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FUNDAMENTAL PARTICLES AND THEIR INTERACTIONS

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Introduction

The quest for the fundamental constituents of matter around us and the forces that operate among them, has been on in the history of mankind, from the time of the Greeks or even before. It has been a long, tortuous but often exciting route from that stage to our present knowledge of 'elementary' particles and the interactions among them. This knowledge constitutes the branch of physics, now called *elementary particle physics*

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For reasans which will become clear later, this branch is also synonymous with the name *high energy physics*. Our knowledge about the elementary constituents of matter has played a relavant role in other branches of theoretical studies such as chemistry or solid state physics. This interplay between the physics at microscopic and macroscopic scales is of great interest, even through not under discussion here.

The discipline of elementary particle physics in its present form and name is not more than ~ 50 years old. However, the attempts to understand the structure of matter at different distance scales and the hunt for its basic building blocks has always been at the forefront of the study of physical sciences. Our notions about 'elementarity' and also about 'high' energies have changed as accelerators capable of accelerating particles to higher and higher energies have been made available by the experimental physicists to their theoretical friends.

To start from the extreme, in the early days of the 19th century, when Dalton proposed the atomic theory of matter, chemical elements were considered to be 'elementary' as the name clearly suggests. The basic building block of an element was called an *atom*. As a matter of fact, the word 'atom' in Greek means an indivisible particle. The discovery of radioactivity (natural as well as artificial) and the classic scattering experiments of Rutherford took the physicists from the ara of *atomic physics* to that of *nucler physics*: study of nuclei inside the atoms. These experiments established nuclei as more 'elementary' than atoms. Now we know that the nuclei are not elementary either, but are made up of protons and neutrons. Particle physics was born as a separate subject from nuclear physics when slowly it was realised that protons and neutrons themselves have fundamental constituents, viz. quarks and gluons.

In this article I would like to follow this development of high energy accelerators and the information yielded by these about the structure of matter. In Section I, starting from Rutherford's experiments which revealed the existence of nuclei, we will see how essentially similar experiments revealed the existence of the quarks and gluons. In the next section, I will briefly review the presently known information about all the fundamental particles and the interactions among them. In Section III the question of a mathematical description of the interactions along with the possibility of a unified description of them all is discussed. Existence of W/Z bosons along with their masses was a unique prediction of some of these ideas. Their discovery has been one of the most exciting events in present day particle physics. Further in this section, this discovery along with the developments of the giant accelerators which made it possible is discussed. Then in Section IV I continue the discussion of the unification ideas and a possible link between particle physics and cosmology. In this section, we will truly come to the frontiers of particle physics. A possibility of a unified, mathematical description of all interactions, including gravitation (which poses most problems to an attempt of such a description), being pursued by a large number of theoretical physicists at present is discussed. This is followed by some concluding remarks.

I. Inside the atom and further ?

> "By convention there is colour, by convention sweetness, by convention bitterness, but in reality there are atoms and space."
>
> Demokritos

As we know, matter around us exists in three different states: solid, liquid and gas. The molecular structure of matter has been known for a very long time now. We also further know that molecules are made of atoms. The initial clues for the existence of molecules and atoms came from the studies of the macroscopic properties of matter. However, it is not possible to 'see' them in the usual sence. This can be understood readily enough. The resolving power Δr of an optical microscope is proportional to the wavelenght λ of the light used. Hence visible light can be used to resolve structures only of $\sim 10^{-7}$ m. However, molecules and atoms are a few Å in size (1 A $= 10^{-10}$ m). Crystal spacing in solids and some molecular structures can be resolved using X-rays with $\lambda \sim 10^{-10}$ m. 'Pictures' of molecules are possible, however, only by using a beam of electrons which are accelerated to high velocities (close to velocity of light c). These behave like a wave. Election microscopas are known for about 60-70 years now (indeed the 1986 Nobel prize went to the inventor of the electron microscope). These allow a study of structures at small distances. Field ion microscopes make even actual pictures of an atom possible. Thus it is possible to 'see' atoms and molecules in a sense, though not optically.

Beyond this level it is impossible to 'see' the constituents of matter directly. As we shall see later, special detectors have to be built to 'see' the particles which we are now interested in, and even then one can see them only indirectly through the effect their passage has had on matter. It should also be clear from the discussion above why elementary particle physics is also high energy physics. A beam of particles (say electrons) which is accelerated to relativistic energies E, shows a wave like behaviour with an equivalent wavelength

$$\lambda = \frac{h}{2\pi P} = \frac{\hbar}{P} \qquad \text{(I.1)}$$

where h is Planck's constant and P is the magnitude of the momentum of the particle. The structures which are smaller and smaller in size can be probed by using particle beams with higher and higher energies.

The constituents of atoms and their distribution inside the region of the size $\sim 10^{-9} - 10^{-10}$ m, which is the extent of an atom, was one of the most important problems in the early part of the century. A detailed study of atomic energy levels and transistions, and the very fact of stability of atoms, was what led to the early ideas of quantum theories. However, in this section, we will only try to follow the historical developments which culminated in the experimental discovery and confirmation of the existence of quarks, without following the simultaneous developments in a mathematical description of this idea and interplay between these two.

By the beginning of the century electrons and atoms were known. It was also conjectured that the atom must consist of negatively charged electrons and also a positive charge so that the net charge of the atom was zero. The distribution of these positive and negative charges inside the atom was a matter of intense debate.

Rutherford suggested and performed the first scattering experiments to study the problems. Energetic α particles are emitted from radioactive elements with energies of a few MeV. Hence these are capable of sensing differences of charge distribution at a distance scale $\hbar/P \sim 10^{-12} - 10^{-13}$ m (see Eq. I.1).

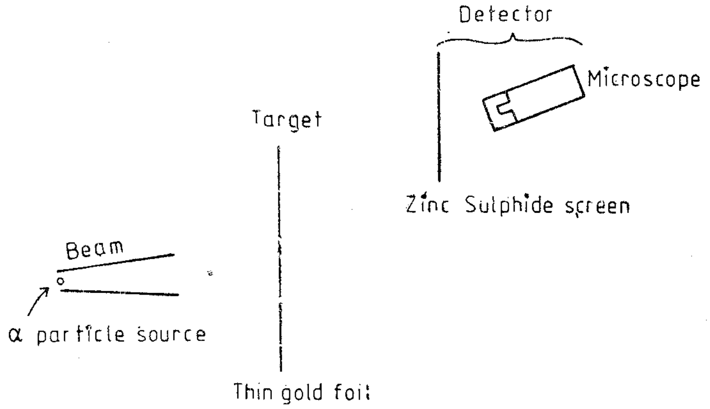

Fig. I.1. Rutherford scattering experiment: schematic drawing.

The experimental arrangement is sketched in Fig. I.1. This is the first beam-target-detector arrangement, now common in particle physics. The *target* was a thin gold foil and the *detector* was the zinc sulphide screen with a microscope. The *signal* for α particles was the flash of light emitted when they hit the screen. Most of the times the α particles were found to pass through undeflected. But many of those which did suffer deflections, were found to be scattered through large angles, some even through 180°. To quote Rutherford himself, "It was about as credible as if you had fired a fifteen inch shell at a piece of tissue paper and it came back and hit you".

The surprise, of course, was that the heavy α particles were deflected through such large angles. Rutherford further demonstrated that the relative number of α particles scattered at different angles was exactly what was expected for an α particle scattered from a positive point charge Ze, where Z is the atomic number. Thus the negatively charged, light electrons balancing the positive charge move in most of the volume of the atom and the massive, positive charge is concentrated at a point, i.e. a 'point' on distance scales that these α particles can resolve. To put it more precisely, this experiment showed that the positive charge in an atom is concentrated in a region of size $<10^{-13}$ m, called the *nucleus* of the atom. This discussion clearly demonstrntes the ability of a scattering experiment to study the structure of an object.

This and the experiments to follow, used the energetic α particles coming from radioactive elements in the beginning. In a sense then the radioactive nuclei were the 'natural accelerators'. An accelerator is the ingredient (missing so far in our discussion) necessary to produce the *beam* in the now common beam-target-detector arrangement. Fig. I.2 shows the first accelerator built by Cockroft and Walton. This accelerated protons by a potential of $\sim$ 500 000 volts and thus these had energies $\sim$ MeV. These proton beams were then used to disintegrate the nuclei. The accelerators have come a long way since then and so has our knowledge about what makes matter and what holds it together.

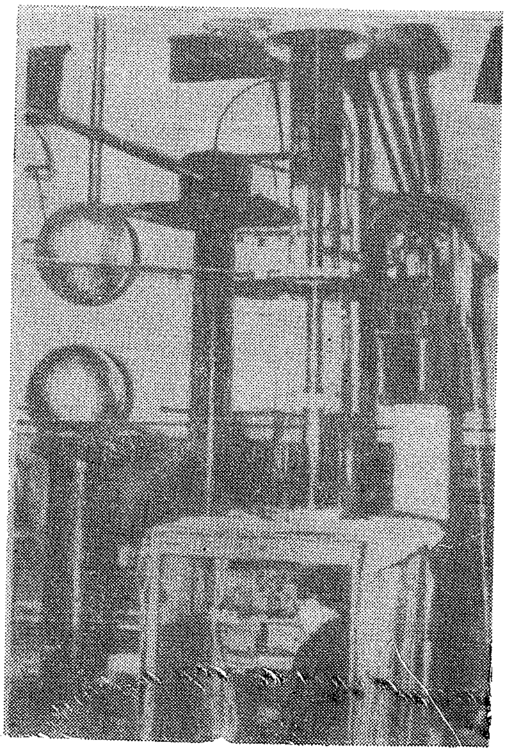

Fig. I.2. Walton and Cockroft accelerator. Courtsey of Cavendish Laboratory.

Thus, Rutherford's experiment in 1911 ushered in the era of nuclear physics. The next 30 years saw vigorous development in the subject and gave us insight that the nuclei themselves are not indivisible and elementary. Chadwick's experiments revealed the existence of the neutron (n), a neutral particle almost as heavy as the proton (p: nucleus of a hydrogen atom) inside the nucleus. Just as the study of the absorption and emission spectra of elements gave information about the energy levels of electrons in atoms, the study of α, β and γ radiations by nuclei gave information about the nuclear energy levels. Using this information from these spectroscopic studies, the spin and parity of nuclei could be determined. These were consistently explained if the constituents of a nucleus with mass number A were A *nucleons*, viz. Z protons and $N = A - Z$ neutrons. Nucleon is the common nomenclature for neutron and proton. Thus in the early 30s of this century (the neutron was discovered in 1932) the picture was clear and as follows: Molecules are made of atoms. The mean atomic separations are $\sim 10^{-9}$ m. In turn the atom which is $\sim 10^{-10}$ m in size consists of electrons around a central nucleus which is smaller than 10^{-13} m in size. The nucleus in turn was found to be made up of protons and neutrons. [Note that as yet we do not discuss what holds them together.]

At this level in this study, the existence of neutrons and protons as constituents of a nucleus, was inferred only from its static properties: mass, spin, parity, magnetic moments, etc. The 'nuclear' equivalent of Rutherford's classic scattering experiment of 1911 was performed by Hofstadter around 1955. In this experiment, an electron *beam* of energy $E \sim 400-600$ MeV was incident upon a *nuclear target*. The energy E' of the electrons scattered through a fixed angle θ was measured (see Fig. I.3). The negatively charged electrons with this energy are sensitive to distances $\sim 10^{-15}$ m (see Eq. I.1) and thus can measure a charge distribution of this size. Any charge distribution over a distance scale smaller than this would be seen as a 'point' by this probe. A finite spread of the charge distribution will be signalled by

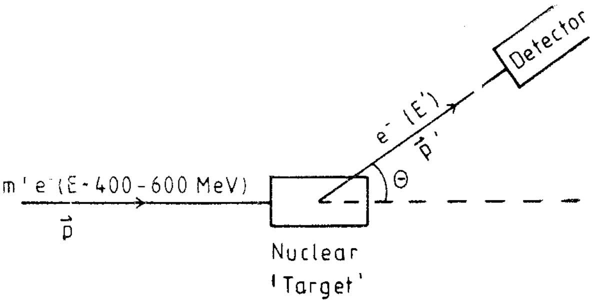

Fig. I.3. Hofstadter scattering experiment: schematic drawing.

a change in the relative number of electrons with different energies arriving at the detector, than the one expected for a 'point' particle. These experiments measured the 'size' of various nuclei and these studies were extremely useful in the development of models of how nucleons are put together to form a nucleus. The information about the relative number of electrons of different scattered energies E' arriving at the detector, can be translated into a map of charge distribution inside a nucleus. A typical result is shown in Fig. I.4. Thus the nuclei are seen to have typically a size about 10^{-14} m.

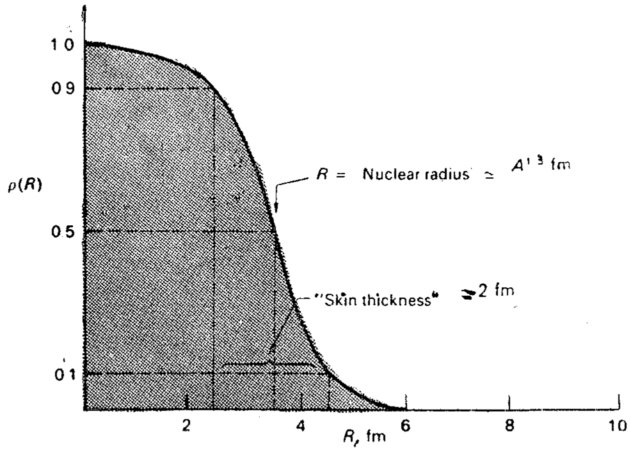

Fig. I.4. Charge distribution in a nucleus.

As the energy of the incident electron beam is increased further, the electrons no longer see the nucleus as a uniform charge distribution depicted in Fig. I.4. Instead they begin to sense the existence of charge centres inside the nucleus, viz. nucleons. This is reflected in the dependence of the relative number of scattered electrons at different angles θ and different energies E'. Let $\mathbf{p}$ and $\mathbf{p}'$ denote the momenta of the incident and scattered electrons and let $\nu = E - E'$. The existence of the individual charge centres is reflected in a study of the number of electrons scattered as a function of the variable

$$x = -\frac{Q^2}{2M\nu} \qquad (\text{I}.2)$$

where $Q^2 = -(\mathbf{p} - \mathbf{p}')^2$ and M is the mass of the nucleus. It turns out that if the scattering takes place from point objects the number of electrons arriving at an angle θ, with energy E' is decided by the value of the variable x alone, and not by θ or E' separately. Furthermore if there are N point-like constituents, the value of $x = 1/N$ is preferred by the process over all others, i.e. electrons tend to scatter most with such values of θ and E' as to have $x \sim 1/N$. This is precisely what was observed when nuclei were hit with higher energy electrons (but still with $E < 1000$ MeV). These observations confirmed the existence of A nucleons, smaller than a few fm in size (1 fm $= 10^{-15}$ m), inside the nucleus. This, of course, also had been inferred in the preceding years from a study of the static properties of nuclei and the attempts to understand it theoretically. However, it must be stated here, that such an analysis of the data on nuclear scattering in terms of the variable x was performed only after the now classic experiments in 60s with higher energy electrons had revealed the existence of pointlike constituents of proton.

Historically, in the same period, 1940–1960, physicists were becoming aware of the existence of particles other than n, p, e^- and γ. Application of energy, momentum and angular momentum conservation in the case of electrons being emitted from a radioactive source, had led Pauli to postulate the existence of a neutral, spin 1/2, almost massless particle which was called a neutrino (ν). Studies of the behaviour of the forces which hold the nucleons in a nucleus together, by Yukawa, had indicated the existence of charged and neutral particles with masses intermediate between those of the nucleons (heavy mass particles called *hadrons*) and electron/neutrinos (light masses, hence called *leptons*). These were named *mesons*. These were indeed found (pi meson π) in the early experiments with the highest energy 'natural' accelerators we have, viz. cosmic rays. The early cosmic ray experiments used cloud chambers. These detected the presence of charged particles by the ionization track left by the particle while passing through the supersaturated vapour in the chamber. Magnetic fields then can be used to measure the charge of the particle. Photographic emulsions were also used to detect charged particles in these experiments. Further cosmic ray experiments revealed the existence of new mesons and hadrons with 'strange' properties—strange in the sense that they were produced as copiously as pions or the excited nucleons (e.g. Δ) but lived long ($\geqslant 10^{-10}$ sec); still longer-lived were mu-mesons (μ) which had life times $\sim 10^{-6}$ sec.

Around the same time, a theoretical formulation to describe the behaviour of an electron in electric and magnetic fields in the language of quantum mechanics, consistent with the theory of relativity was put forward by Dirac. This predicted the presence of 'antimatter', i.e. a particle with the same mass as e^- but positively charged called *positron* (e^+). Using Wilson's cloud chamber placed in magnetic fields, a track of such a positively charged particle was seen.

Soon physicists wanted to build accelerators to replace the uncontrolled cosmic ray experiments. By 1953 the follower of cyclotron called *synchrocyclotron* was built. This could accelerate protons to an energy of 1000 MeV (= 1 GeV). These proton beams hitting the nuclear targets had produced again these 'strange' particles, both mesons and hadrons, similar to those observed in cosmic ray experiments.

As the number of these particles started increasing, so did the suspicion that these in turn are made up of more fundamental constituents. Again in analogy with atomic and nuclear physics, particle physics embarked upon its spectroscopic studies. Many of these particles were short lived with a life time ~ $10^{-11} - 10^{-23}$ sec. The accelerators built at the laboratories in Brookhaven and Berkeley in the U.S.A. and the Rutherford Laboratory in England, along with the progress in the detection techniques, made it possible to produce and study the properties of these particles. The older cloud chambers gave way to *bubble chambers,* which again use the tracks formed by bubbles formed in a superheated liquid, by the passage of a charged particle. Fig. I.5 shows a bubble chamber used in the present day high energy physics experiments. Using similar, if somewhat smaller, bubble chambers, it was possible to measure the properties of the above mentioned particles. Measurement of their masses, magnetic moments, spins, etc (i.e., static properties) indicated certain patterns in these properties. These studies gave indications that p, n, π etc. are all made up of more fundametal constituents: the *quarks.*

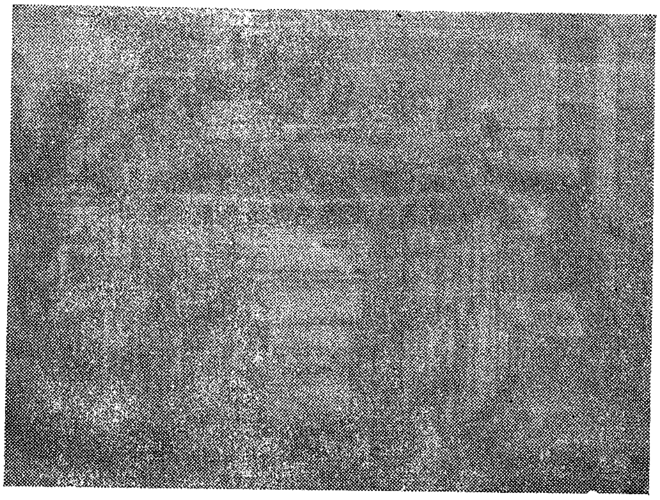

Fig. I.5. Bubble chamber (Photo CERN).

Quarks were postulated to be spin 1/2 particles carrying charges which are a fraction of the electron charge. These conclusions were arrived at by noticing that the patterns observed in the properties of the particles could be explained if all of them were composed of these quarks and if the underlying theory obeyed certain symmetry principles. From this point on the two hunts, one for the underlying symmetry of the physical forces and the other for the fundamental constituents were closely related.

However, just as in the case of nucleons in a nucleus, the dynamical confirmation of these quarks come from a later, still higher energy version of Rutherford's experiment. As explained earlier, Hofstadter's exeriments with low energy (~ 1 GeV) electrons could see nucleons as point scatterers.

Early in the 1960s a linear accelerator was built at Stanford, in the U.S.A., at the Stanford Linear Accelerator Centre (S.L.A.C.). This was 2-mile long (Fig. I.6) and capable of accelerating electrons up to $\sim$ 20 GeV. The beam, target and detector arrangement here was far more complicated than the early counterparts of these experiments. As can be seen it has already acquired the gigantic proportions which we will see again and again in the discussion of present day experimental particle physics.

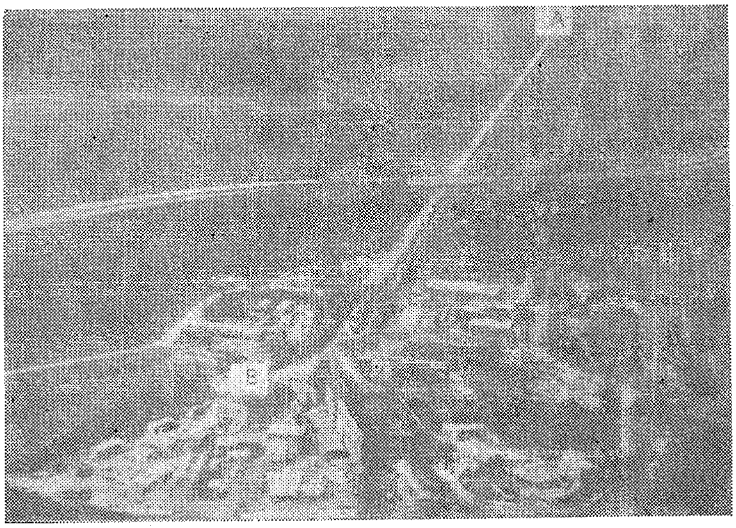

Fig. I 6. Stanford linear accelerator (Photo Stanford University).

The basic experiment here is similar to the one depicted in Fig. I.3. But the target here is proton/deuteron and energies of the electrons are much higher. The 20 GeV electrons can resolve scattering centres which are more than 10^{-17} m apart. In other words they can see structures $\sim 10^{-17}$ m in size. These experiments gave clear evidence of pointlike scatterers inside the proton.

Electrons and protons can inieract with cach other by exchanging a photon as depicted in Fig. I.7a. The high energy electrons impart such large energies to the proton, that the collision is no longer 'elastic', i e. we are no longer studying the elastic collission.

$$e(E) + p \rightarrow e(E') + p$$

but the inelastic process,

$$e(E) + p \rightarrow e(E') + x \qquad (I.3)$$

where x consists of various hadrons and mesons mentioned earlier. Thus the proton 'breaks up' (so to say) into these new particles. This is so violently inelastic, i.e. the combined mass of x is so higher than the mass of

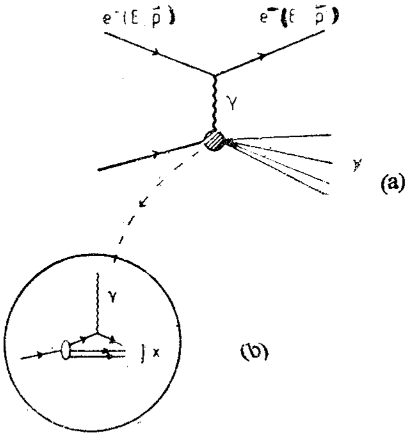

Fig. I.7. Deep ineleastic cattering (DIS) process.

the proton, that it is called *deep inelastic scattering* (DIS). Again by measuring the number of electrons arriving at an angle θ with energy E' seems to be controlled by *only one variabie* x given by

$$x = \frac{(E-E')^2-(\mathbf{p}-\mathbf{p}')^2}{2M_p(E-E')} = \frac{Q^2}{2M_p\nu} \tag{I.4}$$

(which is the counterpart of variable x we have defined earlier) and *not on individual values of E' and θ*. This once again clearly indicated existence of pointlike constituents inside the proton. Larger values of E permit Q^2 and ν to become larger and hence allow a 'closer' look at the proton.

Further identification of these pointlike scattering centres, with the spin 1/2, fractionally charged quarks required a fusion of the theoretical ideas of the behaviour of quarks and the forces that bind them together, with the above experimental information. The variable x above can be identified with the fraction of the momentum of the proton carried by the quark (q) which the electron 'sees' (see Fig. I.7b where the blob in Fig. I.7a is expanded). The experimental information can be used to extract $Q(x)$, the probability for the quarks to carry momentum fraction x of the proton. A typical result from the latest, high energy DIS experiment is shown in Fig. I.8. The curve shows $xQ(x)$. To the utter surprise of the physicists, the area under the curve in Fig. I.8, when added to the area under the corresponding curve for antiquarks ($x\bar{Q}(x)$), yielded only 0.5, i.e. 20% of the proton's momentum was 'missing', so to say. The solution to this mystery of missing momentum was simple enough. It meant that the proton contains additional constituents which are not 'seen' by the electron probe. This could happen if they were electrically *neutral*. The presence of neutral constituents of protons was thus indicated. The description of hadrons as bound states of quarks requires such neutral particles, analogous to photons, to *bind* the quarks together

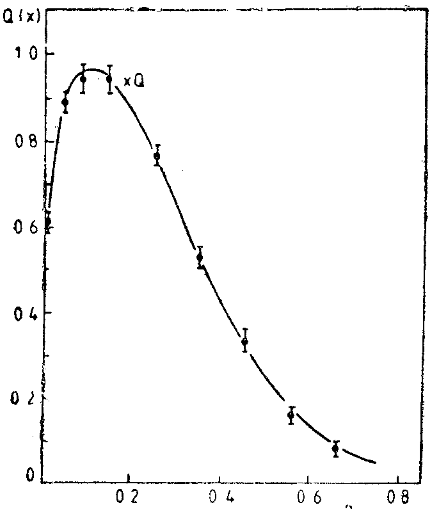

Fig. I.8. Momentum fraction carried by quarks in a proton.

and these are called *gluons*. Thus we see that the fundamental constituents of hadrons, quarks, and gluons, collectively called *partons* (whose existence is required in the formulation of a theory to explain the observed patterns and symmetries in the static properties of hadrons), were independently 'seen' by these dynamical 'probes' of electron beams. Thus essentially similar steps have revealed the constituents of atoms, nuclei and nucleons—first the spectoroscopy, followed by the Rutherford type scattering experiments. The similarity is clearly reflected in the qualitatively similar experimental results obtained with electron beams scattered from atoms, nuclei and proton, examples of which are shown in Fig. I.9a, b and c respectively. With the increasing energy scale the continuum in quasi-elastic scattering has yielded information about constituents with smaller and smaller size.

The most natural question which follows from the above discussion, of course is, "Is this the end? If we increase energies of our probes, will we be able to knock a quark out of the proton (like an e^- from an atom, or a nucleon from the nucles)"? The next question is "Is the quark further made up of 'prequarks'?"

The answer to the first question is that most probably it is impossible to knock a quark out of a proton. It was thought that it should be possible to do so by hitting the proton harder. Hence DIS experiment with beams of muons of energies ~ 200 GeV and neutrinos (ν) of ~ 200 -- 300 GeV have been performed. These high energy μ and ν beams are produced in the laboratory by first accelerating protons to very high energies ~ 500 GeV and hitting a nuclear target with it. These then produce pions and K-meson, which decay producing μ and ν with high energies. Fig. I.10 shows

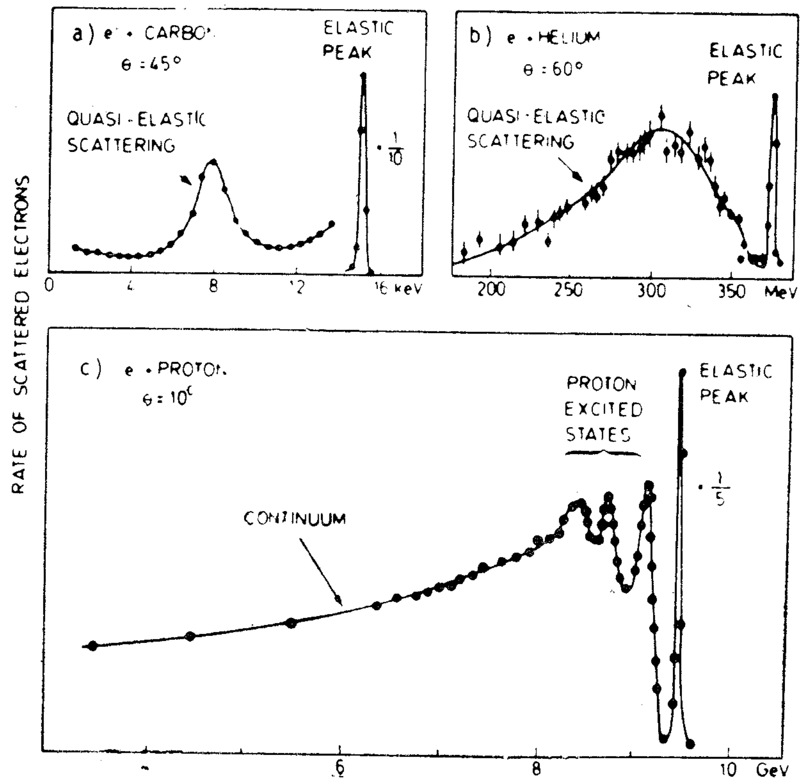

Fig. I.9. Evidence for nuclei, nucleons and quarks

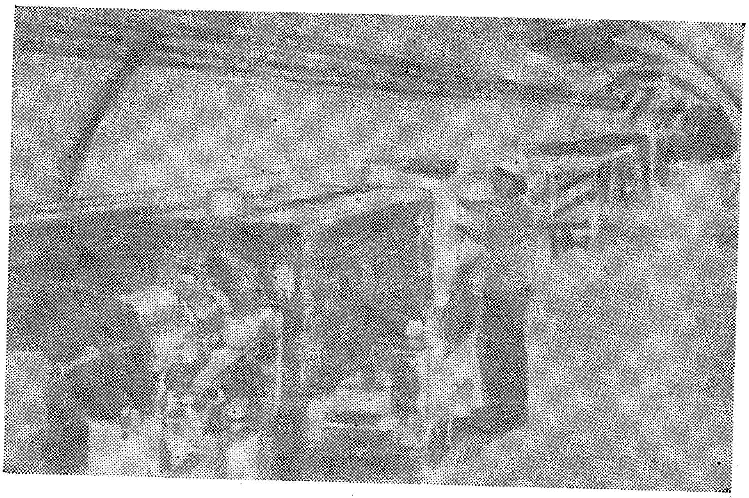

Fig. I.10. Inside SPS tunnel (Photo CERN) the inside of one such accelerator, ***super proton synchrotron*** (SPS) at CERN at Geneva. (CERN is the European Organistion for Nuclear Research.) The size of, and the money required for, the present day experiments is so large that international cooperation on both, the intellectual and the monetary, fronts is required. CERN is one example of such a collaborative effort.

These experiment with the μ and ν beams, have not been successful in breaking the proton, but instead have revealed some curious properties of quarks. Indeed, along with the earlier experiments, these also showed that quarks inside the proton behave as if they are 'almost' free. But as one increases the values of Q^2 of the probe, instead of separating the quark out of the proton, one 'sees' more and more quarks and gluons, of course, with smaller and smaller values of x. (The total momentum fraction can only add to unity!) Thus with increasing beam energies our ability to magnify the blob in Fig. I.7a increases. The situation can be picturised as in Fig. I.11. Thus the photon now is sensitive to quarks and antiquarks produced by gluons which are emitted by the original quark q before it meets the photon. This increase in the number of partons at smaller values of x with increasing Q^2 is in accordance with what the theory of quarks and gluons (QCD) perdicts. So far all the attempts to find evidence for a free quark, outside a proton, have completely failed. QCD provides reasons why, *in principle,* it is impossible to see such a fractionally charged, free object. The technical term is *colour confinement.* Needless to say, any experiment reporting such an observation will cause the greatest upheaval in our ideas about the basic building blocks of nature and the forces that hold them together.

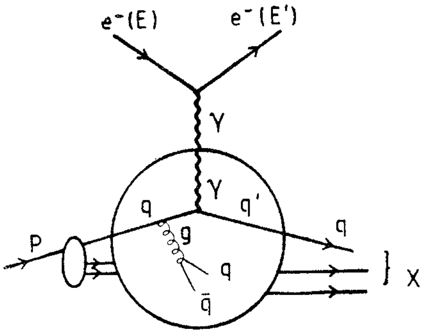

Fig. I.11. QCD corrections to simple parton picture of DIS.

The answer to the second question about 'prequarks' posed earlier, is not known completely. All that the physicists can do, at present, is to quote limits on the size of 'prequarks', if they exist. These limits can be obtained from certain low energy, high precision measurments of effects which are out of the scope of present discussions. But these indicate that quarks show a pointlike behaviour down to distance scales $\sim 10^{-18}$ m. One of the purposes of a high energy accelerator, being planned in Germany, called

HERA, is to probe for such substructure. Fig. I.12 gives the limit which this machine can reach. This will be achieved by colliding a beam of electrons of energy 30 GeV with a beam of protons of energy 820 GeV.

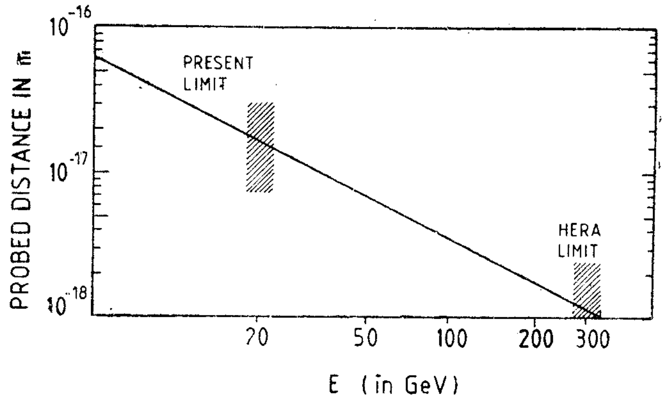

Fig. I.12. Probed distance in particles as a function of energy of the probe.

II. The building blocks and mortar of matter

> "Now the smallest Particles of matter may cohere by the strongest attractions, and compose bigger particles of weaker virtue...There are therefore agents in nature able make the particles of Bodies stick together by very strong attractions and it is the Business of experimental Philosophy to find them out."
>
> Newton, 'Optics', 1680.

In the previous section I have rougly sketched the historical development of scattering experiments, which revealed the existence of partons inside a a nucleon, inside a nucleus in an atom of an element. Fig. II.1 summarizes the current knowledge of the physicists about the constituents of matter as revealed at different energy scales. The discussion in the previous section did not really address the role in this development of the questions such as, "What holds these pieces together ?". However, it cannot be overemphasized. The discovery of these building blocks in the scattering experiments was quite often preceded by the prediction of their existence inferred from information such as the atomic excitation spectra, nuclear energy levels and masses, spins, magnetic moments of particles. Very often these theories predicted existence of as yet undisconvered particles such as Ω^- by Gell-Mann or charm quark by Glashow (analogous to Mendeleev's prediction of existence of gallium, germanium and scandium). The experimenal observations of these particles were important steps in the establishment of the symmetries of the underlying theories which describe the interactions among these fundamental constituents. This is a pattern which has been repeated

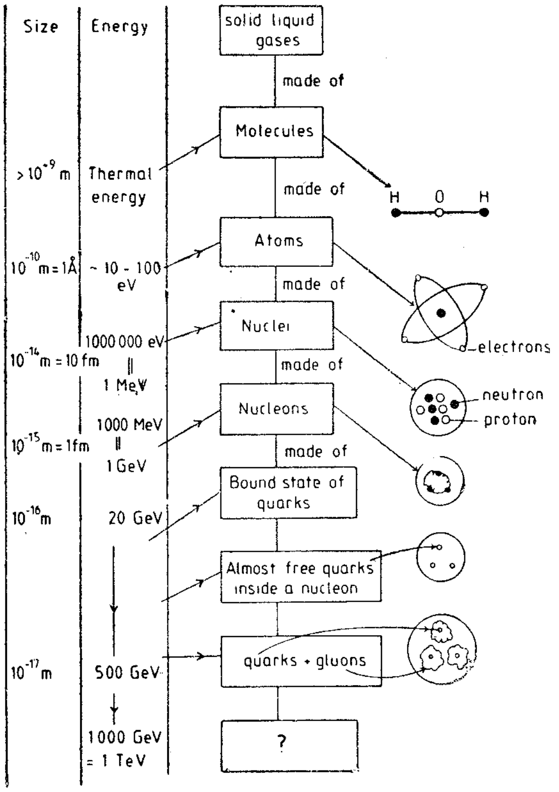

Fig. II.1. Quest for the structure of matter.

in the history of particle physics, again and again, as we will see in the ensuing discussion.

Leptons and Quarks: The basic building blocks of matter, according to our current knowledge, are leptons and quarks. Both, leptons and quarks, are spin 1/2 particles which occur in pairs whose charges differ by unity. The information about leptons is summarized in Table II.1. Three different pairs of leptons are known by now and of course their antiparticles.* All the three pairs of leptons exhibit similar properties. The real difference between them is the mass of the charged lepton of the pair. The third kind, τ^- lepton can be produced only in the laboratory and lives for a very short time $\sim 10^{-13}$ sec. In contrast μ^- lives for 10^{-6} sec, and e^- is stable. However, all such apparently major differences in their properties can be understood in terms of their widely different masses, in our present theoretical framework.

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*If particles have mass M, spin J, electric charge Q, strangeness S, lepton number L, etc., antiparticles have the same mass and spin but charge $-Q$, strangeness $-S$, lepton number $-L$, etc.

Table II.1. Leptons

Lepton family	Mass	Life time	Discovery
ν_e	< 46 eV	stable	postulated: 1931 experimental confirmation: 1956
e^-	0.5 MeV	stable $> 10^{22}$ yr.	1897
ν_μ	< 250 keV	stable	1961 Accelerator Expt.
μ^-	105 MeV	$\sim 2 \times 10^{-6}$ sec.	1936 Cosmic Ray Expt.
ν_τ	< 70 MeV	stable	Confirmation: 1982–1983 $\bar{p}$ p colliding beam expts. e^+e^- colliding beam expts.
τ^-	1.8 GeV	$\sim 3 \times 10^{-13}$ sec.	1975; e^+e^- colliding beam expts.

There is as yet no theoretical understanding of this apparently arbitrary replication of these pairs in nature.

The other components of matter are quarks. The charges of the quarks are fractional when measured in units of electron charge. They also possess, apart from electric charge, isospin, spin, and another attribute called *colour*. They come in three colours, say *red, blue* and *green*. No free particle with a fractional charge outside the nucleus has yet been seen. In the technical jargon it is explained in terms of *colour confinement*. The properties of these quarks have been discussed in some detail in Chapter 12 on 'Quark structure of hadrons'. I merely summarize in Table II.2 the information that is relevant for the discussion here. It goes without saying that antiparticles of the quarks listed here exist too. The technical name for the different varieties in which the quarks occur is *flavours*. The essential difference between different pairs (or families as they are called) is mass. Most of the matter around us (including ourselves) is made up of *up* (u) and *down* (d) quarks. The strange particles mentioned in Section I contain, in addition to u, d, $\bar{u}$, and $\bar{d}$, *strange* quarks (s) and antiquarks ($\bar{s}$). Given the existence of u, d, s and the first two families of leptons, the existence of a fourth quark (c) was predicted on the basis of *gauge theories* (which we will discuss below) and was confirmed experimentally. The discovery of the third generation of leptons and one more quark type b with mass ~ 4.45 GeV now necessitates that a sixth quark with charge $(2/3)e$ should exist, for this theoretical formulation to be consistant. There are indications that the current high energy

Table II.2. Quarks

Quark family	Mass	Charge	Discovery
$\begin{pmatrix}u\\d\end{pmatrix}_{\text{red}} \begin{pmatrix}u\\d\end{pmatrix}_{\text{blue}} \begin{pmatrix}u\\d\end{pmatrix}_{\text{green}}$	~ 300 MeV ~ 300 MeV	+ (2/3) e − (1/3) e	1961 Gell-Mann Postulate. Confirmation and measurement from DIS
$\begin{pmatrix}c\\s\end{pmatrix}_{\text{red}} \begin{pmatrix}c\\s\end{pmatrix}_{\text{blue}} \begin{pmatrix}c\\s\end{pmatrix}_{\text{green}}$	~ 1500 MeV ~ 500 MeV	+ (2/3) e − (1/3) e	1974 e^+e^- collider p-Be collisions 1961 Gell-Mann postulate. Confirmation and measurement from DIS with ν
$\begin{pmatrix}t\\b\end{pmatrix}_{\text{red}} \begin{pmatrix}t\\b\end{pmatrix}_{\text{blue}} \begin{pmatrix}t\\s\end{pmatrix}_{\text{green}}$	~ 30–50 GeV? ~ 4.45 GeV	+ (2/3) e − (1/3) e	(?) 1984 $\bar{p}$ p collider 1977 p-nucleus collisions 1978 e^+e^- experiments

physics experiments may have seen it already. But final confirmation from the data is still not at hand. In the next section, I will give a brief discussion of the yet unconfirmed but possible traces of this heaviest quark which is labeled *top* (t).

The experimental search for these leptons and quark species was facilitated by a new kind of accelerator experiment. In these the electron and positron beams of very high energy are made to collide with each other. Due to the very well defined energies of leptons taking part in these interactions, these experiments are 'clean', i.e. easy to analyse. Fig. II.2 shows a photograph of the experimental arrangements for one such experiment (SPEAR at SLAC). The electrons and positrons meet head on. The annihilation occurs in the tunnel behind the physicist shown in the picture. The complicated array of electronic devices is only a part of the detector system. The *multiwire proportional counters* (MWPC) or the drift chambers, which essentially still work on the principle of detecting ionisation produced by a charged particle, can detect the position of a particle with a resolution of ~ 50–100 microns (1 micron = 10^{-6} m). Of course, p-nucleus or π-nucleus collisions have also been able to see the heavier quarks and leptons successfully.

No reactions which turn members of different families of leptons into one another have been observed, i.e. the total number of leptons of each family type is found to be conserved. The situation is more complicated in the case of quarks and also intimately related to a very small violation of symmetry called CP symmery. CP transformation is the combined operation of charge conjugation (an operation which changes particles into antiparti-

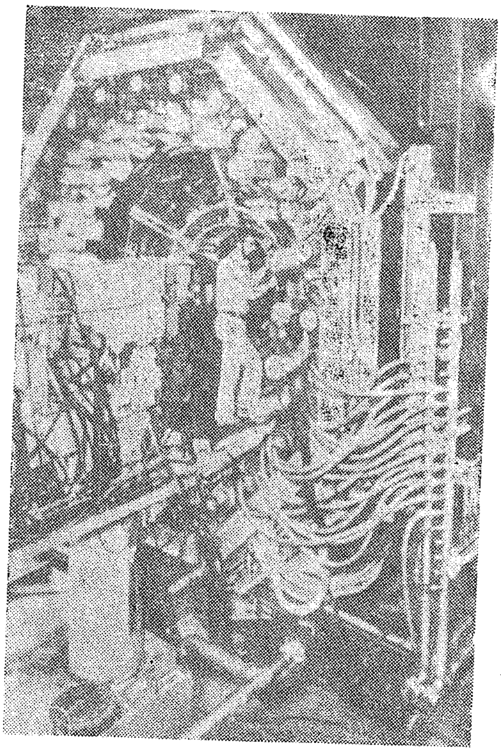


Fig .II.2. Inside of a detector used at e^+e^- collider (Photo SLAC).

cles) and mirror reflection. However, I do not include these details in the following discussion.

Originally μ^+, e^+ were classified separately due to their small masses and hence called 'leptons'. From Tables II.1 and II.2 it is clear that mass can no longer be the dividing line between lepton and other particles, and indeed it is not so. The classification between leptons and quarks comes from the reactions in which they can participate. There are four basic forces. The leptons differ from quarks in the fact that they do not feel the strong force. They are neutral with respect to strong interactions, just like the electrically neutral particles which do not feel electrical forces. The main features of the four basic interactions are summarized in Table II.3.

Mediating Bosons: The relative strength of the interactions lie in the order, gravitational $<$ weak$<$ electromagnetic $<$ strong. This ordering can be justified by constructing a dimensionless measure of interaction strengths, but will not be discussed here. Furthermore as we shall see in Sections III and IV it is possible that this relative ordering *may only be a low energy artifact.*

Table II.3. Interactions between quarks and leptons

Force	Responsible for	Carrier of force	Range	Mass of the carrier	Particles which feel the force
gravitational	e.g. formation of solar system	Graviton (?)	∞	0	all
weak	e.g. radioactive decay of nuclei, generation of solar energy	W, Z bosons	$< 10^{-18}$ m	$\sim$ 100 GeV	all
electromagnetic	e.g. formation of atoms	γ (photon)	∞	0	all charged particles
strong_1	e.g. formation of nuclei form nucleons	π (pion)	$< 10^{-15}$ m	$\sim$ 140 MeV	hadrons
strong	e.g. formation of nucleons from partons	g (gluon)	confining force	0	quarks

The gravitational forces are the weakest and are important only in the systems where large masses or distances are involved—the former because the force is directly proportional to mass and the latter due to the infinite range over which it can be felt. Of course, all the particles with nonzero mass feel the gravitational force. The electromagnetic force can be felt between charged particles and causes the formation of an atom, for example. The electrons are held in place by the attraction of the positively charged nucleus. The force responsible for holding the nucleons together inside the nucleus, inspite of the electromagnetic repulsion between protons, is labeled as strong_1. I separate it from 'strong', because now it can be understood simply as a residual force generated by strong forces between the quarks that bind them in a nucleon (just like the molecular Van der Waal's force is the residual force generated by electromagnetic interactions). The weak force is responsible for the radioactive decays of the nuclei and also for the processes which lead to energy generation in stars.

Associated with each force in Table II.3 there is an 'exchanged particle'. This correlation between the exchanged particle and various characteristics of the corresponding force is due to the development in the subject of field theories. Unlike quantum mechanics, these can deal with creation and absorption of particles and antiparticles, and can explain 'the apparently impossible' *action at a distance.* The initial developments were in the field of electromagnetism. The interaction of two charged particles e_1 and e_2 can be understood in two alternative pictures sketched in Fig. II.3. We can understand the interactions between the two charges as the effect on e_2 of the electromagnetic field generated by e_1 (and vice versa) or as the effect of the exchange of a spin 1 photon between e_1 and e_2. This is obvious even from the ideas of wave-particle duality of quantum mechanics. The development of a consistent, exact mathematical formulation which establishes this exactly and describes electromagnetic interactions of a charged particle, was the development of *quantum electrodynamics* (QED) in 1940–1950. Similarly all the other forces can also be associated with the exchange of a particle.

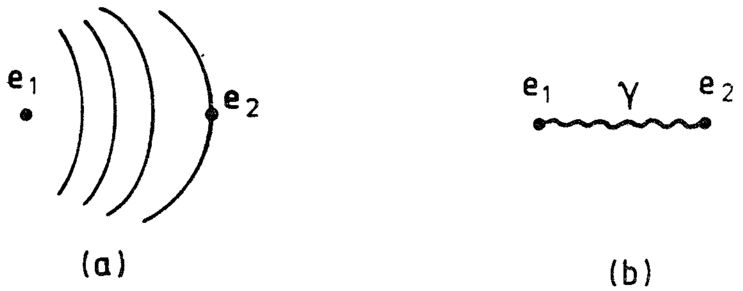


Fig. II.3. Electromagnetic interaction between charges.

The character of the force is decided by the mass and the spin of the exchanged particle. This correlation can be understood using Heisenberg's uncertainty relation. If the exchanged particle has a mass m, then a picture such as in Fig. II.3(b) means that energy conservation is violated by an amount $\Delta E \sim mc^2$. But the uncertainty relation tells us that this can exist only for time Δt such that

$$\Delta E \Delta t \sim (h/2\pi) = \hbar \tag{II.1}$$

The maximum speed with which this exchanged particle can travel is the speed of light c. Hence the maximum distance to which the particle can convey the force is $\hbar/cm$. Hence its range is given by

$$R \sim \hbar/cm \tag{II.2}$$

This is rather like a soccer ball. The lighter the ball is, the farther is the distance one can throw it easily. If m is zero, then the range of the force is infinite. The zero mass of the photon can thus be inferred from Coulomb's law. As we know, nuclei are only a few fm in size. Hence if the force that holds the nucleons together is mediated by particle exchange, then the particle must have a mass ~ a few hundred MeV (Eq. II.2). The observed equality of forces for n-n, p-p and n-p system further indicates the need for three particles of similar mass but different charges (see Fig. II.4). These were the famous π mesons predicted by Yukawa, which got him his Nobel prize.

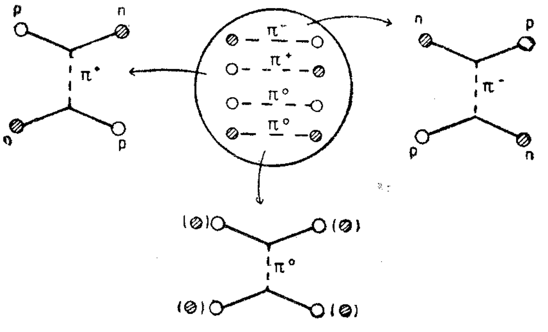


Fig. II.4. Meson exchange picture of strong interactions.

As mentioned in the earlier section, the DIS experiments with e, μ and ν beams discovered the existence of gluons, e.g. the neutral partons. These are the strong interaction analogues of photons. They mediate forces between quarks and also have spin 1. The fact that each variety of quarks, i.e. u, d, s, c, etc, occurs in three colours implies that there exist eight distinct gluons. This is sketched in Fig. II.5. Why there exist eight distinct gluons instead of nine as would follow from Fig. II.5, requires a little involved argument

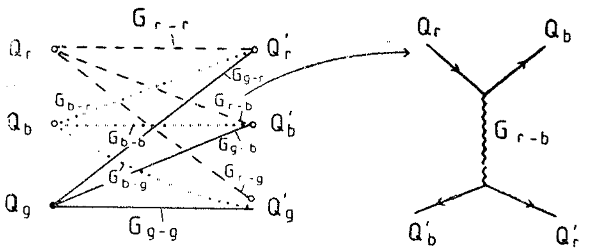


Fig. II.5. Gluon exchange picture of strong interactions.

and is discussed briefly in another chapter in this book. So to carry on the analogy with QED a little further, colour of the quarks can be treated as the charge which the gluons see. A theory of forces between coloured quarks caused by gluon exchanges, similar to QED can be formulated and is called *quantum chromodynamics* (QCD). A gluon differs from a photon in that it itself carries a colour charge. This can be seen from Fig. II.5. This has important consequences for strong interactions. As a result of this the force between quarks exhibits a Coulomb-like behaviour (implying zero mass for gluons) only for small values of r (the distance between the quarks). At large values of r the potential energy of a two quark system grows like $\ln r$ or even some power of r. Hence it is impossible to separate a quark from a nucleon or meson. This self interaction of gluons is also responsible for almost 'free' behaviour of quarks, when they are inside a nucleon/pion, which is exhibited in the high energy reactions. These basic features of QCD are tested by DIS experiments. How such a basic force between quarks will lead to formation of hadrons and further to a correct description of the force I call strong$_1$ is very much an open problem, and hence also an area of high activity.

The force responsible for the radioactive decay of nuclei turns out to be different from all the above three. It acts only in the limited nuclear volume. This indicates a short range and hence an associated exchange of a heavy particle. The picturisation of β decay at the nucleon and quark level is depicted in Fig. II.6a and II.6b, respectively. The observation of both β^- and β^+ decay in

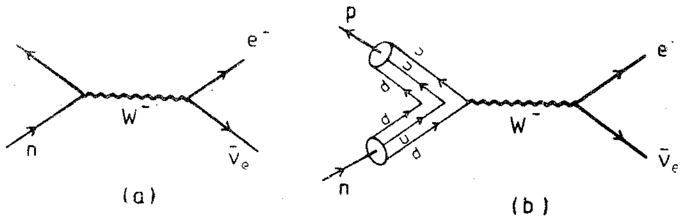
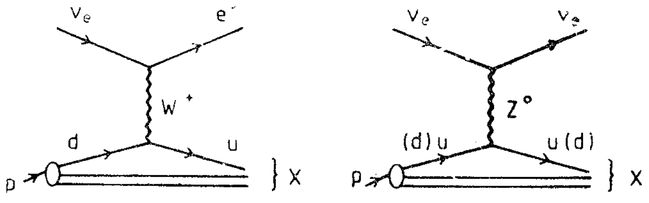


Fig. II.6 (a) Nuclear β decay through W exchange; (b) Quark level picture of nuclear β decay.

nuclei implies that the reactions $n \rightarrow pe^- \bar{\nu}_e$ as well as $p \rightarrow ne^+ \nu_e$ take place inside the nucleus. This indicates the existence of mediating particles with both charges, negative and positive. As will be discussed in the next section there exist actually three heavy carriers of weak interactions with spin 1 called $W^\pm$ and Z^0. The presence of Z^0 was indicated by interactions of ν. The weak interaction analog of DIS process depicted in Fig I.7 is shown in Fig. II.7a. The presence of Z^0 was first conformed by observation of ν interactions in which the lepton does not change its charge. Now even the weak neutral current analog of the DIS, shown in Fig. II.7b, has been seen experimentally successfully. $W^\pm$ and Z^0 are called the *weak vector bosons*. Note that all the particles mediating these various interactions have integral spin and hence are bosons. These are collectively referred to as gauge bosons, for reasons that will be explained in the next section.



(a) (b)

Fig. II.7 (a) Charged current scattering, (b) neutral current scattering.

Thus to summarize the discussion of this section, we have three families of spin 1/2 leptons and three families of spin 1/2 quarks which occur in three colours, their antiparticles and the twelve gauge bosons which mediate weak, electromagnetic and strong interaction among them. Table II.4 summarizes this. In the next section the question of a unified description of these interactions and the discovery of $W^\pm/Z^0$ is discussed.

Table II.4 Quarks, leptons and gauge bosons

	Quarks (u, d), (c, s), (t, b)		Leptons (ν_e, e^-), (ν_μ, μ^-), (ν_τ, τ^-)
Gauge Bosons	gluons g	photon γ	Weak vector boson $W^\pm$ and Z^0
Number	8	1	3
Interactions	strong	electromagnetic	weak

III. Electroweak unification and $W^{\pm}/Z^0$ discovery

> "I have long held an opinion, almost amounting to conviction, in common, I believe, with many other lovers of natural knowledge, that the various forms under which the forces of matter are made manifest have one common origin."
>
> Micheal Faraday

Gauge Field Theories: The discussion in the previous two sections shows that at present we have a reasonably economical (!) description of all the matter in terms of 60 constituents: 6 leptons, $3 \times 6 = 18$ quarks, their antiparticles and the 12 gauge bosons mediating various interactions. The mathematical framework for a description of all the interactions among these is provided by a class of quantum field theories (QFT) called *gauge field theories*. Their development has been one of the major conceptual advances of the past few decades. Having abstracted the constituents of matter at a fundamental level, the quest now has been to give a unified description of all these interactions, including perhaps even gravitation. Gauge theories have made it possible to provide a partial answer to this question of unification. A prototype of these, and most successful of them all, is QED. QED is the field theoretic description of the interaction of an electron with light. We first, very briefly, discuss some features of QFT in general and then of QED in particular, that are important to understand the ideas of unification of all the interactions.

As said earlier QFT provides a framework consistent with relativity and quantum mechanics, to describe creation and annihilation of particles and antiparticles and also their propagation in space. Associated with each point in space and time $(\mathbf{x}, t)$ we have a field operator $\Phi(\mathbf{x}, t)$ for each kind of particle. The dynamics of this field operator describes the dynamics of creation, annihilation and propagation of corresponding particles. This dynamics, the time evolution, is controlled by the Hamiltonian H constructed out of these field operators. The observed symmetries and patterns exhibited by the particle properties translate into invariances of H or equivalently the Lagrangian.

One of the problems with field theories is certain infinities that occur in its formulation. When interactions are present, similar to the case of classical and quantum mechanics, very often the problem can be solved only perturbatively. Quantum electrodynamics gives an excellent description of the observed phenomena, e.g. Compton scattering, when calculated in the lowest order in perturbation theory. But calculations of the corrections in the next higher order yield infinities. It was due to the conceptual advances made by Feynman, Tomanaga and Schwinger, that physicists learnt how to handle these infinities, through a program called *renormalization*. It is possible to absorb these infinities in a 'redefinition' of the parameters of the theory. A theory is said to be *renormalizable* if at the cost of a finite number of parameters introduced in the theory via such redefinitions (to be determined from experiments), we can render the predicted amplitudes of all the physical processes finite, to all orders in perturbation theory and at all energies. It is clear that any physically relevant theory better be so. In QED, e.g. these two parameters are the electron mass and charge.

The effective charge then is a function of masses and energies involved. It is not so arbitrary as it sounds. We already know an example from classical electrodynamics. A test charge immersed in a *dielectric* causes *polarization* of charges as shown in Fig. III.1a. This charge exerts a potential, at distances comparable to molecular dimensions, smaller than the Coulomb potential in free space. This is known to us as *screening*. Similarly vacuum itself can act as a dielectric. The photon being exchanged can split into an e^+e^- pair and recombine (Fig. III.1b). This alters the forces between two electrons (of course, these effects are larger at smaller distances and hence at larger Q^2). This is the so called *vacuum polarization.* In QCD the gluon can either go into a $Q\bar{Q}$ or GG pair (Fig. III.1c). This again alters the behaviour of the force (and hence the coupling between two quarks). These vacuum polarization effects make the coupling (charge) dependent on distance scales involved. This is called *effective coupling.* Actually it is the existence of the second type of diagrams in Fig. III.1c, which gives rise to *antishielding* and hence qualitatively different dependence of coupling on energy for QED and QCD.

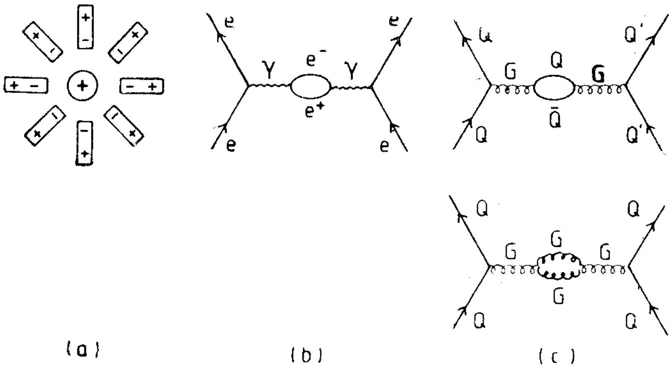


Fig. III.1. Shielding and antishielding effects.

For QED, after the normalization program is carried out, one can calculate the corrections to, e.g., hydrogen atom spectrum, called *Lamb shift,* due to the vacuum polarization. Similarly quantum corrections to the electron's g factor can be computed exactly. The experimental measurement of Lamb shift or the deviation of g_e and g_μ from 2, have been confronted with theoretical predictions to better than one part in a million million. This is the most precise theory we have.

A feature of QED relevant for further discussion is the unified treatment of the electric and magnetic fields. This unified treatment is actually a legacy of Maxwell and exists in classical electrodynamics too. Maxwell's equations are nothing but a shorthand and elegant description of the various laws of interactions of charged particles with electric and magnetic field (e.g. Gauss' law, Faraday's law, Coulomb's law, Biot-Savart's law), in terms of an electromagnetic potential. This consists of four components

$$A_\mu \equiv (\phi, \mathrm{A}), \mu = [1, 4],$$

where ϕ is the *scalar potential* and A is the *vector potential.* By simply changing the Lorentz frame of reference, we can describe the interactions in terms of only the electric field **E** or only the magnetic field **B** or a combination thereof. Thus electricity and magnetism are but two manifestations of the same basic phenomenon. These ideas predicted the existence of the electromagnetic radiation travelling with velocity of light *c*. Verification of this prediction proved the correctness of this unification idea, which is the 'grandfather' of all the present unification attempts.

Another important feature of QED is the *gauge invariance.* Again the ideas are known to us from classical electrodynamics. The electric and magnetic fields which produce the forces on charged particles are unchanged if we change the potentials ϕ and **A** as

$$\phi \rightarrow \phi + \frac{\partial\alpha}{\partial t}, \mathbf{A} \rightarrow \mathbf{A} - \nabla\alpha \qquad \text{(III.1)}$$

Thus the equations of motion of the charged particles remain unchanged under such a transformation. This transformation is called a gauge transformation. If instead of starting with electrodynamics, we simply start from Schrödinger equation and investigate the invariance of the Lagrangian under a phase transformation of the wave functions,

$$\psi(x) \rightarrow \exp\,(iQ\alpha(x))\;\psi(x) \qquad \text{(III.2)}$$

then the existence of a field A_μ which transforms like Eq. (III.1) and couples to matter fields in a specific manner is forced upon us. Note that the phase of wave function in Eq. (III.2) is a function of space and time. This is a nontrivial phase transformation called *local gauge transformation.* We demand that the theory be invariant even when we change the phases arbitrarily differently at different points in space and time. This can be achieved only if we have a field A_μ which transforms like in Eq. (III.1) and couples to matter precisely in the manner of an electromagnetic field. These local phase transformations form a group. This group is called U(1) in the language of mathematics. Thus the *gauge group* of QED is U(1). Invariance of the theory under the U(1) *local gauge transformations* implies the existence of a *massless, spin* 1 *gauge boson*, which in this case is photon γ. The gauge invariance requires that the gauge boson be massless. Attempts to describe all the other interactions as gauge theories have led physicists to the unification ideas. Using the analogy from QED, we will try to understand this description of all the interactions as *gauge theories.*

Quantum Chromodynamics (*QCD*): First I will very briefly summarize the features of the gauge theory of strong interactions, viz. QCD, which has been referred to from time to time in this article and discussed elsewhere in detail. QCD is a gauge theory whose matter fields are quarks carrying colour charges. There are three different types of colour charges. The gauge group is SU(3); it is the group of transformations generated by 3×3, unitary, traceless matrices with determinant unity. Again local gauge invariance requires the existence of eight massless, spin 1 gauge bosons: the eight gluons. The SU(3) symmetry group means that the interquark interactions are independent of the colour charge. The matrices representing the group transformations are noncommuting. Hence this is called a *nonabelian gauge theory*. The fact that these gauge bosons themselves carry the colour charge is related to this. As discussed earlier, this is also reflected in a dependence of coupling on energy, different from that for QED. With this brief summary we move on to a possible gauge theory description of the weak interactions.

Electroweak Theories: The similarity between weak and electromagnetic interactions, inspite of their widely differing strenghts and ranges, was first noted by Fermi. His model for the β decay of the neutron is depicted in Fig. III.2a. The e^- and $\bar{\nu}_e$ emitted in the decay can have a total spin 0 or 1. In analogy with electromagnetic interactions, Fermi proposed (correctly) that they emerge only in spin 1 combination. The analogy was furthered when Klein suggested the existence of a spin 1 boson, mediating weak interaction, hence called 'boson' (Fig. III. 2b). Schwinger later tried to give a unified treatment of weak and electromagnetic interactions by proposing that W^+, W^- and γ may be the weak and electromagnetic interaction analogues of π^+, π^- and π^0 of strong interactions. However, the observed

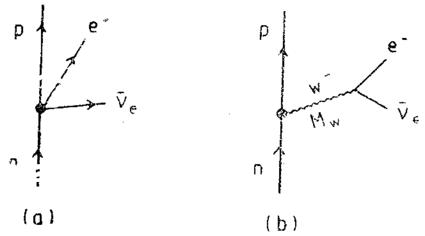


Fig. III.2 a, b. β decay.

strenghts of weak and electromagnetic interactions differ very widely. Hence if one supposes that the strength of $W^- - \bar{u} - d$ or $W^- - e^- - \bar{\nu}_e$ coupling is the same as γ-e^--e^- coupling, the observed strenghts can only be explained if mass of W^+ bosons is $\sim$ 100 GeV.

The large, nonzero mass of the W^+ bosons was a great obstacle in a possible formulation of a gauge theory of weak interactions. Not only did it preclude any possibility of a unified treatment with photon, but also made it impossible to write a theory invariant under local gauge transformations generated by them. Studies in QED had shown that gauge invariance demands massless gauge bosons. Also such nonzero mass terms made the theory *nonrenormalizable*, i.e. it was no longer possible to absorb all the infinities at the cost of a few experimentally measurable parameters. Both the problems, viz. to construct a gauge invariant, renormalizable theory of these 'weak-bosons' and to unify the 'electromagnetic' with 'weak' carriers were solved mainly as a result of three different important ideas. Glashow was the first one to notice certain patterns in the weak interaction properties of quarks and leptons. Based on these ideas the final gauge theory model of electromagnetic and weak interactions was given by Weinberg and Salam separately. (All three shared a Nobel prize for this work.) Construction of a gauge invariant theory in spite of the large weak boson masses, was made possible by an idea due to P. Higgs. Most important of all was the renormalizability of these theories (hence physicist's ability to calculate experimentally measurable quantities accurately and uniquely), demonstrated by G. t'Hooft. Let us try to understand some of these ideas.

From the discussion in the previous section (cf. Tables II.1, II.2 and Fig. II.5) it is clear that both leptons and quarks occur in pairs, e.g. a W^- (W^+) boson couples to e^--$\bar{\nu}_e$ (e^+-ν_e) pair or a $\bar{u}d$($u\bar{d}$) pair. Thus, from the point of view of weak interaction, the basic units are these quark or lepton doublets. Hence by using the langauge of matrices, we can describe W^--e^--$\bar{\nu}_e$ (equivalently W^+-e^+-ν_e) coupling by a weak charge, just like γ-e^--e^- coupling is given by the electric charge. In other words one could think of a 'weak isospin' in analogy with isospin known from the physics of hadrons. The quarks and leptons from weak-isospin doublets, e.g.,

$$Q_1 = \begin{pmatrix} u \\ d \end{pmatrix}, \; Q_2 = \begin{pmatrix} c \\ s \end{pmatrix}, \; L_1 = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \; L_2 = \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \qquad \text{(III.3)}$$

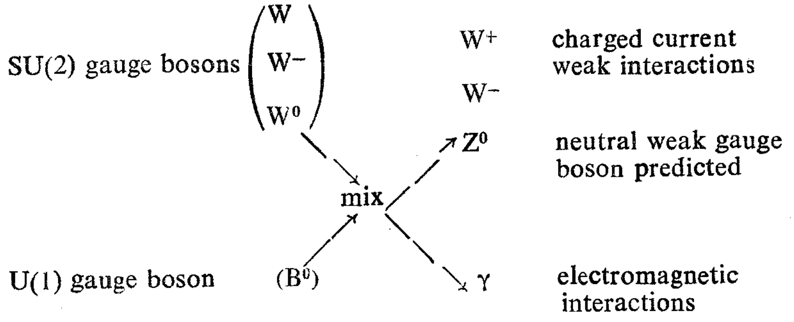
Further we can use this matrix notation to demonstrate how different members of the doublets Q_i and L_i transform into one another. This is just like the co-ordinate axes which can transform into one another under a spatial rotation. These transformations of the doublets can be represented by 2 × 2 unitary, traceless matrices with determinant unity and form a group called SU (2). Considerations of a gauge theory based on this group imply the existence of a third, neutral, gauge boson which also exhibits weak interactions. Let us call it W^0. As we know, the requirement of gauge invariance decides the form of the interactions W^0 can have. Actually it relates the interactions of W^0 with matter to those of $W^{\pm}$.*

Glashow noticed another similarity between Q_i and L_i of Eq. (III. 3). Gell-Mann and Nishijima had noted in a different context that, electric charge of particles in such isospin doublets can be written as

$$Q = \pm\frac{1}{2} + \frac{Y}{2} \tag{III.4}$$

Y is called *hypercharge* and $\pm 1/2$ corresponds to the value of the weak isospin of the upper and the lower member of the doublets in Eq. (III.3). The quarks in doublets Q_i have $Y = 1/3$, whereas lepton doublets L_i require $Y = -1$. Glashow was the first one to note this hypercharge degree of freedom, i.e. quarks and leptons have different values of Y, and use it in the construction of weak interaction model. Since Y is a real number for all the leptons and quarks (just like electric charge itself) it can be considered as a unit matrix. The corresponding group is U (1), the corresponding gauge particle must be neutral and must have spin 1 (say B^0). Let all the leptons and quarks couple to $W^{\pm}$, W^0 with strength g_2 (analogous to electron charge e) and to B^0 with strength g_1.

All the above discussion of Glashow's model seems to take us away from the main point. In an attempt to write a gauge theory of weak interactions, we seem to have introduced two new weak bosons W^0 and B^0 which as yet have no relation to the well known neutral gauge boson: photon. But all of the above falls into place with Glashow's idea that the physical, zero mass photon be identified with a linear superposition of W^0 and B^0. The linear superposition of the B^0 and W^0 orthogonal to the γ is the 'new' neutral weak boson predicted in this model and was called Z^0. Thus γ mediates electromagnetic interactions whereas exchange of Z^0 predicts new kind of reactions in which ν can be involved and there is no change in the lepton charge. These are called *neutral current* interctions. The $W^{\pm}$ mediates the well known β decay where the charge of the lepton is changed and hence called *charged current* reactions. Thus we have the following picture:



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*It must be stated here that in the discussion above and the one to follow, I have suppressed a very important property of the weak interactions, viz. their *asymmetric behaviour under a mirror reflection,* in contrast to electromagnetic and strong interactions.

The superposition of W^0 and B^0 to produce Z^0 and γ is depicted in Fig. III.3. We can thus write,

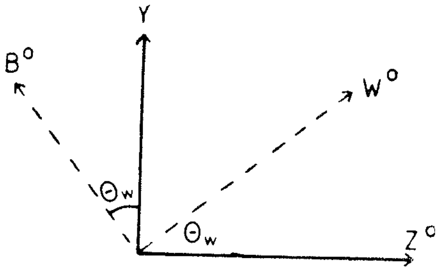


Fig. III.3. B^0–W^0 mixing.

$$\gamma = \cos\theta_W\, B^0 + \sin\theta_W\, W^0 \qquad \text{(III.5)}$$

$$Z^0 = -\sin\theta_W\, B^0 + \cos\theta_W\, W^0$$

We know that γ, B^0 and W^0 couple with matter with strength e, g_2 and g_1 respectively. Eq. (III.5) implies a relation between these three:

$$e = g_2 \sin\theta_W = g_1 \cos\theta_W \qquad \text{(III.6a)}$$

Then, using $\sin^2\theta_W + \cos^2\theta_W = 1$, we can easily see that

$$e = \frac{g_1 g_2}{(g_1^2 + g_2^2)^{1/2}} \qquad \text{(III.6b)}$$

Considerations of charged current interactions (similar to Fig. III.2a and III.2b with n and p replaced by d and u) give us,

$$\frac{G_F}{\sqrt{2}} = \frac{g_2^2}{8M_w^2} = \frac{e^2}{8M_w^2 \sin^2\theta_W} \qquad \text{(III.7)}$$

where G_F is the Fermi constant, which can be accurately determined from the study of μ decay and β decay. Thus we have M_W in terms of G_F, $\sin^2\theta_W$ and e^2.

The above model thus *unifies* weak and electromagnetic interactions. The correctness of this idea can be tested by looking for the effects of the neutral, weak boson Z^0 predicted above. Its coupling to leptons and quarks, at low energies, is given completely in terms of a parameter $\sin\theta_W$, the quark and lepton charges and the Fermi constant. Thus this unification idea predicted the existence of *neutral current reactions*, somewhat analogous to the prediction of electromagnetic radiation from Maxwell's unification ideas. Such reactions were observed for the first time at CERN in 1973 in ν reactions,

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^- \qquad \text{(III.8)}$$

shown in Fig. III.4. Note that this is similar to the second part of Fig. II.5. A bubble chamber photograph of this event is reproduced in Fig. III.5.

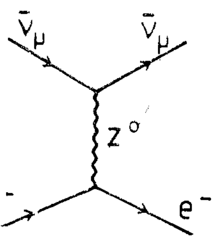


Fig. III.4. Neutral current reaction process.

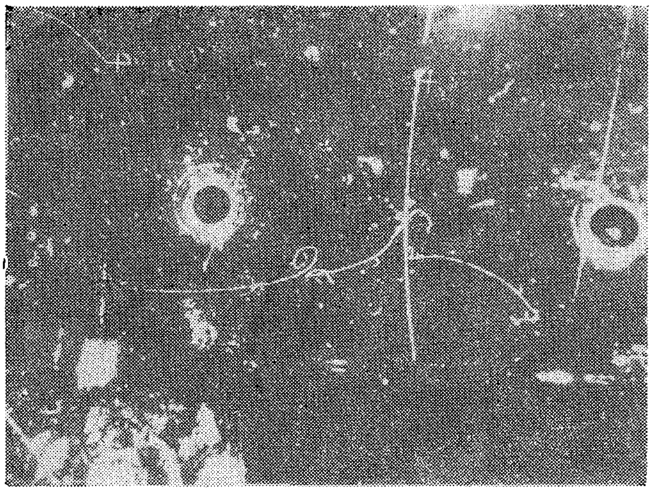


Fig. III.5. Bubble chamber photograph of neutral current reaction (Photh CERN).

The only arbitrary parameter of the model is sin θ_W. It can be determined by a detailed measurement of charged current and neutral current interactions of leptons and hadrons. The experimental measurements yielded $\sin^2 \theta_W \sim 0.23$. Thus it is clear from Eq. (6) that e, g_1 and g_2 are all of the same order. The observed difference in the strengths of electromagnetic interactions caused by γ exchange and weak interactions caused by $W^\pm/Z^0$ exchange (cfs. Figs. I.7, II.7) can then be attributed to the widely different masses of γ and $W^\pm/Z^0$. Thus the apparent difference between them becomes essentially a low energy phenomenon. If we go to high enough energies $E \gg M_W$, then the two interactions have the same strength. Thus the two are just different forms of the same basic interaction. The symmetry between them is masked at low energies and is apparent when we go to energies where M_W can be neglected.

It was also clear from the rate of observed neutral reactions that Z^0 has to be heavy like $W^\pm$ and cannot be the photon. For this SU (2) × U (1) model of electromagnetic and weak interactions to be complete, the questions of widely different masses of $W^\pm$, Z^0 and γ, as well as of maintaining gauge invariance in the presence of massive gauge bosons had to be addressed. This was achieved by Weinberg and Salam separately.

The formulation of Weinberg-Salam (W-S) model (as it is now called) was made possible by an observation by P. Higgs. He showed that it is possible to construct locally gauge invariant theories with massive gauge bosons at the cost of introducing one additional particle in the theory. The mechanism is called Higgs mechanism for spontaneous symmetry breaking. This additional particle has spin zero, its interactions with all the other particles, i.e. quarks and leptons, can be predicted but *not its mass.* A discussion of this mechanism, though important, will be a further digression and hence will not be given here. Using these ideas Weinberg and Salam extended Glashow's model. In this description of electro-weak unification, one could predict masses of all the gauge bosons in terms of sin θ_W. It was possible to show that γ given in Eq. (III. 3) remains massless and M_Z (in this model) has mass

$$M_Z = \frac{M_W^\pm}{\cos \theta_W} \qquad \text{(III.9)}$$

whereas M_W is already given in Eq III. 7. Note only the masses of $W^\pm/Z^0$, but also the particles into which they will decay and how often they will do so, is predicted in terms of three measurable quantities: sin θ_W, Fermi constant G_F and electron charge e. This is really the weak interaction analogue of the exact prediction for the velocity c of the electromagnetic radiation in terms of other quantities measured in laboratories.

On course, as said earlier, it was essential to prove that these gauge theories with spontaneously broken symmetry are still renormalizable. This was proved by G. t'Hooft. This was the last step to establish *quantum flavour dynamics* (QFD) as a consistently formulated, testable, unified theory of electromagnetic and weak interactions.

There was also one more interesting episode in the saga of electroweak theories. The prediction of the neutral, weak carrier Z^0 implied the existence of large flavour changing, neutral current decays of mesons, like $K^0 \to \mu^+ \mu^-$, at a level far higher then seen experimentally. It was shown by Glashow, Illiopolous and Maiani that these decays would be suppressed only if there existed a fourth quark c with electric charge (2/3) e. As a matter of fact even its mass could be predicted from the experimentally observed suppression of these flavour changing processes. The discovery of c quark in 1974 was certainly another proof of the correctness of this picture. Actually it can be shown more generally that the SU (2) × U (1) gauge theories are renormalizable (to be technically correct, anomaly free), only if the number of quark and lepton families are equal. This is why the discovery of the τ lepton and the b quark makes the discovery of top quark now imperative.

Following the discovery of neutral current in ν experiment mentioned earlier, various predictions of W-S model were tested in ν interactions. Fig. III. 6 shows a photograph of one of the detectors used for studying ν reactions. Since even for the high energy ν ($E \sim 200$ GeV or so) the probability of an interaction is very small, one has to employ truly massive detectors. The inherent asymmetry under mirror reflection of weak interactions (*parity violation*) predicts specifically the form and amount of parity violation to be expected in atomic physics and also in scattering of polarized electrons by deuterons. All these predictions involve only the electrical charges of the quark/leptons, the value of weak-isospin and $\sin^2 \theta_W$. The values of $\sin^2 \theta_W$ extracted from all these ν experiments agree very well with each other. The neutral-weak current effects also imply forward asymmetries for the reaction $e^+ e^- \rightarrow \mu^+ \mu^-$, $\tau^+ \tau^-$, etc. These also yield a value of $\sin^2 \theta_W$ consistent with all the above measurements. Thus by 1979, short of the actual discovery of $W^\pm$ and Z^0, all the other features of the W-S model were tested experimentally and it was found to stand this scrutiny quite well. The final test of the model, as said earlier, was the production of $W^\pm/Z^0$ in the laboratory and a study of their properties. This discovery of $W^\pm/Z^0$ with properties exactly as predicted by the W-S model has been perhaps the most exciting event in history of particle physics, since the

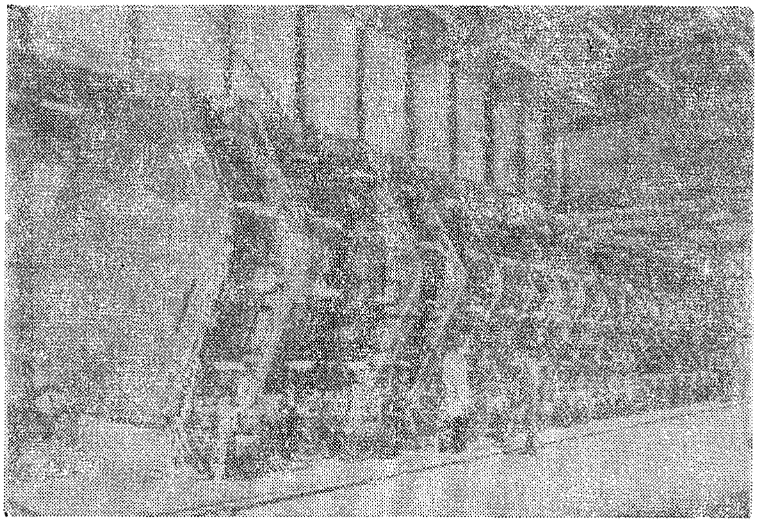


Fig. III.6. The CDHS neutrino detector (Photo CERN) discovery of neutral currents and charm quark. This is discussed in some detail below.

Experimental Discovery of $W^\pm/Z^0$: Our discussion so far has already indicated that the present day particle physics experiments have acquired really very gigantic proportions. The experiments performed for the $W^\pm/Z^0$ search involved the most stupendous effort of them all. One of the two collaborations which discovered them, called UA-1 collaboration, consisted of ~ 150 physicists from 12 different laboratories all over the world. The UA-1 detector was over 2000 tonnes in weight and perhaps the size of a two story house. The ingenuity displayed by the theoretical physicists in arriving at such a precise electroweak model, was matched by their experimental colleagues in testing it in the laboratory.

As said earlier, M_W and M_Z can be predicted precisely. After the radiative corrections are included we have,

$$M_{W^\pm} = \frac{38.65}{\sin\theta_W} = 82.4 \pm 1.5\ \text{GeV}/c^2,\quad M_Z = \frac{M_W}{\cos\theta_W} = 93.3 \pm 1.2\ \text{GeV}/c^2 \tag{III.10}$$

The large mass clearly indicates that if we want to produce them in the laborotory, we need machines capable of accelerating particles to very high energies. Since both $W^\pm$ and Z^0 couple to q, $\bar{q}$, they can be produced by reactions such a those shown in Fig. III.7. Since in a proton (antiproton), the q ($\bar{q}$) carry larger momentum fraction than $\bar{q}$ (q) it is best to use p, $\bar{p}$ beams instead of p,p beams to produce $W^\pm/Z^0$. From our earlier discussions, we know that $\langle x\rangle \sim 1/6$ for a q ($\bar{q}$) in a p($\bar{p}$). Hence to produce $W^\pm$ with mass ~ 83 GeV, we will need total energy of p-$\bar{p}$ beams ~ 500 GeV ($M_W = (E_p + E_{\bar{p}})\langle x\rangle$).

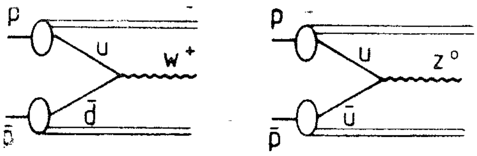


Fig. III.7. $W^\pm/Z^0$ production.

The CERN SPS (Super Proton Synchrotron) could produce a proton beam ~ 450 GeV. However, the real problem was that of producing antiprotons in large enough numbers, accelerating them, keeping them away from the rest of the matter so that they do not get annihilated and focussing them in a narrow beam. Simon van der Meer of CERN shared the Nobel prize in 1984 for precisely achieving this feat. A new technique for focussing the $\bar{p}$ beam, called *stochastic cooling* was developed which formed an important step in the project. The difficulty of the project can be appreciated by realizing that one needed about a *million* protons incident on a Tungston target to produce *one antiproton* with an energy ~ 3.5 GeV. Then these antiprotons have to be separated and accelerated to the final energy ~ 270 GeV (now ~ 315 GeV). Stochastic cooling implies applying correcting electric fields to circulating beams, which give a 'kick' to an antiproton which tends to defocus and thus compress the antiproton beam.

Apart from producing $W^\pm/Z^0$, $\bar{p}p$ collisions at such high energies, produce also a large number of other particles through a large number of processes. On the average each $\bar{p}p$ collision can produce around 50–75 particles. How often do these collisions result in $W^\pm/Z^0$ production? How does one notice their presence? These questions were exactly answered in the W–S model, combined with QCD. Theoretical calculations indicated that, at the total collision energy of 540 GeV, only about once in every 10 million $\bar{p}p$ collisions a $W^\pm$ will be produced. Due to the higher mass, a Z^0 will be produced 10 times less often. Since $\bar{p}p$ collisions occured at the rate of ~ 5000/sec, the question of recording this information was also a formidable challange. And after being produced so rarely how do the $W^\pm/Z^0$ signal their presence?

Since $W^\pm/Z^0$ is created by a $q\bar{q}'/q\bar{q}$ fusion it can clearly decay into a $q\bar{q}'/q\bar{q}$ pair. The q, $\bar{q}$ of course do not appear in the final state as free $q/\bar{q}$. They 'dress' themselves up as hadrons. They usually appear in a narrow cone of hadrons around the original $q/\bar{q}$ direction, called jets. However, events with hadronic final states are ~ 100–1000 times as likely to be produced through gluon exchanges than through $W^\pm/Z^0$ production and decay. So the best decay channel to focus upon is $W^+ \to l^+ \nu_l$, $W^- \to l^- \bar{\nu}_l$ and $Z^0 \to l^+l^-$ and not the hadronic one. Here $l^\mp$ a denotes charged lepton and $\bar{\nu}_l$ the associated (anti)neutrino.

The W mass is ~ 83 GeV. Hence it will produce a lepton with large

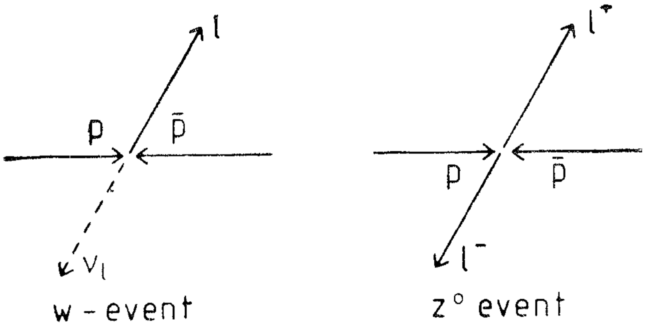


Fig. III.8. Expected W/Z^0 event.

energy, on the average ~ 40 GeV. In these high energy reactions a large number of particles are produced, but most of them with very small angles to $\bar{p}p$ collision axis. On the average the momentum in a direction normal to the beam, called transverse momentum (p_T), is as small as 1–2 GeV. The relative probability for the decay lepton to be emitted at various angles with the beam direction can be computed. This computation implies that often $l^{\mp}$ track will have a large value of $p_T \sim 40$ GeV. The ν_l will of course escape detection. Thus a good signal for $W^{\mp}$ production and decay is a high p_T lepton and 'nothing' to balance its p_T. Similarly $Z^0 \rightarrow l^+l^-$ gives a spectacular signal—two oppositely charged leptons with $p_T > 45$ GeV. The expected topology is shown in Fig. III.8.

Thus producing $\bar{p}$ beam with 270 GeV, though extremely difficult, is not enough in this search. One must develop a detector capable of handling the large number of interactions per second, measuring momenta of all the particles produced in each collision, identifying them and then looking for these $W^{\pm}/Z^0$ events. It was like the proverbial needle in the haystack, and this, in spite of the fact that some excellent pointers were provided by theory even in the haystack. C. Rubbia shared the Nobel prize for achieving this.

The detector that found $W^{\pm}/Z^0$ (and more) is shown in Fig. III.9. This

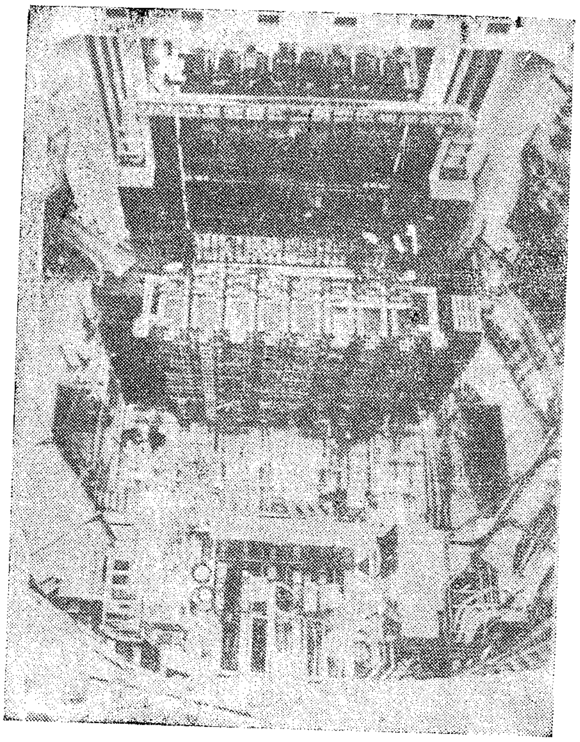


Fig. III.9. UA-1 Detector (Photo CERN).

covered the collision point down to very small angles to the beam line. The complex detector consisted of extremely sophisticated and complicated elecltronics and needed several on-line microprocessors to ensure everything was working properly. It took about four years for it to be developed in this final form. Fig. III.10 shows what an event, after being reconstructed by the computer, looks like in this detector. Note the large number of particles produced in a collision.

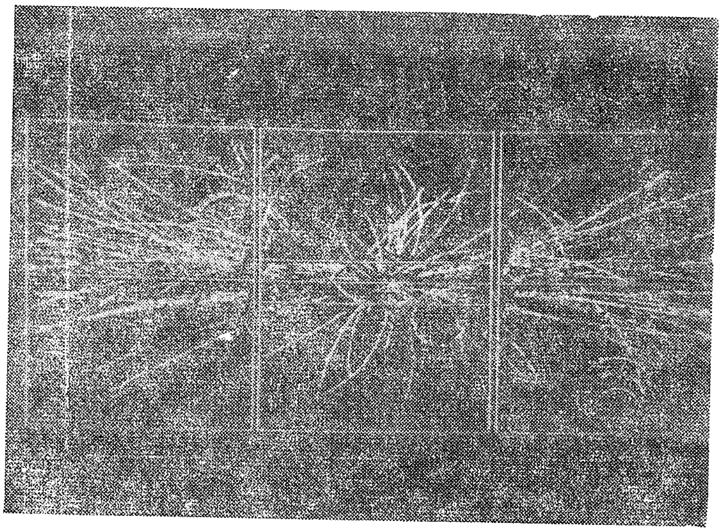


Fig. III.10. Typical reconstructed event (Photo CERN).

In the years 1983-1984, this experiment indeed found the 'missing' energy events with energetic leptons expected for W± production and decay and similarly l^+l^- events for Z^0. After an analysis of the information noted by the detector, the computer-reconstructed pictures of a W event and a Z^0 event are shown in Figs. III.11 and III.12 respectively. For fun, I have

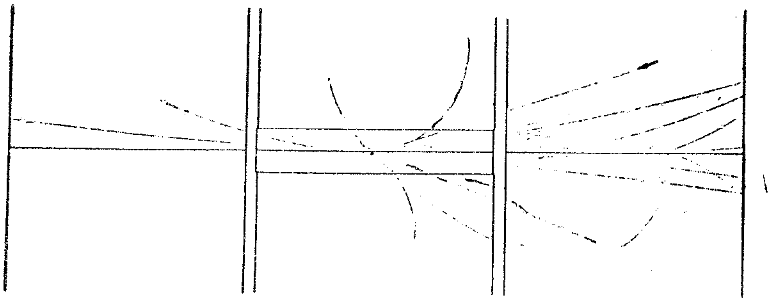


Fig. III.11. W event seen in UA-1 detector (Photo CERN).

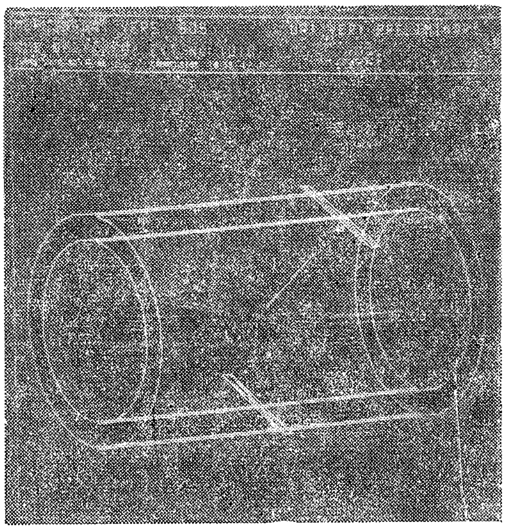


Fig. III 12. Z event seen in UA-1 Detector (Photo CERN).

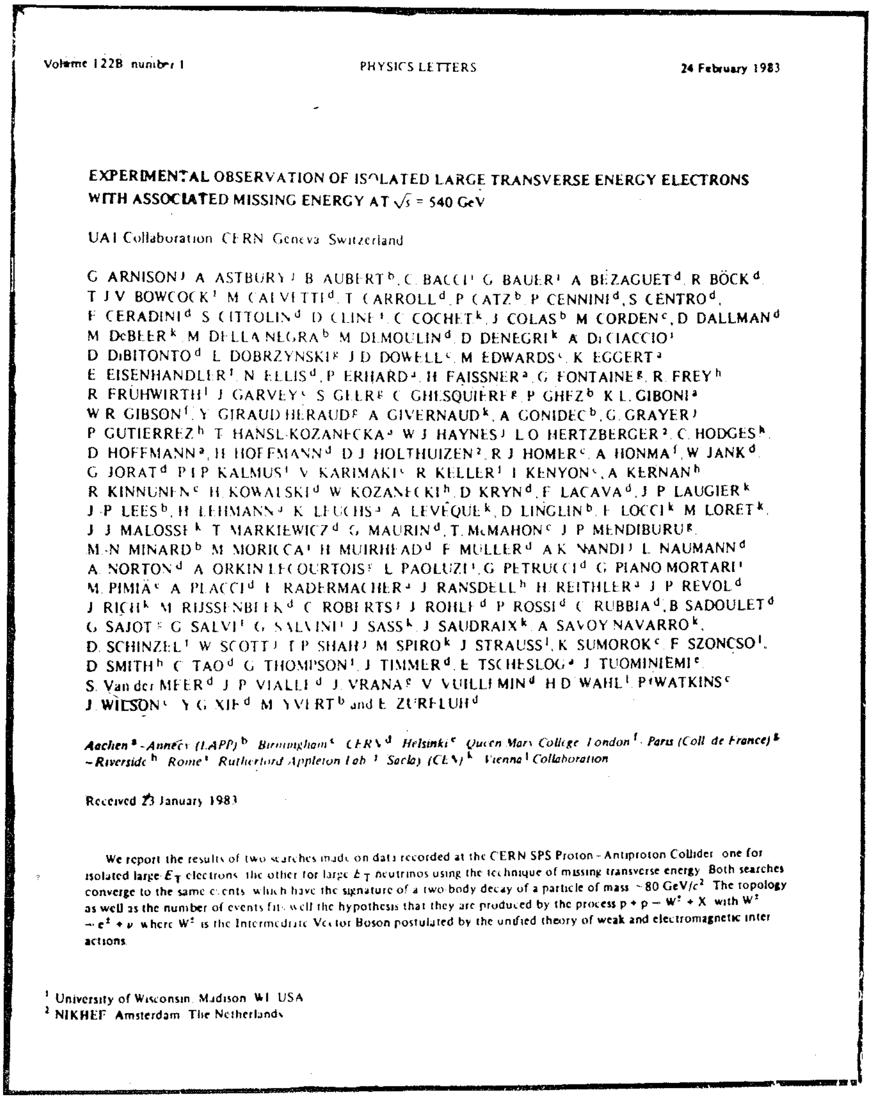
also reproduced the title page of one of the papers announcing the W discovery in Fig. III.13.

By now the experimentalists have recorced sufficiently large number of $W^{\pm}$ and Z^0 events. Their masses can be determined from measured values of p_T^l. The relative number of leptons emerging at different angles to the $\bar{p}p$ beam (for W decay) can be used to prove that the spin of W is 1. The number of events with e, μ and τ in the final states for W have been found to be equal (after correcting for different detector response in each case). This proves universal nature of the W coupling. Measured values of M_W and M_Z agree with Eqs. (III.7), (III.9) and (III.10). Thus indeed, now we have a theory other than QED, where both theory and experiments have reached a high level of precision and agree with each other to a high level of accuracy. The only missing members in this successful picture of gauge theoretical description of

$$\text{QED} \oplus \text{QFD} \oplus \text{QCD} \equiv U(1) \otimes SU(2) \otimes SU(3)_{\text{colour}}$$

are the Higgs particle and the top quark.

The same experiments which discovered $W^{\pm}/Z^0$ also reported a few events with a high energy, high p_T lepton accompanied by large p_T jets of particles. It was conjectured by theorists, including some in India, that these events are the evidence for the production and decay of the elusive top quark. It turned out that the experimentalists could not be completely sure whether these 'leptons' were truly leptons or π^0 faking as leptons. (Particle indentification has become quite an art in these experiments.) However, all



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EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS
WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

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Received 23 January 1983

We report the results of two searches made on data recorded at the CERN SPS Proton-Antiproton Collider one for isolated large E_T electrons the other for large E_T neutrinos using the technique of missing transverse energy. Both searches converge to the same events which have the signature of a two body decay of a particle of mass ~80 GeV/c^2. The topology as well as the number of events fits well the hypothesis that they are produced by the process $p + \bar{p} \to W^{\pm} + X$ with $W^{\pm} \to e^{\pm} + \nu$ where $W^{\pm}$ is the Intermediate Vector Boson postulated by the unified theory of weak and electromagnetic interactions.

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Fig. III.13. Title page of a paper published by UA-1.

this theoretical activity was useful, because through it was discovered a very clean way of isolating the events due to t quark.

The only definite information about m_t at present is that $m_t > 22.5$ GeV. This follows from the e^+e^- experiment at DESY in Germany and SLAC in the USA. It can be shown that when such a heavy quark decays semileptonically as $t \to bl^+\nu_l$ or $\bar{t} \to \bar{b}l^-\bar{\nu}_l$, the lepton in the decay will usually be well separted from ν_l and $b(\bar{b})$.

The t quark can be produced in the reactions

(i)

$$\begin{tikzcd}[column sep=small]
\bar{p}p \to WX \arrow[dr] & & & \\
& t\bar{b} \arrow[dr] & & \\
& & bl^{+}\nu_l \arrow[dr] & \\
& & & \text{jets}
\end{tikzcd}$$

(ii)

$$\begin{tikzcd}[column sep=small]
\bar{p}p \to t\bar{t}X \arrow[dr] \arrow[ddr] & & \\
& \text{jets} & \\
& bl^{+}\nu_l \arrow[dr] & \\
& & \text{jets}
\end{tikzcd}$$

These two are shown in Fig. III.14. Thus both of these will usually give rise to final states with an *isolated, high p_T leplon and hadronic jets.* UA—1 has

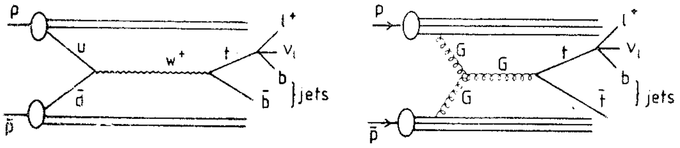

Fig. III.14. Production of top quark in pp collisions.

reported six such events which could be interpreted as an evidence for a t quark with mass between 35–50 GeV. However, this still needs to be confirmed.

The search for the Higgs particle H is most difficult, because its mass is a complete unknown. Confirmation of relations such as Eq. III.7 has indicated correctness of the W-S model. But as long as H is not found, discussions about other possible mechanisms of spontaneous symmetry breaking of gauge invariance will continue.

IV: Beyond the standard model

> "For the road to a knowledge of the stars leads through the atom; and important knowledge of the atom has been revealed through the stars."
>
> Sir Arthur S. Eddington

In the previous section we tried to understand the important ideas about gauge theories. We saw that the electroweak theory can be successfully described as a gauge theory, with spontaneously broken gauge symmetry, with SU(2) × U(1) as the gauge group. The strong interactions can be described as an unbroken gauge theory with gauge group $SU(3)_{\text{colour}}$. This description of electroweak and strong interactions goes by the name *Standard Model.*

The standard model, successful as it is, still has quite a number of mysteries:

(1) Why are there three families? Are there more?
(2) Why are the quarks fractionally charged or why $Q_e = -Q_p$?
(3) Why are the masses of quarks, leptons what they are? Is it a hint of their substructure?
(4) Why are the weak interactions asymmetric with respect to mirror reflections?
(5) Is Higgs mechanism the only way to break the gauge symmetry spontaneously?
(6) Why is there a difference in the strengths of the strong and electroweak interactions?
(7) Why does $\sin^2 \theta_W$ have the value it has?
(8) Why is it that the inverse size of quarks and leptons, viz. $E \sim \hbar c/l > \hbar c/10^{-18}$ m ~ 200 GeV (since $l_{\text{quark}}, l_{\text{lepton}} < 10^{-18}$ m), so much larger than their masses? The situation is qualitatively different from the one observed in the case of atoms and nuclei.

After the success of the electroweak unification and the way it solved some of the mysteries of weak interactions, it was only natural to hope that, at least some of the above, if not all, mysteries will be found to be consequences of further unification. Indeed ideas of unification of all the three interactions of the standard model into a single gauge group, called *The Grand Unification* did provide partial or full answers to some of the above questions, viz. 2, 3 and 7. It also provided interesting answers to some puzzles in cosmology — a totally unexpected bonus! Below very briefly, we discuss the main ideas of these theories.

Grand Unified Theories (GUTs): As the name suggests these theories attempt a grand unification of the strong, electromagnetic and weak interactions. As we have seen earlier the strengths of interactions depend on the energy scale involved. The electron charge is 'screened' less and less as we can get 'closer and closer' to it. Thus the effective electromagnetic coupling increases with increasing energy scales, whereas the effective couplings for the nonabelian gauge theories decrease with increasing energy due to the 'antishielding' effects. Thus it is conceivable that at some very high energy all these three couplings (weak, electromagnetic and strong) are the same, but this symmetry is concealed at lower energies. In other words *at some very high energies the leptons too will feel the colour force.*

Let G denote the gauge group for this unified theory, and g_G the common coupling. Then the energy dependence of the three couplings is completely specified in the theory, and they are found to merge into one another at an energy scale $M_x \simeq 10^{14} - 10^{15}$ GeV as shown in Fig. IV.1. The exact value of M_x depends on e gauge group G.

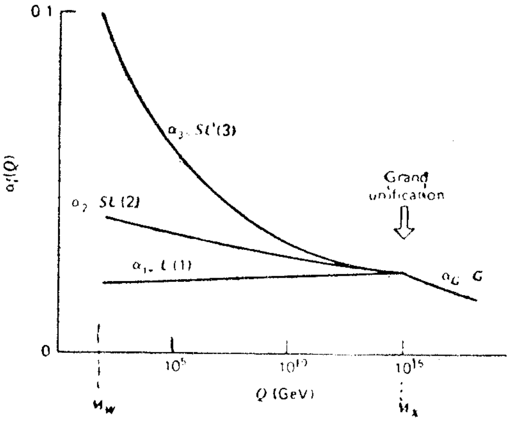

Fig. IV.1. Energy dependence of the effective coupling $\alpha_i(Q) \equiv g_i'^2(Q)/4\pi$ where g_i' is the coupling for SU(i) gauge group, and are related to couplings g_1, g_2, g_3 mentioned in the text through a G dependent relation.

The highest energy produced in the laboratory so far is 2000 GeV at the *tevatron* at the Fermi National Laboratory in USA. But we can certainly not hope to produce energies $\sim 10^{15}$ GeV in laboratory. So how are these ideas to be tested experimentally? Also another question is which of the above mentioned mysteries are addressed by this idea?

From the experience of electroweak theories, it is clear that tests of unification need not necessarily involve unification energies (recall neutral currents). A good feature of these ideas is that they can be tested by certain low energy experiments. Let us discuss them in the context of one specific model of unification. In this the gauge group is SU(5) which is the simplest possible choice of G, such that $G \supset \mathrm{SU(3)_{colour}} \otimes \mathrm{SU(2)} \otimes \mathrm{U(1)}$. G has to satisfy this condition because our discussions of the last two sections have shown us that QCD along with the electroweak theory does describe the low energy physics quite well.

Considerations of local gauge invariance under SU(5) transformations imply the existence of 24 group bosons. Twelve out of these can be identified with the ones we already know and which are tabulated in Table II.4. The extra twelve bosons are the analogues of the extra Z^0 predicted in the case of the electroweak unification. These (hypothetical as yet) gauge bosons are called X and Y bosons. Just as the emission of W^+ converts an upper member of weak-isospin doublets L_i, Q_i of Eq. (III.3) (say u) to a lower member (say d), the emission of these coloured X and Y bosons converts the leptons into quarks and vice versa. So the presence of grand unification should be signalled by interactions in which such transformations occur. A dramatic consequence is that the proton is no longer stable but can decay through X or Y exchanges. Fig. IV.2 shows a diagram, which can give rise

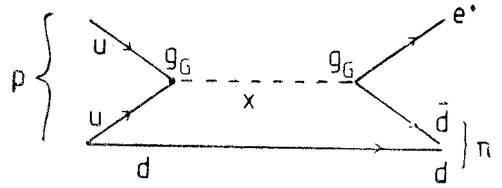

Fig. IV.2. Possible proton decay.

to one of the possible decays, viz. $p \to \pi^0 e^+$. This is the most probable decay mode in SU(5) models. Obviously the stability of everything around us, including ourselves, implies that the proton must decay extremely slowly, if it does so at all. It is also clear that this directly implies that masses of these extra bosons M_X, M_Y must be very large indeed (recall Sec. II).

Actually, for a given gauge group G and the values of α_3 and $\alpha = e^2/4\pi$ at a scale $Q_0 = M_W$ (say), we can calculate M_x and $\sin^2 \theta_W$ at any scale Q. For SU(5) these calculations yield $M_x = 10^{14} - 10^{15}$ GeV and a value for $\sin^2 \theta_W$ which agrees with the experimentally measured one. So we can actually answer the point number 7 above, by this unification scheme.

From this value of M_x, we can predict the rate at which the proton should decay. This lifetime of the proton $\tau_p \sim 10^{30}$ to 10^{32} years. Ofcourse this is consistent with our stability because the universe is only 10^{10} years old. But how to see this proton decay? The idea is to watch large number of protons $\sim 10^{32} - 10^{33}$ for a small time ($\sim$ 2 years) and wait for one of them to decay. In India, in the deepest mines, in the Kolar gold mines, such an experiment had reported condidates for $p \to \pi^0 e^+$. However, the ν produced by the cosmic radiations can mimic these events. So one cannot be certain that one has seen a proton decay. There have been other experiments running in deep mines, as well as some involving a search for p decay in huge water tanks. All these experiments are capable of detecting p decay if $\tau_p < 10^{32}$ years and $p \to \pi^0 e^+$ is the dominant decay mode. Combining results from all the current experiments, it seems right to conclude that these have failed to see the $p \to \pi^0 e^+$ decay and $\tau_p > 10^{32}$ yr. While it is possible to construct models based on larger gauge groups which are in agreement with experiments, this simplest grand unification model seems to be disproved.

However, we ought to remember that the concept of unification does give a possible way of predicting $\sin^2 \theta_W$. Also it is possible in these models to relate mass ratios for leptons and quarks in different families, even if they cannot as yet predict these masses themselves. Also, just the requirement of charge conservation here predicts that $Q_p = -Q_e$. Thus some of the questions in the list seem to be answered in the unification approach.

If all the discussion above makes you feel that the situation is very confused, then you are indeed right. But things are always like this till one reaches the correct theory. The early days of the electroweak theory or QCD which appear here so orderly and in so complete a from, were equally confusing. One can easily locate a few assumptions in the grand unification models which may not be entirely justified, e.g. the above unification model assumes that there is no new physics between M_W and M_X. This assumption may not be valid at all. What is important to appreciate is that although this may not be the 'final theory', this certanly contains elements of one.

GUT is just one of the several approaches which have been tried to go beyond the standard model. All such attempts have to deal with the problems caused by the presence of Higgs scalars. Supersymmetry is an elegant way to handle some of these problems and we discuss it next.

Supersymmetry and Supergravity: As said earlier, in the W-S model, the mass of the Higgs scalar H, m_H, is not predicted at all. Field theories of scalars, i.e. particles with zero spin, have a problem. Whatever we may fix their mass to be, higher order perturbative corretions tend to make them as heavy as the heaviest particle in the theory. In case of leptons certain symmetry arguments forbid it. In the case of GUT, this mass is $M_X \sim 10^{15}$ GeV. Should m_H become so large, W-S model may no longer be internally consitent. Hence one has to avoid such large corrections to m_H. This can be done only at the cost of fixing some parameters in the theory to one part in 10^{30}. This is wholly unnatural and is called the *gauge hierarchy problem.*

In supersymmetry a very elegent solution to this problem is provided by postulating a symmetry between fermions (spin 1/2 particles in the theory) and bosons (integral spin particles). As a result of this, associated with every particle, there exists another particle (*superpartner*) which differs from it only in spin by a unit of 1/2. If the masses of the particles and their *superpartners* (*sparticles*) are exactly equal, the above mentioned mass corrections to scalar masses will be exactly zero. We do not see in nature such particle pairs differing in spin by 1/2 but having otherwise identical properties. Hence obviously the symmetry is not an exact one. If the symmetry is broken but the mass difference between particles and their superpartners $\Delta m \leqslant 200$ GeV, the problems about gauge hierarchy do not arise.

These theories have another extremely appealing feature. The mathematical realization of this fermion-boson symmetry mixes an internal symmetry with translations in space-time. An important consequence of this is that if we make these transformations local (i.e make them dependent on the space-time coordinates of a point) then the invariance now demands the existence of a massless, spin 2 field which couples to matter. (Recall our discussions of gauge invariance for the case of electromagnetism.) This is the graviton mentioned in Section II. Thus gravity is naturally united with all the other three forces in this framework. This theory is called supergravity.

Of course, physicists would want some experimental proof for these theorise, howsoever great their asthetical appeal may be. These theories can tell us nothing at all about the masses of the superpartners. At present their nonobservation gives us only lower limits on the masses of these sparticles, and a search for them forms an extremely important part of all the forthcoming e^+e^- and $\bar{p}p$ collider experiments.

Superstring Theories: While experimental parlicle physics is gearing itself to test all these exciting ideas in the laboratory, theoretical speculation has gone on even further. This has led to superting theories which hold the promise of not only uniting gravity with all the other forces but providing a *finite quantum theory* of gravity. This is the first time that a theory holds such a promise. According to this, the dynamics of all the interactions can be described in unified manner in terms of the dynamics of one dimensional objects, *strings*. The lowest lying, massless excitations of these objects are the particles that we have been talking here about. These theories do not even live in regular three space and one time dimensions. The four dimensional space-time is really only a 'low energy' ($\sim 10^{18}$ GeV!!) picture according to this description. This is an extremely oversimplified version of this really complicated (both mathematically and conceptually) theory. Asthetically it is appealing because it gives a finite theory of gravitation. In certain limits it leads to supergravity theories, which in turn can encompass the standard model. Unfortunately, as yet there is no success in identifying some low energy prediction (like p decay, existence of sparticles) which is characteristic of these theories and which can be tested in the laboratories. But nevertheless this theoretical activity is extremely exciting.

Cosmology and Particle Physics: A common feature of all these attempts to go beyond the standard model or unification with gravity is the appearance of very large energy scales $\sim 10^{15} - 10^{19}$ GeV. Clearly we cannot even dream about any manmade machines creating these energies. However, there existed a 'natural' accelerator which had accelerated particles to these energies. According to the generally accepted theory of early universe, temperature $\sim 10^{27}$ K (energy $\sim 10^{24}$ GeV) existed after $\sim 10^{-35}$ sec from the instant of *big bang* (or more accurately from the instant after which gravitational effects can be neglected). At these temperatures the X and Y bosons can be freely created and annihilated. As a result of these the GUT have very important implications for cosmology.

One example of the above is the observed value for the ratio of the baryon density to the photon density in the universe: $n_B/n_\gamma \sim 10^{-9} - 10^{-10}$. One of the puzzles in cosmology is the so calld *baryon asymmetry*, i.e. the universe seems to contain only matter and no antimatter. GUT gives a possibility of baryon number nonconservation. It can be shown that even if one started with equal amount of matter and antimatter, the presence of (a) X, Y,

$\overline{X}, \overline{Y}$ bosons, (b) CP violation in the decay of X bosons and (c) a condition of thermal nonequilibrium, can give rise to Baryon asymmetry.

$$M_X \sim 10^{14} - 10^{15} \text{ GeV}$$

yields n_B/n_γ of the right order of magnitude. But the agreement is necessarily qualitative and not quantitative.

The presence of Higgs scalar also can play an important role in possible explanations for homogeneity and isotropy of the universe or the so called *horizon problem.* Also most of the GUT models imply a small mass for the ν. Such a small mass ν (or the lightest supersymmetric particle) can explain the problem of *dark matter* in the universe. If the ν are massive, even if $m_\nu \sim 0$ (a few eV), they can contribute a major fraction to the mass of the universe. As a matter of fact an upper bound on the possible value of m_ν as well as possible number of distinct ν types n_ν, can be obtained from such considerations. Till the recent $W^\pm/Z^0$ experiments this was the best limit on n_ν. But now the particle physics experiments are in a position to compete with this cosmological bound and give $n_\nu < 7$. Supergravity theories, superstring inspired models have their own implications for astrophysics and cosmology. This interplay between the 'smallest' (particle) and the 'largest' (universe) is very interesting. But we must remember that it still is at a very qualitative level.

Future Accelerators: So does it mean that all our attempts to go beyond the standard model and much further can only be tested through their indirect implications for what may have happened 10^{-35} sec after the Big Bang? Fortunately not.

To begin with a $p\bar{p}$ collider capable of having a total energy of 2000 GeV has gone into action at Fermi National Laboratory in the USA. This will look for the missing quark t, the sparticles and the elusive Higgs scalar. If the ideas of supersymmetry have any relevance for the low energy world at all, then at least some of the sparticles should be seen at the collider. At SLAC in the USA a linear accelerator is used to accelerate electrons and positrons. The sum of the energies of e^+ and e^- will be = 100 GeV. Similarly another e^+e^- collider, called LEP is being built at CERN. These experiments will be able to make very accurate measurements of the properties of Z^0 and begin to check the SU (2) × U (1) theory with radiative corrections. Any deviation from the standard model predictions may give us a clue as to what the correct direction to go beyond the standard model is.

Besides this another accelerator is being planned in the USA. This will be a pp or $\bar{p}p$ collider, with total energy of 40 000 GeV = 40 TeV. As we know already, the partons carry only a fraction of the proton or antiproton energy. Hence this energy will correspond, on the average, to an energy ~ 1-2 TeV for the subprocess similar to those depicted in Figs. III.7 or III.13. It can be seen, after some what lengthy arguments, that the first clues of the physics beyond the 'standard model' have to appear at an energy of 1-2 TeV. The focus of the research done at this possible accelerator will be a search for Higgs boson, even more accurate studies of QCD predictions, search for the supersymmetric particles (if they are not in the meanwhile found by the Fermilab accelerator tevatron), etc., and of course the most important of all will be the unexpected physics that this *superconducting supercollider* (SSC) may reveal.

Our earlier discussions in this section show that all the theoretical attempts to go beyond the standard model, to answer any or all of the questions raised at the begining of this section, to include gravitation in a unified treatment involve very high energy scales $\sim 10^{10} - 10^{19}$ GeV. The SSC will create only a small fraction of this energy. But particle physicists do believe that, even then, the findings of this accelerator will be able to constrain the possible extensions of the 'standard model' and help us to find the answers to some of the questions.

This planned accelerator has an estimated cost $\sim$ 3 billion US Dollars. The particles will be accelerated using superconducting magnets. These reduce the power requirements of the accelerator. Fig. IV.3 gives a photograph of the original cyclotron built by Lawrence in 1930. This was about 5 inches in diameter and accelerated protons upto 80 keV $= 8 \times 10^{-5}$ GeV. Fig. IV.4 shows a possible design of SSC. This ring will have a circumference of about 100 km and will accelerate protons to an energy of 1000 GeV.

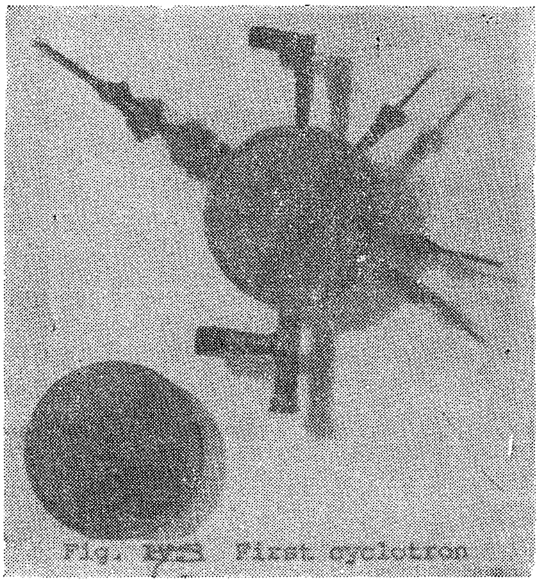

Fig. IV.3. The first cyclotron (Courtesy: Lawrence Berkeley Laboratory)

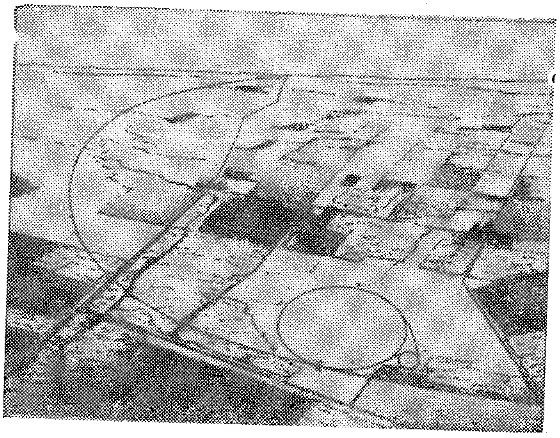

Fig. IV.4. Proposed design of S.S.C. Courtesy: Fermi National Laboratory.

This gives us an idea of the change in the scale of the experiments in high energy physics.

Of course this accelerator will require developments of detectors which are able to record and analyse information about the hundreds of particles that will be produced in these collisions. These have set as stiff a challenge to the experimental high energy physicists as the development of the correct theoretical ideas beyond the standard model to the theorists.

V. Conslusions

Thus in this chapter we have learnt a little bit about the quest for the fundamental consituents of matter and the knowledge of the forces that bind them together. The current understanding in terms of quarks, leptons and the twelve gauge bosons mediating the strong, electromagnetic and weak interactions among them, has been arrived at as a result of the great conceptual and technical advances of this century. The particle accelerators which can be called the ultimate 'microscopes', along with the giant radio telescopes* of the astronomers, have now made it possible to get a comprehensive picture of the formation and evolution of the universe. The particle physics principles operative at the distance scales $\sim 10^{-15}$ m or less have indeed provided us with possible answers to some of the cosmological puzzles which of course involve distance scales of thousands of light years or more. We do have a rather attractive and elegant theoretical description of the 'fundamental' particles and forces among them. But then is this the end of the road? That is far from being true. There still exists a fair number of unanswered questions. They do pose a great challenge to the theoretical physicists of today. A lot of very imaginative ideas exist at present. These present partial—some more satisfactory than others—answers to these ques-

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*See Chapter 15.

tions. This certainly is a field of very exciting and great theoretical activities currently. As we have seen in this description, the developments in our theoretical understanding are closely linked with the developments of particle accelerators. Sometimes these gave experimental confirmation of some very innovative, daring theoretical ideas (e.g. Gell-Mann's idea of quarks. Dirac's prediction of the positron). Sometimes they gave a great impetus to the theoretical activity by giving totally unexpected results (e.g. DIS experiments, the famous τ-θ puzzle). The CERN $\bar{p}p$ collider with a total energy of 640 GeV and the Fermilab tevatron with a total energy of 2000 GeV are the highest energy accelerators in the world at present. The former has already been responsible for the spectacular discovery of $W^{\pm}/Z^0$. Also planned to run in the next two years are the $e^+ e^-$ colliding machines at SLAC and at CERN. These will reach a total $e^+ e^-$ collision energy $\sim$ 100 GeV. In Germany, another electron-proton collider with a total energy $\sim$ 0.3 TeV is underway. And of course, last but not the least, is the planned SSC with a total energy of 40 000 GeV. We expect these accelerators to confirm some more details of the 'standard model'. But more importantly, we hope that these will produce some totally unexpected results, which in turn will be instrumental in revealing the correct path to follow beyond the 'standard model'. In the words of Avvaiyar, as quoted by F. Close in his book *The Cosmic Onion*,

> What we have learned
> Is like a handful of Earth
> What we have yet to learn
> Is like the whole world.

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