The Quest for Elementary Particles: From Atoms to the Higgs Boson

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1 Introduction

Elementary particles are the basic building blocks of the universe which cannot be broken down into smaller constituents. The quest for these building blocks started long ago and has been continuing ever since. However, as science and technology progressed **the concept of elementary particles had to be revised** time and again. This talk will be a story of this quest full of twists and turns.

In the 19th century the main experimental tools for studying the properties of matter were chemical reactions while John Dalton (1766 - 1844) and others built up the theoretical foundation: the atomic theory. According to the atomic theory the universe is made of elements like hydrogen, oxygen, carbon etc. The smallest unit of each element is an **atom** with its own characteristics. The more complex matter (i.e., the compounds) form due to combination of atoms of different elements in chemical reactions. However, the atoms themselves do not change in chemical reactions. This lead to the belief that the atoms are forever - **they cannot be created or destroyed**. But the idea had to be revised even before the end of the 19th century. Armed with a new instrument called the cathode ray tube Sir J.J. Thomson (1856 - 1940) proved that the atoms were indeed divisible. He showed that when the atoms in a metal plate are subjected to a strong electric field in a cathode ray tube, tiny negatively charged particles called **electrons** come out of them.

The next powerful experimental tools were streams of three types of particles, popularly known as α, β and γ rays, emitted by radioactive substances. By analysing the results of alpha particle scattering by gold atoms in a thin gold foil, Lord Rutherford (1871 -1937) concluded that almost the entire mass and positive charge of each atom is concentrated in a tiny, point like object called the **nucleus**. The rest of the atom consists of almost empty space apart from the tiny electrons moving in circular or elliptical orbits around the nucleus. Further research showed that even the tiny nucleus is made of smaller constituents: the positively charged **proton (p)** and the electrically neutral **neutron (n)**. Both are approximately 2000 times heavier than the electron ($m_p \approx m_n \approx 2000 m_e$). An important lesson follows from Rutherfords theory. Scattering high energy particles from a target one can learn a lot about the internal structure of the particles in the

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target. This method has frequently been applied by the physicists to learn more about the elementary particles.

Most of the stable matter that we ordinarily deal with are made of electrons, proton and neutrons. These along with the photons, the particles of light, constitutes the visible universe. But this is not the end of the story. There are many more particles whoose presence are not easily noticable because they are highly unstable with incredibly small average life times (10^{-6} - 10^{-23} sec). They have to be produced and detected by special experiments.

2 The Zoo of New Particles and the Quarks

The clue for producing these particles came from A. Einstein (1879 - 1955). We know that there are different forms of energy (heat, light, sound ......) and one form can be converted into another. Einstein proved that **mass is yet another form of energy**. Consider the collision of two particles A and B where the colliding particles have large kinetic energies. During the collision a part of the total kinetic energy of A and B can be converted into the mass of one or more new particles which can be created in the reaction without violating the conservation of energy. However, the task is technologically challenging since in order to produce even the smallest particle at least one of the colliding particles must be accelerated to very high energies.

During the early phases of new particle searches we had to depend on the natural sources of high energy particles - the **cosmic rays**. These rays are actually streams of high energy particles - mostly protons - coming from cosmic sources. They collide with the atoms in the earth's atmosphere and produce new particles. To detect the very short lived particles is not a simple task either. A number of novel particle detectors like cloud chambers, emulsion strips etc were designed using new technologies . The list of new particles thus discovered was impressive - the positron (1932), the μ (1937), the pi (π) meson (1947), the K -meson (1947), the Λ (1950) etc. The positron (e^+), the anti-particle of e^-, carries the same mass as that of electron but carries opposite electric charge. The anti-particles of most of the known particles like the antiproton ($\bar{p}$), antineutron($\bar{n}$) have been discovered.

However, particle discovery made a giant step forward with the advent of the man made particle accelerators. The circular accelerator Cycltron invented by E. W. Lawrence (1901 - 1958) in 1932 was the predecessor of the modern accelerators. In course of time accelerator physics and technology improved tremendously. Even the most powerful cyclotron could accelerate protons to energies of a few hundred million electron volt (MeV). The Large Hadron Collider (LHC) currently operating at CERN in Geneva can accelerate protons to energies of 13 TeV (1 TeV = 10^6 MeV). The top quark (see below) with a mass of approximately 170 m_p is the heaviest particle discovered at an accelerator till date.

In accelerator based experiments the particles could be produced in large numbers and their properties could be studied in much more details. Many new particles like the antiproton ($\bar{p}$)(1955), the Omega (Ω)(1964) etc were discovered as more energetic colliding particles were available. New detectors based on advanced technologies like the bubble chamber also helped the progress of particle physics in this era. However in course of time a huge number of very short lived particles called the resonance particles were discovered . Scientists now started doubting whether such large number of particles could indeed be elementary.

In 1964 M. Gell-Mann (1929 -; Nobel prize in 1969) proposed that all strongly interacting particles like the proton, the neutron, the π meson etc - collectively called **hadrons** - have smaller constituents. They are made of three particles - the **quarks**. According to the quark model there are three quarks, denoted by u,d and s. All the hadrons known till that time were shown to be made of these quarks and their antiparticles - the **antiquarks** ($\bar{u}, \bar{d}$ and $\bar{s}$). For example the proton is a uud bound state while the π^+ is made of $u\bar{d}$. The quark model, however, has one puzzling feature. In that age the scientists believed that there is a fundamental unit of charge. The positive unit charge is carried by a proton and the negative unit charge by an electron. On the other hand the charges of the quarks must be fractions of the fundamental unit of electric charge. In spite of many years of painstaking searches no fractionally charged particle has been found till date. It is believed that due to some very special type of force the quarks are **permanently confined** in the proton and other hadrons. Finding the exact mechanism responsible for this confinement is a major challenge for modern particle physics.

Indirect evidence of the existence of quarks inside the proton, however, has been found in deep inelastic $e-p$ scattering experiments. In these experiments very high energy electrons are scattered from the protons which are smashed in the process. By analyzing the characteristics of the scattered electron it was found that there are three point like particles in the proton Thus this experiment in principle served similar purposes as did α scattering on gold foil in revealing the structure of the atom. Subsequently it was established that these particles have the same properties as the quarks proposed by Gell-Mann. For their pioneering contribution to the deep inelastic scattering experiments J.I. Friedman (1930 -), H. W. Kendall (1926 -) and R. E. Taylor (1929 -) were awarded the noble prize for physics in 1990.

3 The Force Carriers and the Higgs Boson

We are mostly familiar with the interactions between macroscopic bodies by contact. However, two elementary particles separated from each other can interact even in vacuum. According to modern quantum mechanics they interact by exchanging **force carrier particles**. For example two electrons repel each other by exchanging photons which in this case are the force carrier particles. There are four types of fundamental interactions among the elementary particles. Two of them the electromagnetic and the weak interactions share certain common features. Many people suggested that this similarity is due to a symmetry of nature.

As a result the carriers of these two forces are expected to share some common properties. In particular the carriers of both types are required to be massless. However, the photon, the carrier of electromagnetic forces, is known to be massless while the **W boson**, the carrier of weak forces must be very heavy ($m_W \approx 80 m_p$). Generating this mass difference by breaking the symmetry in a theoretically consistent way was a big challenge for theoretical physicists.

An attractive way of creating the mass of a force carrier was explained by several scientists including P. Higgs (1929 -) in 1964 by postulating a new particle now known as the **Higgs boson** (H). This process of mass generation is now known as the Higgs mechanism. A generalized version of this mechanism was implemented to generate the mass difference between the photon and the W-boson. In simple terms one can say that the force carriers like the W, which interact with the Higgs boson, acquire mass. On the other hand the photon does not interact with the Higgs boson and remains massless.

Using the Higgs mechanism S.Glashaw (1932 -), A. Salam (1926 - 1996) and S. Weinberg (1933 -) (GSW) proposed the **unified theory of electromagnetic and weak interactions** in 1967. According to this theory the quarks and the leptons are the basic building blocks of matter. The electron and two other negatively charged particles - the μ and τ - are collectively called charged leptons. In β decays an electron comes out of a radioactive nuclei along with a tiny, electrically neutral particle called the neutrino (ν). This neutrino is called the electron type neutrino (ν_e) since its interaction with matter can only creates electrons and not μ or τ. Similarly the other two leptons have associated neutrinos- ν_μ and ν_τ. The quarks and the charged leptons also acquire masses due to their interactions with the H boson although via a different mechanism. In the GSW model the neutrinos - called the neutral leptons - remain massless since they do not interact with the Higgs boson. Subsequently the last statement had to be **revised drastically** as we shall see later. In the GSW model there are two massive force carriers - the W and the **Z-boson** which mediate the interactions among the quarks and leptons. The photon is a massless force carrier. Moreover, the consistency of the GSW model requires that there must be **more quarks** in nature beyond the three proposed by Gell-Mann. Subsequently the W and Z bosons and three new quarks **charm (c), bottom (b)** and **top(t)** were experimentally detected. Glashaw, Salam and Weinberg shared the Noble Prize in 1979.

However, the Higgs boson is rather difficult to detect due to some of its properties. The most powerful accelerator in the history of particle physics - the Large Hadron Collider (LHC) was required to detect the Higgs boson. After its discovery at the LHC the Nobel Prize in physics in 2013 was shared by F. Englert (1932 -) and P.Higgs for their independent contributions to the physics of the Higgs boson.

So far we did not mention the strong forces among the quarks and their carriers called the **gluon** (g)as they are not ingredients of the GSW model. Nevertheless they are very important in understanding the binding of the quarks in the protons and other hadrons. In fact it follows from the deep inelastic e-p scattering that the total energy and momentum of the proton is not carried by the quarks alone. Almost 50

% of the proton momentum is carried by other other particles in the proton which were later identified with the gluons. Like the quarks the gluon also remain permanently confined within the hadrons.

In conclusion we recall that currently the quarks, the leptons, the force carrier particles and the Higgs boson appear to complete the list of elementary particles. This is summarized in Fig.1. Here any two particles joined by a link directly interact with each other. The photon (γ), the gluon (g) and the neutrinos are the only particles which are not linked to the highs boson (H) and remain massless. However, bearing in mind the history of particle physics and the rapid progress in modern scientific ideas and technology one should always be prepared for future surprises. We shall next talk about one such surprise which has forced us to think afresh.

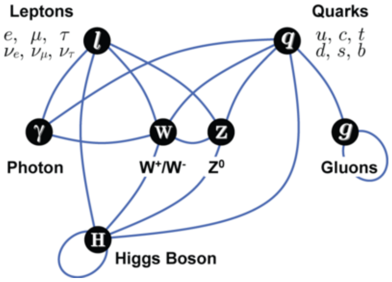

Figure 1: Elementary particles and their interactions

4 The Nobel Prize in Physics 2015 and the Elusive Neutrinos

The three neutrinos ν_e, ν_μ and ν_τ have rather curious properties. Their interaction with all forms of matter is very weak so that they can pass through tons of matter without making a single interaction with the atoms and nuclei of the medium. It is therefore extremely difficult to detect them. Moreover among the quarks and leptons in the GSW model they were assumed to be **the only massless paricles**. Until the end of the last century many painstaking experiments for measuring their masses supported this assumption.

All the elementary particles are governed by the laws of quantum mechanics. The laws of quantum mechanics when applied to the neutrinos predict that the three neutrinos while propagating can **change into one another** with certain probabilities **provided they have masses**. For example, the ν_e's produced by the nuclear reactions in the core of the sun - the solar neutrinos - can **change into** ν_μ **or** ν_τ as they propagate in space. Of course according to the theory the large number of neutrinos produced in a nuclear reactor should behave similarly.This phenomenon is known as **neutrino oscillstion**. If this happens then the number of ν_e's arriving on the earth should be less than their number originally produced in the solar interior. This deficit was observed by several experiments counting the solar neutrinos arriving on earth. Experiments with reactor neutrinos also indicated that they oscillate as well. However, this deficit could be due to other reasons too. For example, if the neutrinos are massive they can decay into lighter particles while in transit. A large group of experimentalists at the Sudbury Neutrino Observatory (SNO) in Canada under the leadership of Arthur McDonald (1943 -) cleared all doubts and conclusively proved in 2001 that neutrino oscillation is indeed responsible for the solar neutrino deficit. Mcdonald was awarded the Noble Prize in physics last year.

Subsequently it was found that the ν_μs also oscillate. A deficit was observed while physicists were counting on the earth the number of ν_μs produced up in the earth's atmosphere by cosmic ray interactions. This deficit was also related to neutrino oscillation. Many experiments reported this deficit but the Super-Kamiokande experiment in Japan obtained the first conclusive results in 1998. T. Kajita (1959 -) an important member of the Super-Kamiokande experiment shared the Nobel Prize with Macdonald.

As we have already noted the neutrinos are massless within the framework of the original GSW model. On the other hand the quantum mechanical explanation of neutrino oscillation holds only if the neutrinos are massive. Thus the observation of neutrino oscillation strongly indicates that **the GSW model must be revised**. It may be recalled that the other quarks and the charged leptons get masses due to interactions with the Higgs boson. Do the neutrino masses arise in a similar way? The answer to this question may not be a simple yes. No experiment has measured the neutrino masses precisely. However, the oscillation experiments indicate that they are incredibly tiny compared to the masses of the quarks and the charged leptons. Many physicists believe that this smallness indicates that the tiny neutrino masses arise due a novel mechanism which has not been understood so far. Intense research for revealing this mechanism is in progress.

References: Many reader friendly popular articles on the topics discussed here can be downloaded from the Internet. A particularly useful source is the website of the Royal Swedish Academy of Sciences. For example go to www.nobelprize.org/nobel_prizes/physics/laureates/2013/popular.html and download the pdf file containing an article on the Nobel Prize in 2013 (i.e., on the Higgs Boson). If you replace 2013 by 2015 you will get a similar article on neutrino oscillation.