GeV beams in 1999. After many discoveries, CERN management finally closed LEP2 forever on November 02nd, 2000 and prepared the way for the construction of a new accelerator, LHC (Large Hadronic Collider). The LHC, which is under construction, is a highly complex project, both technically and organizationally. The accelerator and the detectors involve sophisticated technologies, in many cases on industrial scales never attempted before in a scientific project. This machine is designed to deliver proton beams of energy 7 TeV amounting to the collision energy of proton-proton of 14 TeV and expected to be operational in 2006.

Some of the high-energy particle accelerators in the past and at present are listed in Table 1 and Table 2. Some of them are not operational at present.

Table 1: Proton synchrotrons

Name/Location	Energy (GeV)	Date Started
CERN PS, Geneva	28	1959
CERN SPS, Geneva	500	1976
BNL AGS, Brookhaven	32	1961
KEK, Tokyo	12	1979
Serpukhov, USSR	71	1967
Fermilab, Illinois, USA	400	1972
Fermilab, Illinois, USA	900	1987

Table 2: Collider Beams

Machine/Location	Energy (GeV)	Particle	Date Started
PETRA, DESY, Hamburg	23+23	$e^+ e^-$	1978
PEP, Stanford	15+15	$e^+ e^-$	1980
CESR, Cornell, NY	6+6	$e^+ e^-$	1979
TRISTAN, Tokyo	32+32	$e^+ e^-$	1987
SLC, Stanford	50+50	$e^+ e^-$	1989
LEP, CERN(27km)	45+45	$e^+ e^-$	1989
	87+87	$e^+ e^-$	1996
	100+100	$e^+ e^-$	1999
CERN (6.9km)	315+315	$p\bar{p}$	1981
Tevatron, Fermilab(4.2km)	900+900	$p\bar{p}$	1987
	980+980	$p\bar{p}$	2001
HERA, Hamburg	30e+820p	ep	1992

5. COSMIC RAY EXPERIMENTS

During the late 1800's, physicists used electroscopes to study radioactivity. An electrically charged electroscope loses its stored charge when exposed to high-energy radiation.

Surprisingly, a loss of stored electric charge was detected even when the electroscopes were shielded from the most powerful rays known to be given off by radioactive substances. In 1912, the Austrian physicist Victor F. Hess, by taking electroscopes up in a balloon demonstrated that the unknown radiation increased with altitude. Hess concluded that the radiation must originate in the upper atmosphere or beyond. In 1936, he received the Nobel Prize for physics for discovering cosmic rays. Cosmic rays are the flux of energy in the forms, first, of high-energy particles that are incidents upon the earth's atmosphere from outer space (primaries) and, second, of particles that the incident primary flux produces in the earth's atmosphere (secondaries). A large number of particles have been discovered through cosmic ray experiments since early 1930s.

In 1932, the American physicist, Carl D. Anderson, in analyzing cloud-chamber tracks of cosmic-ray particles had detected a track that appeared to be the track of a particle equivalent to an electron but with positive charge. Anderson called this particle *positron*, as the positive charged equivalent of the negatron, the negatively charged electron. The existence of a positively charged counterpart to the electron had been proposed before its discovery. In 1930, the British theoretical physicist Paul A. M. Dirac describing his relativistic quantum theory for electrons (spin-half particles) first introduced the concept of antimatter, the antiparticle of the electron – electron with positive charge.

In 1934, the Japanese theoretical physicist Hideki Yukawa proposed a model for nucleon-nucleon interaction. He deduced directly from the principles of quantum mechanics that a consequence of the short range of nucleon-nucleon interaction is that the particle associated with the interaction has a nonzero rest mass. He estimated the mass of the particle to be about 200 times the mass of the electron. This particle was called mesotrons, now contracted to *mesons*. Almost immediately after the prediction, C.D. Anderson and S.H. Neddermeyer discovered a particle of about the same mass in their cosmic-ray tracks of the cloud chamber experiment. However, in 1943 it was shown that the particle detected didn't interact strong enough with nuclei to consider as the mesotron of Yukawa. Physicists were convinced that the particle detected by Anderson was not the mesotron but a new particle. These particles are now known as muons (μ). The muon is identical to electron except the mass; the muon is much heavier than electrons. The meson of Yukawa was discovered as a component of cosmic rays in 1947 by the English physicist Cecil F. Powell and his colleagues. These particles are called π mesons or pions. Three kinds of pions (π^- , π^+ (the antiparticle of π^-) and π^0) exist.

By 1947, it seemed that the behaviour of matter could be explained completely in terms of the known particles as the building blocks, although the theories were not adequate enough. The neutrons and protons interacting via the exchange of pions make the nucleus and nucleus and electrons interacting via the exchange of photons make the atoms. The neutrino explained the β decay and antiparticle was needed to satisfy the relativity theory. Only the muon did not fit into this scheme.

The destruction of this simple scheme began in late 1947 with the discovery of another cloud-chamber photograph of cosmic ray event reported by G.D. Rochester and C.C. Butler of the University of Manchester. They discovered the decay products of a particle of rest mass about 500 MeV, which was not known previously. One of these particles was a neutral particle decayed into two charge particles providing V shape tracks in the cloud-chamber. These particles were initially called V particles.

6. STRANGE PARTICLES

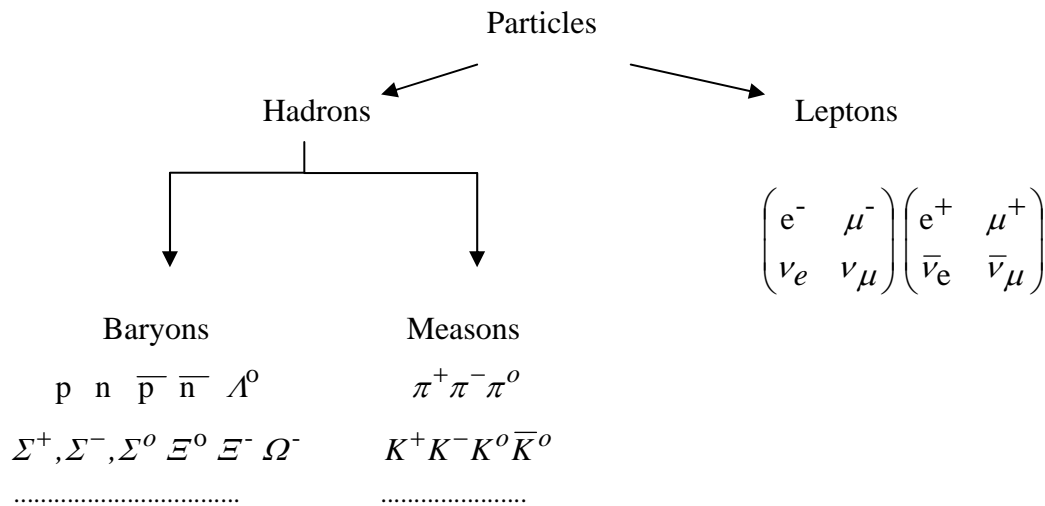
The study of V particles in the cosmic radiation was supplemented in the early 50s when the particle accelerators were operational. The man-made V particles could be investigated under laboratory conditions. It was found that they were produced in abundance in high-energy collisions, for example, of fast negative pions incident on protons. There is a large disparity between the production rate and the decay rate of these V particles. The typical time for their production was found to be about 10^{-23} sec, which is a typical strong interaction. On the other hand, the characteristic decay time is about $10^{-8} - 10^{-10}$ sec, a time typical for weak interactions. This puzzling feature, strong production and weak decay, of the behaviour of these particles led to the V particle being called strange particles. The Dutch-American theoretical physicist Abraham Pais resolved this paradox, strong production and weak decay, by introducing the associate production of strange particles. This hypothesis predicted that the strange particles were created in pairs, and once they were separated and isolated from each other they cannot decay in the same manner by which they were produced. This principle was related to a conservation law in 1953 by the Dutch-American theoretical physicists Murray Gell-Mann and independently by the Japanese physicists Kazuhiko Nishijima. They introduced a dynamical variable strangeness, S, which is conserved in strong interaction but not conserved in weak interaction. The 500 MeV strange particle is called K-mesons and associated particle is

called Λ hyperon. Some of the other early detected strange particles were sigma ($\Sigma^+, \Sigma^-, \Sigma^0$), Ξ^0 and Ξ^- .

In late 40s the picture of the atom grew more complicated as physicists discovered more and more subatomic particles. In 1955, the American physicists Owen Chamberlain and Emilio Segre discovered the antiproton (a negatively charged proton). A large number of particles were identified in laboratories of high-energy experiments by early 1960s.

7. CLASSIFICATION OF PARTICLES

By 1960s the known particles were classified into several groups depending on their characteristics properties.



First, all particles were classified in to two groups, leptons and hadrons. By middle 60s four leptons and their anti-leptons were known. Hadrons were divided in to two groups, mesons and baryons as shown above. A large number of mesons and baryons were discovered in cosmic-ray experiments and in particle accelerator experiments. The continuing discovery of more and more "elementary" particles showed no signs of abating. Several hundreds of hadrons are known to date.

8. QUARK SUBSTRUCTURE OF HADRONS

Further studies of properties of hadrons indicated that all properties of baryons and mesons could be explained if they were consisting of three and two hypothetical particles,

respectively. In 1964, two California Institute of Technology physicists, the American Murray Gell-Mann and Russian-born George Zweig, proposed the quark (the name given to hypothetical particle) hypothesis. They suggested that baryons could be made out of three flavours of quarks and mesons could be made out of a quark and an anti-quark. These three flavours were named up, down and strange quarks.

In 1968, the high-energy electron beam at SLAC was used to probe the structure of the proton. It was found that the electrons were scattered with large transfer of momentum more frequently than had been anticipated, which indicated that the proton consists of discrete scattering centers. The energy and angular distributions of scattered electrons exhibited a phenomenon called scale invariance that indicated the scattering centers had no internal structure and hence point-like particles. In 1969, introducing a theoretical model (parton model) to explain these results Richard Feynman called them "partons". These experiments were continued with particle colliders. Two protons collided each other produced particles with large momentum transverse to the collision axis with larger probability than expected which indicated the existence of scattering centers, or partonic structure, within the proton. It was easily realized that the partons have the same properties of quarks.

The conclusion of the above experiments was the hadrons were not elementary but were made of partons. There appear to be two types of partons, electrically neutral particles that are called gluons and fractionally charged quarks (u, d and s). Proton consists of (u,u,d) and neutron consists of (d, d, u). These assigned quarks for each hadron are called valence quarks. Strange particles contain at least one s-quark. However, at high energies there is a probability to find any other quark or anti-quark (called sea quarks) in addition to valence quarks and gluons in a given hadron. The structure of all observed hadrons until 1974 could explain in terms of u, d and s quarks.

However, in 1970, Glashow, Iliopoulos and Maiani had indicated the possibility of existing the fourth quark in their theoretical studies. In 1974, two groups (SLAC and BNL) independently discovered the fourth quark, called charm (or c-quark). $e^+ + e^-$ collisions at SLAC produced a sharp resonance at 3.1 GeV and the introduction of charm quark with mass $1.6 \text{ GeV}/c^2$ was necessary to explain this resonance which was called ϕ . Same result was seen at BNL by colliding protons on Be target and they called it J/ψ .

Another sharp resonance was discovered at 3.56 GeV in 1975 at Stanford (PEP). A new particle very similar to muon but heavier ($1.78 \text{ GeV}/c^2$) than muon was introduced to explain this result. This particle was called tau (τ) lepton and this discovery expanded the lepton family to third generation. In comparing with the other two lepton families it was almost certain the existence of ν_τ , the tau-neutrino.

Another narrow resonance in the energy region 9.5-10.5 GeV was observed at Fermilab in 1977 in a fixed target experiment, proton beam colliding on Be, Cu or Pt targets. This state is called Y . A quark-like particle but heavier than all the known quarks was needed to explain this result. Bottom quark (b-quark) of mass $4.5 \text{ GeV}/c^2$ was introduced to explain the observations, which led to the third generation of quarks. Soon after the discovery of b-quark the existence of a 6th quark were expected due to the symmetry properties. This quark was named top (t-quark).

During the period of 1967-1968 a great theoretical development has been taken place after the realization that non-Abelian gauge field theories may play a role in high-energy physics. The most celebrated non-Abelian theory, unified field theory of weak and electromagnetic interactions was developed by Abdus Salam (Pakistani) and Steven Weinberg (American) with the incorporation of some previous (1961) ideas of Sheldon.L.Glashow (American), which is normally called the Weinberg-Salam model or Electroweak Theory. This model postulated that the weak and electromagnetic interactions occur through coupling of the fermions to weak isospin and weak hypercharge gauge vector bosons. In this original model gauge bosons and all particles were massless. (Glashow, Salam and Weinberg received 1979 Nobel price for this work) This theory became realistic after 't Hooft (1971) proved that if the particles and three of the gauge bosons acquire masses by the mechanism of spontaneous symmetry breaking then the theory remains renormalizable. This theory predicted the existence of new particles, three massive vector Bosons (W^+ , W^- and Z^0 Gauge Bosons) and a massive scalar Boson (Higgs Boson). These three gauge bosons were discovered at CERN's super-proton synchrotron (SPS), the laboratory's most celebrated achievement, in 1983. The leaders of the experiment Carlo Rubbia & Simon van der Meer received the Nobel Prize in 1984 for the discovery.

It should be pointed out that one of the most important contributions to the modern technology from high-energy physics is the development of World Wide Web. Scientists at CERN invented this in 1990 as a tool for scientists at high-energy physics laboratories to

collaborate with their colleagues, which has been extended to many applications worldwide today.

During late 80s and early 90s experimental physicists attention was focused on finding the two missing pieces in particle physics, the top quark and the Higgs particle. Finding the top was more difficult than finding a needle in a Haystack. Out of every trillion proton-antiproton collisions, about ten top-antitop quark pairs are produced. Physicists had to search out these desirable events. Top cannot be directly seen in particle detectors, since they have very short lifetime. Physicists can identify a top quark by looking at its descendants. Quarks and gluons appear in a detector as a narrow spray of particles called a jet. When physicists observe the decay products, they can infer that top has been created. Although, the existence of top was expected since 1977, after 18 years, two experimental groups D0 and CDF at FNAL discovered it in 1995. As of October 1998, the best measurement of top mass is $174.3\text{GeV}/c^2$ which is two orders of magnitudes higher than the bottom quark.

The other missing piece of the puzzle is the Higgs particle. All searches, in particular at CERN electron-positron collider, so far have failed to detect this particle and has set the lower mass limit to be about 114.3 for the standard model Higgs. In addition to Higgs, physicists are searching for supersymmetric (SUSY) partners of known particles. SUSY is a generalization of the space-time symetries of quantum field theory that transforms fermions into bosons and vise versa. It also provides a framework for the unification of particle physics and gravity. Each known fermion and boson should have an associated supersymmetric boson and fermion, respectively. However, no signs of existence of SUSY particles detected so far. At present, physicists at FNAL have more chances of detecting these particles, if they exist. However, we may have to wait until the construction of the new particle accelerate at CERN, the Large Hadronic Collider (LHC), is completed (by 2006?) to conclude the faith of these missing pieces.

As of today, one can consider 6 quarks and 6 leptons with their anti-particles as the fundamental building blocks of the universe, while photons, W and Z particles and gluons mediating the interactions among the particles. The structure of the ordinary matter that can be seen experimentally depends on the resolution of the experiment. The molecules, atoms, nucleus, protons and quarks can be seen in length scales of 10^{-9} , 10^{-10} , 10^{-14} , 10^{-15} and 10^{-19} m, respectively. The obvious question, are these particles really indivisible? Attempts

have been made to probe the structure of quarks, but at the present energy scales no structure has been seen yet. However, the compositness search continues.

The ordinary matter composed of baryons, essentially protons and neutrons, and electrons. Therefore they made of mostly up and down quarks and electrons. However, it should be pointed out that the matter in the form of beryons is responsible for only a tenth of total matter that produced the observed gravitation of the universe. The rest of the universe appears to consist of non-baryonic "dark matter" of an as yet unknown nature and "dark energy", the repulsive force that is considered to be responsible for accelerating the rate of expansion of the universe.

A collection of all relevant references and more technical details on particles and their properties is available in the web site given below.

References:

1. <http://pdg.lbl.gov>