Lancaster Particle Pamphlets

Number 4 The Elementary Particles

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Elementary Particles Contents

The Elementary Particles

Introduction

The purpose of this pamphlet is to introduce the reader to the collection of particles that are believed to be the building blocks of the universe. Some of the physical characteristics of these particles are accurately known, for example their electric charges. Other characteristics are shrouded in mystery, for example, no one knows their dimensions and they may even be point like objects. There is a relatively small number of types of elementary particle and all members of each type are identical. The current list has six types of *quarks* and six types of *leptons*. This makes twelve types in all and if we include the *antiparticles* of each type, there are twenty-four types. Some people think this is too many! Others think it is too few and are convinced more must soon be discovered. However we can only describe the current situation and hope it is not completely out of date by next year.

This introduction will introduce the particles in approximately historical order and some attempt will be made to explain their curious names. However, no attempt will be made to follow all the experimental and theoretical work that lead to the current picture. Thirty years ago, the author was involved in experimental tests of the "quark model". It was probably true that most experimentalists then believed that quarks must exist because the model seemed to make such dramatically correct predictions! However, many theoretical physicists did not believe in quarks because there was no proper fundamental theory to describe their behaviour! Today there is such a theory and we will outline some of it in later pamphlets.

M. Gell-Ma
and G. Zwe
introduced t
quark mode
1963

The Leptons

The First Family

The word "lepton" is derived from a Greek word and essentially means "light particle". The first lepton was discovered one hundred years ago by J. J. Thomson and is the familiar electron. The mass and charge of the electron have been accurately measured and are quoted here to just two decimals:

$$m_e = 0.51\,\mathrm{MeV/c^2} \qquad q_e = -1.60\times10^{-19}\ \mathrm{C}$$

The charges of elementary particles are always *quoted in units of the magnitude of the charge on the electron*. We will use capital Q to represent charge in this way:

$$Q_{\mathrm{e}} = q_{\mathrm{e}} / |q_{\mathrm{e}}| = -1$$

Enrico Fermi
Italian/Ameri
physicist. (19
– 1954)

Another fundamental property of the electron is its *spin*. The spin is the unique angular momentum possessed by each electron. This is not to be confused with angular momentum due to orbital motion around a nucleus and is intrinsic to the electron. The spin is determined by the spin quantum number s as shown briefly in the appendix. Electrons and indeed *all* the leptons and quarks have the spin quantum number $s = 1/2$. Historically all particles with spin quantum number ½ are known as “Fermions” after the famous Italian physicist Enrico Fermi.

The partner to the electron to make up the first family of leptons is the *electron neutrino* given the greek symbol n_e. This is pronounced “ nu subscript *e*”. The first indications of the existence of the neutrino were given by the details of nuclear beta decay. We will take a close look at beta decay from the quark and lepton view in P8.

The neutrino has zero charge, mass less than $10\,\mathrm{eV/c^2}$ and spin quantum number ½. We put the electron and electron neutrino together as a pair like this:

$\begin{pmatrix} n_e \\ e^- \end{pmatrix}$ the first family of leptons

Paul Dirac
predicted the
existence of th
positron in 193
Carl Anderson
found it in 193

The antiparticle to the electron was discovered in the 1930’s. It has the same properties as the electron, except its charge is positive. We call it the *positron* or anti-electron and give it the symbol e^+. There is an electron antineutrino, distinct from the electron neutrino, paired with the positron to make the first family of antileptons. The electron antineutrino has the symbol $\bar{n}_e$ (“nu bar subscript *e*”). We shall have much more to say about antiparticles in later pamphlets.

$\begin{pmatrix} \bar{n}_e \\ e^+ \end{pmatrix}$ the first family of antileptons.

The Second Family

Here on the Earth’s surface we are continuously bombarded by cosmic radiation. If you hold your hand out horizontally then roughly one cosmic ray particle per second will pass through it. Measurement made many years ago showed that 90% of these high-energy particles behaved like very heavy electrons and 10% were ordinary electrons. The heavy electrons were given the name "muons" and the Greek symbol μ (mu). The muons were found to have charge $Q = +1$ or $Q = -1$ and mass $m_\mu = 105.7\,\text{MeV/c}^2$. A single muon has a mass roughly two hundred times the mass of an electron.

Later experiments using accelerators to create large numbers of muons showed that each decays with mean lifetime 2.2×10^{-6} s into an electron and *two neutrinos*. One of the neutrinos is the ν_e (or the $\bar{\nu}_e$) and the other is a new kind of neutrino associated only with the muon. This neutrino is the muon neutrino ν_μ (pronounced "nu subscript mu"). The mass of the muon neutrino is less than $0.17\,\text{MeV/c}^2$ and may even be zero. Now we have the second family of leptons. We bracket the *negative* muon with the ν_μ and the positive muon with the $\bar{\nu}_\mu$:

$\begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}$ the second family of leptons.

$\begin{pmatrix}\bar{\nu}_\mu\\ \mu^+\end{pmatrix}$ the second family of antileptons.

The Third Family

In 1975 Martin Perl and co-workers were conducting experiments with the new electron positron colliding beam machine called SPEAR at Stanford in California. They noticed a startling new reaction when the beam energy reached 1.78 GeV. Pairs of particles were produced with opposite charge each behaving like extremely heavy electrons and positrons. The new particles were given the name tau and the Greek symbol τ. They had discovered the third generation of leptons. The rest mass of the τ^+ or τ^- is $1.78\,\text{GeV/c}^2$.

Of course there are tau neutrinos and tau antineutrinos to partner the τ^- and τ^+. The mass of the tau neutrino is less than $24\,\text{MeV/c}^2$ and, like the other neutrinos, may well be zero.

$\begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}$ the third family of leptons.

$\begin{pmatrix}\bar{\nu}_\tau\\ \tau^+\end{pmatrix}$ the third family of antileptons.

The Quarks

The First Family

The quark model was developed forty years ago to explain and simplify the structure of protons, neutrons and many other nuclear particles produced in large numbers by the new high energy accelerators. However, it was not until 1968 that direct evidence was obtained for the existence of point like constituents of single neutrons and protons.

Ernest
Rutherford. 1
Baron Ruther
of Nelson. (1
– 1937)

You will recall that the nucleus was discovered by Rutherford who scattered alpha particles of 5 MeV from thin foils. The number of alphas scattered at *large* angles was very much greater than expected from the Thomson “plum pudding” model and proved the existence of a tiny nucleus inside the atom carrying the positive charge and most of the mass.

In 1968, teams used the two-mile long linear accelerator, again at Stanford, to fire 20 GeV electrons at liquid hydrogen and deuterium targets. They were looking at the electrons scattered at *large angles* from single protons and neutrons. History seemed to repeat itself! Far more electrons were scattered at large angles than would be expected from a smooth distribution of charge. Analysis of these experiments and other similar experiments in the USA and CERN Geneva showed that protons and neutrons contained three “quarks”. The quarks were spin ½ objects with charge +2/3 or –1/3. The size of the quarks could not be measured, but must be less than 10^{-18} m.. Today we call the quark with $Q = +2/3$ the “up quark” and it has the symbol u. The $Q = -1/3$ quark is called the “down quark” and has the symbol d. Simple arithmetic shows that the *charge* of the proton can be explained by the three quarks $u + u + d$. The neutron charge can be explained by $u + d + d$. These high-energy scattering experiments had established the first family of quarks. We can write them as a pair just like the lepton pair:

$\begin{pmatrix} u \\ d \end{pmatrix}$ the first family of quarks.

The antiquarks have the opposite charges to the quarks $Q_{\bar{u}} = -2/3$ and $Q_{\bar{d}} = +1/3$:

$\begin{pmatrix} \bar{u} \\ \bar{d} \end{pmatrix}$ the first family of antiquarks.

Physicists often refer to the two types of quark as *flavours*. There are two flavours in the first family: the up flavour and the down flavour.

The Second Family

In the early days of the quark model, it was always assumed that a third variety of quark should exist. This was called the "strange quark" and given the symbol *s*. Its role was to account for the behaviour of "strange particles". We will discuss strange particles in a later pamphlet, it is sufficient to say that the *s* quark should have spin ½, charge $Q_s = -1/3$ and mass greater than the first generation quarks. It seemed to form the bottom half of a second family of quarks but, until 1974, there was no sign of its partner. Even before its discovery, the second family partner was given the name "charm" and the symbol *c*. Its existence was crucial to the theories of particle physics at that time. Theoretical physicists were so convinced of its early discovery that one bet (and won) a crate of champagne!

Shortly before the tau lepton was discovered, Burton Richter and co-workers, also at the SPEAR machine, discovered a huge increase in the event rate when the colliding beam energy reached 1.50 GeV. Large numbers of a new particle were being produced. It was named the y particle. All the characteristics of the y were consistent with a charm quark and a charm antiquark bound together. The expected partner for the strange quark had been found. Simultaneously a group led by Sam Ting working at Brookhaven, but using a fixed target experiment, found evidence for the same particle. They named it the *J* particle. Since then, this particle has been known as the J/y! Further experimentation has confirmed the *c* quark has charge $Q_c = +2/3$, spin ½ and mass $1.50\,\mathrm{GeV/c}^2$.

Burton Richte
and Sam Ting
awarded the
Nobel Prize i
1976

It is interesting to note that Richter produced the J/y by colliding electrons and positrons. Ting produced the particle in a fixed target machine and identified it by its decay into electron positron pairs!

$\begin{pmatrix} c \\ s \end{pmatrix}$ the second family of quarks.

$\begin{pmatrix} \bar{c} \\ \bar{s} \end{pmatrix}$ the second family of antiquarks.

There are two flavours in the second family: The charm flavour and the strange flavour.

The Third Family

After the discovery of the charm quark, *symmetry* between leptons and quarks was becoming very clear. The leptons were spin ½ particles appearing in pairs with the charge difference of 1 between members of each pair. Each lepton family had an antilepton equivalent. The pattern was repeated with the 1st and 2nd families of quarks and antiquarks. The hunt was definitely on for the 3rd family of quarks. Sadly perhaps, the desire for silly names seemed to have diminished and the members of the 3rd family were named simply “bottom” and “top” and given the symbols *b* and *t*. (Some optimists preferred “beauty” and “truth” but that soon fizzled out!)

The first evidence for *b* quarks was found by Leon Lederman’s group in 1977 working at Fermilab near Chicago. They used a technique similar to Sam Ting’s successful charm experiment and fired 30 GeV protons at a fixed target. Conclusive evidence was found for a new particle with mass $9.4\,\mathrm{GeV/c^2}$ and it was named the Y (upsilon). The Y decayed into lepton-antilepton pairs, just like the J/y, and it was interpreted as a $b\,\bar{b}$ pair bound together. Each *b* quark has a mass of about $4.7\,\mathrm{GeV/c^2}$.

Indirect evidence for the *t* quark accumulated over the years particularly at the LEP colliding beam machine in CERN. However, it was the giant proton - antiproton collider built at Fermilab that finally produced the direct evidence for *t* quark production. The “Tevatron” collides 1000 GeV protons with 1000 GeV antiprotons. Events were observed showing *t* and $\bar{t}$ quarks decaying into *b* and $\bar{b}$ quarks and then into showers of leptons and pions. The teams of experimenters were able to measure the *t* quark mass at an incredible $174\,\mathrm{GeV/c^2}$, this is nearly 200 times the mass of a single proton! That was a clean sweep for the USA in discovering the three families of quarks. However, Europe has done well in identifying the so-called “force particles” W^+, W^-, Z^0 and the gluon. These will be the subjects of P5!

$\begin{pmatrix} t \\ b \end{pmatrix}$ the third family of quarks.

$\begin{pmatrix} \bar{t} \\ \bar{b} \end{pmatrix}$ the third family of antiquarks.

There are two flavours in the third family: The top flavour and the bottom flavour.

Any More Families?

Naturally the question arises, are there any more families of quarks and leptons? The answer is probably “no”. In later pamphlets we will discuss the properties of a very heavy particle with mass $91.2\,\mathrm{Gev/c}^2$ called the Z^0 . The Z^0 can decay into any lepton - antilepton pair including of course neutrino - antineutrino pairs. The probability of decay is the same for all pairs, provided the lepton mass is less than half the Z^0 mass. For example: $Z^0 \rightarrow n_e + \bar{n}_e, Z^0 \rightarrow n_m + \bar{n}_m$ and $Z^0 \rightarrow n_t + \bar{n}_t$ all have the same probability. The charged leptons in additional families could have high mass but the neutrinos are likely to have small or zero mass. The more lepton pairs there are the faster the Z^0 will decay and the shorter its mean lifetime. Measuring the Z^0 lifetime allows us to calculate the number of light neutrino types. The answer comes out at almost exactly *three*. There cannot then be any additional families with light neutrinos.