Fundamental particles and their interactions

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Abstract

In this article the current understanding of fundamental particles and their interactions is presented for the interested non-specialist, by adopting a semi-historical path. A discussion on the unresolved problems is also presented.

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1 Introduction

The subject of this article is to present a sketch of the understanding we have today of what we consider to be fundamental particles and the interactions between them. By adopting a semi-historical path, we shall meander through a century or so of discoveries which have led to the establishing of the currently accepted picture and outline some of the outstanding unsolved problems of this picture.

At a semantic level, one is accustomed to a unique principle or object as being fundamental. However, in the title of this talk, one has already invoked the plural for both particles as well as interactions. This latter has been imposed on us by all that has been established through decades of observations and experiments, and runs somewhat contrary to the notions of philosophers who sought to find a unique building block, *e. g.* Democritos of Greece who called this the 'atom', or ancient Indian philosophers who spoke of *anu* in a similar spirit. Although the name atom has been appropriated by chemistry, and today we know of 92 atoms associated with all the naturally occuring elements, the idea of such an elementary or fundamental atom is an intriguing one. It must be mentioned that the picture that will be presented in this discussion is one that stands in this year 2005, and yet has to be replaced by another picture, if current day and future experiments reveal more elementarity. The picture we present today will then stand as an approximation to what is now an unknown fundamental theory.

It is easy to list the interactions, which are the electromagnetic, weak, strong and gravitational interactions[1]. Of the fundamental particles the only one that is familiar in day to day life is the electron, whose presence is known from a myriad daily experiences, as most devices that one uses implicitly uses the properties of this fundamental particle. In daily experience, this particle interacts through the electromagnetic interactions.

This year 2005, is the 'Year of Physics 2005' and commemorates three remarkable discoveries of A. Einstein in the year 1905, namely those of the discovery of the theory of Brownian motion, the special theory of relativity, and the photo-electric effect. The latter proved unequivocally that associated with the electromagnetic interactions was a 'quantum' that was to be later called the photon. The heuristic picture of the electromagnetic interactions that was to emerge is one where electrically charged particles would exchange such photons between themselves which would give rise to the effective force between them. Note that the idea of a 'particle' associated with light dates back to I. Newton, who spoke of a 'corpuscular theory', which was replaced by the 'wave picture' in light of discoveries of diffraction phenomena of C. Huygens. In modern quantum theory, the 'particle-wave' duality is an inevitable feature.

In the 1905 work of Einstein is also one of the most famous equations of all time, the energy-mass equivalence $E = mc^2$. It is on this equation that the principle of nuclear energy is based, *i.e.*, that in certain nuclear reactions, part

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[1] The theoretical framework that describes the first three is referred to as the 'standard model'.

of the mass of the nuclei that participate in the reactions is released as energy. [This is in contrast to chemical reactions, where binding energies of molecules is liberated in a chemical reaction.] On the other hand, if particles are accelerated to very high energies in a controlled manner, and are brought to a collision, in such reactions, the energy could be converted into mass of the daughters of the reaction process. Einstein's theory also predicts that for every particle, there are so-called 'anti-particles', e.g., for the electron there is a 'positron' which is like an electron in every respect, except that its electric charge is of the opposite sign. That this should be the case was discovered by P. A. M. Dirac who was studying a relativistic generalization of Schrödinger's equation in order to describe the motion of an electron. His studies led him to an equation which seemed to admit solutions that did not permit a conventional interpretation. Although he was himself hesitant to suggest his equation required that the electron have a partner, the situation was clarified by the experimental discovery by C. Anderson of a particle that was identical to an electron, except that it had a positive electric charge, in cosmic ray experiments. A photon, on the other hand, is its own anti-particle. Therefore new kinds of particles could be produced in this manner, subject to certain conservation laws[2], and their interactions studied. This is the basis of many experiments today. In the past, very energetic particles from other parts of the cosmos, so-called cosmic rays would enter the earth's atmosphere and interact with the nuclei of the atoms therein and produce showers of well known and new kinds of particles which could then be detected in terrestrial or balloon borne detectors.

2 The electron and the nucleus

When one spells out the word electromagnetic interaction, it is manifestly a union of two other forces known through antiquity, *viz.*, the electric and magnetic forces. It is worth spending a little time on the etymology of word 'electric' which comes from the latin word *electrum* for amber, a substance formed from wood resin, and from which electric forces could be generated by rubbing. Ancient humans were accustomed to electric forces generated by the formation of clouds and the subsequent lightning bolts. Magnetic forces were also known by the time of the Greeks due to the property of magnetized ore that could be used as 'lodestones' and were mined in the *Magnesia* prefecture of Thessaly, one of the thirteen peripheries of Greece. It was through the work in recent history, in the 18th and 19th centuries, of C. A. Coulomb, C. F. Gauss, H. C. Øersted, M. Faraday, A. M. Ampère, culminating in the work of J. C. Maxwell, that it was shown that electricity and magnetism are manifestations of a unified electromagnetic force, which is experienced by electrically charged and magnetized objects. With the advent of the quantum theory of M. Planck which was further developed by N. Bohr, E. Schrödinger and W. Heisenberg a new theory would

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[2] For instance, protons and neutrons belong to a family of particles known as 'baryons'. If an electron and positron are collided, then the reaction products must contain for every baryon produced, an anti-baryon.

have to be found to generalize 'classical' electromagnetism of Maxwell.

The discovery of the electron itself as a fundamental charged particle is attributed to the renowned English physicist J. J. Thomson who discovered it in the year 1897, and came to be known as the father of the electron. He had established the charge to mass ratio of the electron. Subsequently, the famous 'oil-drop' experiment of R. A. Millikan allowed one to determine the electronic charge and it was established the mass of the electron[3] is 0.511 MeV/c^2.

It may also be noted here that the electron carries 'spin' [4] which is an intrinsic property of elementary particles and has a value that is denoted by $\hbar/2$. A photon on the other hand carries a spin of $\hbar$. Electrons are examples of fermions, named for the Italian physicist E. Fermi since they obey 'Fermi-Dirac' statistics, while photons are examples of bosons, named for the famous Indian physicist S. N. Bose, as they obey 'Bose-Einstein' statistics.

Having measured some of the basic properties of the electron, Thomson needed to understand why atoms are electrically neutral under most circumstances, and how they may be ionized. He advanced a picture of a watermelon like atom where a positively charged medium would have embeddeed in it, the negatively charged electrons, much as the watermelon seeds, and the net charges would cancel out. This plausible picture was subjected to experimental tests by the eminent scientist E. Rutherford. By taking a thin gold foil and bombarding it with so-called $\alpha-$particles arising from the radioactive decay of certain naturally occuring elements, and by counting the scattered particles, he was able to establish that there was an uncommonly large number of backward scattering events of the projectiles. The only way of understanding this was to replace the watermelon picture of Thomson with one where the entire positive charges were concentrated in a very small region, later to be called a nucleus which would be constituted of both the 'protons' as well as 'neutrons', so that an $\alpha-$particle projectile would essentially pass unhindered if it did not pass near the vicinity of the nucleus, or would suffer a head-on collision and turn around and be scattered in a backward direction.

Thus Rutherford came to be regarded as the father of the nucleus, and also the father of the proton, the particle associated with the Greek word, *protos*, meaning first. In other words, Rutherford advanced the picture of the atom being consituted of these fundamental particles, a picture which was soon revised with the discovery by J. Chadwick of what was named as the 'neutron' which was another consitutent of nuclei. Nevertheless, the picture that stayed with us,

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[3] The unit chosen here is common in elementary particle physics: the M stands for Mega which is equal to a million and eV stands for electron-volt, the energy gained by an electron when it falls through a potential of 1 Volt. We have divided MeV by c^2, to express the mass in terms of its energy equivalent via the Einstein relation. For future reference, another convenient unit is GeV, where G stands for Giga which equals a billion. We shall not use the conventional units here, which are cumbersome for our purposes; e.g, the mass of the electron in these units is 9.11×10^{-31} kg.

[4] The constant $\hbar \equiv h/(2\pi)$ is a fundamental quantity of nature, where h is called Planck's constant. In particular, a photon γ of frequency ν carries energy $E_\gamma = h\nu$. Note that angular momentum has the same units as energy×time, which is why the spin is associated with the same unit.

until the 1950's was that only protons, neutrons (collectively known as nucleons) and electrons were fundamental particles. In particular, it was established that the masses of the proton and neutron are 938.2 MeV/c^2 and 939.6 MeV/c^2 respectively. These also each carry spin of $\hbar/2$.

A word now about the quantum electrodynamics, the full relativistic quantum field theory describing the interactions of electrons and the photon. This is the theory which explains the quantum motion of an electron in the field set up by another charged particle, which is heuristically imagined as the exchange of photons between the electron and say another electron which would be the source of the field (so-called Møller scattering). One would understand the scattering of an electron in such a field; furthermore, it would also be possible to understand how an electron and a positron could annihilate each other by producing energy briefly as a photon which could then produce another electron and positron pair, in addition to the electron scattering off the field set up by the proton. This process was first discussed by the Indian physicist H. J. Bhabha and is named Bhabha scattering.

In addition to the above, it is also possible that an electron and positron could annihilate and the energy of the collision could be converted into, say a muon and anti-muon pair, which can be detected in laboratory detectors. Such process have distinct probabilities that can be computed in accordance with the principles of quantum mechanics and special theory of relativity (quantum field theory), and there is remarkable agreement between theory and obesrvation. Note here that in this manner, particles that did not 'exist' earlier can actually be 'created'. This is a profound manifestation of energy and mass equivalence. In the context of quantum electrodynamics, the theory was worked out first by Dirac, P. Jordan and others, and put on a sound footing through the work of R. P. Feynman, J. Schwinger and S-I. Tomonaga, and that of F. J. Dyson.

One unanswered question was of course that which pertained to the forces between protons and neutrons necessary to keep them inside the nucleus. In other words, where did the inter-nucleon forces come from? H. Yukawa proposed that there ought to be particles, later called pions, that would mediate the forces between the nucleons. These particles were subsequently discovered in cosmic ray experiments in 1947 by C. Powell. These particles carry no spin.

The question then was whether or not these are carriers of fundamental forces just as the photon was the carrier of the electromagnetic force, after recognizing that this particle must have a non-vanishing mass, unlike the photon, in order for it to have a limited range, *viz.* at the inter-nucleon level[5]. The answer is no, and in the modern picture of interactions, the internucleon force is a residue of the so-called 'strong force' that not only gives rise to the proton and neutron in terms of constituents called quarks, while the pions are bound states of quark-anti-quark pairs, and mediate the effective internucleon force, as we will see in some of the following sections.

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[5] There are, in fact, 3 pions in nature, the charged pions $\pi^{\pm}$ which weigh 139.6 MeV/c^2 and the neutral pion π^0 which weighs 135.0 Mev/c^2.

3 Radioactivity and the weak force

We had already mentioned that Rutherford carried out his experiments with α-particles that came from radioactive decays of some natural radioisotopes. This decay was effectively due to the mother nucleus spitting out a helium nucleus, which is what the α-particle is, and turning into a daughter nucleus.

Another kind of radioactivity was so-called β-decay, where the particle emitted was either an electron or a positron. A free neutron itself decays into a proton and an electron. However, by the early 1930's it was clear that another particle was also produced which evaded direct detection at that time, and was introduced by the Austrian physicist W. Pauli. This was named the 'neutrino', the little one of the neutron by Fermi. It had been realized at that time an unfamiliar force of nature must be responsible for this and was named the 'weak' force which seemed to play a role only at sub-nuclear distance scales and was so weak that its impact on day to day life on terrestrial scales was negligible. Indeed, in light of our prior experience, this force would also require a mediator, and one that was massive to ensure the short-range nature of the force, which we today know to be the $W^{\pm}$ particles. These particles are very massive[6], weighing roughly 80.4 GeV$/c^2$; despite this decays can take place in accordance with the principles of quantum mechanics and special relativity, where a 'virtual' W particle can be produced, turning a neutron into a proton and this virtual particle decaying into an electron and anti-neutrino pair. Here the additional energy locked up in the larger mass of the neutron, compared to that of the proton, is converted into the electron and anti-neutrino pair, when the neutron gets converted into a proton.

Today, we have a complete picture of this weak interaction and why it is short ranged, and we also know that we cannot really speak in isolation of an electromagnetic force and a weak force, but instead we speak of an 'electroweak' theory, where the two forces above are different manifestations of the same. The price to pay was the introduction of another massive cousin of the photon, designated as the Z^0, which weighs 91.2 GeV$/c^2$. This theory was sucessfully constructed by S. Glashow, A. Salam and Weinberg (GSW) and was put on a sound mathematical footing through the work of G. 't Hooft and M. J. G. Veltman.

The weak forces themselves are very peculiar indeed and are unlike any other; it is the only one that changes the particle type, *e.g.* changes a neutron into a proton, then it had been discovered by T. D. Lee and C. N. Yang that they violate mirror-symmetry (also known as parity (P)) maximally, *e.g.* left-handed neutrinos alone participate in the weak reactions. Before the rise of the GSW theory siginificant work on this was due to R. E. Marshak and E. C. G. Sudarshan and R. F. Feynman and M. Gell-Mann, who had given the $V - A$ theory for the weak interactions. The weak forces alone also violate so-called CP violation, where C stands for charge conjugation, which related particles to anti-particles in a mathematical sense. The weak forces are the only ones that

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[6] These are about 90 times as heavy as a proton, which in turn is about 2000 times as heavy as an electron!

require the mediators of the force through massive particles. The manner in which these particles acquire their mass is a complicated phenomenon and goes under the name of the 'Higgs mechanism.' Many future experiments have as their goal, the discovery of this particle and a detailed study of its properties.

4 Particle zoology

In the 1950's a whole set of new particles were identified from cosmic ray experiments and from so-called fixed target experiments. It led to what was referred to as the 'particle zoo', where particles would live for a short time and decay into stable daughters. In particular, in cosmic ray experiments one found showers of energetic and massive particles. In one discovery predating that of the pion, a particle that we now call the muon was discovered independently by J. C. Street and E. C. Stevenson and by C. Anderson and S. Nedermeyer. Today we know that it is just like an electron except that it is about 210 times heavier, and due to the weak interaction it decays into an electron and into a neutrino and an anti-neutrino, the anti-neutrino of the electron type and a neutrino of the muon type, in about a micro-second[7]. Much later in laboratory experiments, a third type of 'heavy electron' (τ-lepton) was discovered by M. Perl, which is 3600 times as heavy as an electron. Correspondingly, its lifetime compared to that of the muon is orders of magnitude lower. The detection of these neutrinos themselves has itself been a rich field; the electron type neutrinos were discovered in reactor experiments by F. Reines and C. L. Cowan, Jr., while the muon type neutrinos by L. M. Lederman, M. Schwartz and J. Steinberger. The existence of a τ-type neutrino has only recently been established in Fermilab experiments.

In meantime, cosmic ray experiments also showed all kinds of 'strange' events, where particles produced in pairs lived for a relatively long time, compared to what one expected. This was explained by Gell-Mann and A. Pais by introducing particles which had 'strange' constituents, such that a strange and anti-strange particle pair was produced. Laboratory experiments also continued to see plethora of heavier and excited particles that lived fleetingly. This caused a serious crisis for physics which sought to see fundamental constituents. This was eventually resolved through the discovery of a theory for the strong interactions, the subject of our next section.

5 The strong force

All this was put in place by assuming that these particles, and also the nucleons were all made of underlying constituents which we today call quarks, and the plethora was nothing but energized bound states of these quarks. The quarks

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[7] Muons produced high up in the atmosphere when a cosmic ray strikes a nucleus of a nitrogen or oxygen atom (the earth's atmosphere is mainly consituted of these elements), would not be able to reach a terrestrial detector in their short lifetime, but for the fact of dilatation of their life due to their very large velocity, an effect predicted by Einstein's theory of relativity.

themselves came in ‘flavours’ of the up, down and strange type, and carried some unknown strong charges, and the forces were mediated by unknown carriers of the strong forces, strong cousins of the electromagnetism’s photon. These would be called the gluons, and the strong charges would be called ‘color’. Today, we think that all observed strongly interacting matter is the result of the dynamics of this theory called quantum choromodynamics. This theory was the result of the work of a generation of scientists primarily led by Gell-Mann. Note however, that the strong interaction binds quarks and gluons into states such as the nucleons, and till date the dynamics that leads to this is not known; this is referred to as the ‘confinement’ hypothesis. Furthermore, it is due to the peculiarities of quantum field theories that this theory behaves in such a way that when protons and neutrons are struck by projectiles with very large energy transfer between the projectile and the target, that the constituent quarks behave as though they are quasi-free. This remarkable property known as ‘asymptotic freedom’, was established firmly by the work of D. J. Gross, H. D. Politzer and F. Wilczek. Indeed, these physicists are the most recent winners of the coveted Nobel prize for physics for the year 2004.

As time went along, it became clear that the picture needed some more enlargement. Indeed as there were the electron and its neutrino, muon and its neutrino, and the τ-lepton and its neutrino, it would be necessary to group the quarks as well. Apart from a technical detail that we leave out here, it would be necessary to group the up and down quarks together. This would require that the strange quark would require a partner; S. Glashow, J. Iliopoulos and L. Maini would propose one called the charm quark, which was discovered in experiments led by S. C. C. Ting and B. Richter, and finally there would be the top and bottom quarks, discovered at Fermilab by the CDF and D0 collaborations, and by L. Lederman respectively. This essentially completes the list of fundamental particles.

As mentioned earlier, the strong interactions present a very difficult challenge in finding the solution of the microscopic theory. Consider for instance, the proton which is said to be made up of 2 u quarks and 1 d quark. It is now established that each of these quarks weights roughly 5 MeV/c^2. However, the mass of the proton is about 938 MeV/c^2. It is only through the (as yet unsolved) dynamics of the strong interactions that these quarks which together weigh only about 15 MeV/c^2 become so much more massive. The strange quark is believed to weigh about 150 MeV/c^2, while the charm quark weighs about 1.5 GeV/c^2, while the top and b quarks weigh respectively 175 GeV/c^2 and 4.2 GeV/c^2. This incredible spread of masses of these particles over orders of magnitude remains one of the great unsolved problems of elementary particle physics.

6 Synthesis

Let us now spend a little time going over what we have learnt so far. Elementary particles come in two varieties, those that do not participate in the strong interactions and those that do not. The former are known as leptons, which participate in the weak interactions, and of these the'charged' leptons are those that also carry electric charge also participate in the electromagnetic interactions in a significant manner. On the other hand,'colored' quarks participate in the strong and weak interactions. All of them carry electric charge. All the above are spin $\hbar/2$ particles and are fermions.

As regards the forces, the electromagnetic force is carried by the photon. The full electro-weak sector contains the $W^{\pm}$ and the Z^0 in addition. These mediate forces between leptons and quarks. They were experimentally discovered at CERN in 1984 for which the Nobel prize was awarded to C. Rubbia and S. van der Meer. The gluons are responsible for transmitting the strong force. All the above are spin $\hbar$ particles and are bosons. They were experimentally discovered by by the PETRA collaboration at the German laboratory DESY.

There is one as yet undiscovered particle in the 'standard model' which is known as the Higgs. It must weight at least 120 GeV/c^2.

While we have discussed in the earlier sections masses of all the particles, we have made no mention of the masses of neutrinos. It is notoriously difficult to carry out measurements of the masses of these particles and for a long time one only had upper bounds on their masses. In the recent past, however, there is much evidence that they do indeed possess non-vanishing masses, which comes from deep underground experiments. Such masses are required to resolve the 'solar neutrino problem'. The latter, simply stated, is that fewer than expected neutrinos reach the earth from the solar interior where they are produced in copious numbers in reactions that power the sun. These masses are the first concrete indication that the standard model is incomplete.

There are still a huge number of unresolved problems. We do not have understanding of why there are these different types of forces. We do not know why their strengths are what they are. Are they all seemingly different manifestations of an unknown unique force? Even in the framework of these forces, there are unresolved questions: for instance, why does electric charge come in multiples of a fundamental unit? Dirac had pointed out that if there were magnetic monopoles, then this conclusion would have been inevitable. However, decades of experiments have searched for magnetic monopoles that may be floating around in the Universe, and may have had a chance encounter with a terrestrial detector, but have remained fruitless. Why are there so many particles, so like each other, except for their different masses? Why do these elementary particles replicate themselves? Why are their masses what they are?

What is the role of gravitation in this picture? How is it to be included in a relativistic formulation? There are many heroic attempts, but each has its own set of technical problems and is beyond the scope of the present discussion.

The upcoming generation of high energy physics experiments, space probes and the current generation of scientists are hard at work hoping to unravel these mysteries.

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8 Further Reading

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