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Elementary Particle Physics

TIMOTHY L. BARKLOW AND MARTIN L. PERL

Stanford Linear Accelerator Center
Stanford University
Stanford, California 94305

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GLOSSARY

Antiparticle	Each particle has a partner, called an antiparticle, which is identical except that all charge-like properties (electric charge, strangeness, charm, etc.) are opposite to those of the particle. When a particle and its antiparticle meet, these properties cancel out in a process called annihilation. The particle and antiparticle can then disappear and other particles be produced.
Asymptotic freedom	The concept that the strong force between quarks gets weaker as the quarks get very close together.
Baryon	A type of hadron. The baryon family includes the proton, neutron, and those other particles whose eventual decay products include the proton. Baryons are composed of 3-quark combinations.
BNL	Brookhaven National Laboratory, near New York City, U.S.A.
CERN	The European Center for Nuclear Research, located near Geneva, Switzerland, and supported by most of the nations of Western Europe.
Color	A property of quarks and gluons, analogous to electric charge, which describes how the strong force acts on a quark or gluon.
Electromagnetic force or interaction	The long-range force and interaction associated with the electric and magnetic properties of particles. This force is intermediate in strength between the weak and strong force. The carrier of the electromagnetic force is the photon.
Electron volt	The amount of energy of motion acquired by an electron accelerated by an electric potential of one volt: MeV = million electron volts; GeV = billion electron volts; TeV = trillion electron volts.
Electroweak force or interaction	The force and interaction which represents the unification of the electromagnetic force and the weak force.
Flavor	A general name for the various kinds of quarks, such as up, down, and strange. Also sometimes applied to the various kinds of leptons.

Generation	The classification of the leptons and quarks into families according to a mass progression. The first generation consists of the electron and its neutrino, and of the up and down quarks. The second generation consists of the muon and its neutrino, and of the charm and strange quarks. The third generation consists of the tau and its neutrino, and of the bottom and expected top quarks.
Gluon	A massless particle which carries the strong force.
Hadron	A subnuclear, but not elementary, particle composed of quarks. The hadron family of particles consists of baryons and mesons. These particles all have the capability of interacting with each other via the strong force.
LEP	A circular electron-positron collider with a maximum design energy of about 200 GeV at CERN, Switzerland.
Lepton	A member of the family of weakly interacting particles, which includes the electron, muon, tau, and their associated neutrinos and antiparticles. Leptons are not acted upon by the strong force, but are acted upon by the electroweak and gravitational forces.
Luminosity	A measure of the rate at which particles in a collider interact. The larger the luminosity the greater the rate of interaction.
Meson	Any strongly interacting particle that is not a baryon. Mesons are composed of quark-antiquark combinations.
Photon	A massless particle that carries the electromagnetic force.
Quantum Chromodynamics (QCD)	A theory that describes the strong force among quarks in a manner similar to the description of the electromagnetic force by quantum electrodynamics.
Quantum Electrodynamics (QED)	The theory that describes the electromagnetic interaction in the framework of quantum mechanics. The quantum of the electromagnetic force is the photon.
Quarks	The family of elementary particles that make up the hadrons. The quarks are acted upon by the strong, electroweak, and gravitational force Five are known, called up, down, strange, charm, and bottom. A sixth, called top, is expected to exist.

SLAC	Stanford Linear Accelerator Center in Stanford, U.S.A.
SLC	Stanford Linear Collider, a linear electron-positron collider with an initial total energy of about 100 GeV at SLAC, U.S.A.
Standard Model	A collection of established experimental knowledge and theories in particle physics which summarizes our present (1986) picture of that field. It includes the three generations of quarks and leptons, the electroweak theory of the weak and electromagnetic forces, and the quantum chromodynamic theory of the strong force.
Strong force or interaction	The short-range force and interaction between quarks that is carried by the gluon. The strong force also dominates the behavior of interacting mesons and baryons and accounts for the strong binding among nucleons.
W	The charged particle that carries the weak force, also called an intermediate vector boson. Its mass is about 90 times the proton mass.
Weak force or interaction	The force and interaction that is much weaker than the strong force, but stronger than gravity. It causes the decay of many particles and nuclei. It is carried by the *W* and *Z* particles.
Z	The neutral particle that carries the weak force, also called an intermediate vector boson. It is slightly heavier than the *W* particle, with a mass about 100 times the proton mass.

This article has two parts. The first part provides a general introduction to elementary particle physics: the nature of elementary particles; the basic forces and the gauge bosons which carry the forces; the lepton family of particles; the quark family of particles; the interaction of particles in collisions and decays; and experimental techniques. The second part, beginning with Sec. VII, summarizes on a more detailed and technical level: the quark model of hadrons and quantum chromodynamics, the electromagnetic and weak interactions, and current issues in elementary particle physics.

I. THE NATURE OF ELEMENTARY PARTICLES

A. Definition of an Elementary Particle

An elementary particle is the simplest and most basic form of matter; it is very small, much smaller than atoms or nuclei. There are three kinds of elementary particles: leptons, quarks, and force-carrying particles also called gauge bosons. The best known example of an elementary particle is the electron which is a lepton. The best known example of a force-carrying particle or gauge boson is the photon which carries the electromagnetic field.

A piece of matter is called an elementary particle when it has no other kinds of particles inside of it, and no sub-parts that can be identified. How does one know whether a particle is elementary? Only by experimenting with it to see if it can be broken up, or by studying it to determine if it has an internal structure or parts. This is illustrated in Fig. 1. Molecules are not elementary because they can be broken up into atoms by chemical reactions or by heating or by other means. Nor are atoms elementary: they can be broken up into electrons and nuclei by bombarding the atom with other atoms or with light rays. Nor is the nucleus elementary: by bombarding nuclei with high energy particles or with high-energy light rays called gamma rays, the nucleus can also be broken up into protons and neutrons. For about fifty years physicists considered the neutron and proton to be elementary, but in the last two decades it was found that they are made up of yet simpler particles called quarks. Hence the neutron and proton are not elementary particles, but to the best of our knowledge the quarks are elementary. With respect to the other constituent of ordinary matter, the electron, no experiment has succeeded in breaking it up or in finding an internal structure for it. Hence the electron is an elementary particle.

B. Size of Elementary Particles

As one proceeds down through the sequence, Fig. 1, of molecule, atom, nucleus, proton and neutron, and finally quark and electron, the size of the particles gets smaller and smaller. The size of atoms is of the order of 10^{-8} centimeters

(.00000001 centimeters). This one hundred millionth of a centimeter is very small by everyday standards. Molecules are larger, their size depending in a rough way on the number of atoms in the molecule. Molecules containing hundreds of atoms, such as organic molecules, can be examined by electron microscopy, and thus can almost be "seen" in the ordinary sense of the word.

But once one goes below the atomic level to nuclei, there is no way to "look" at these particles with any sort of microscope. The nuclei consist of neutrons and protons packed closely together. The proton and neutron are each about 10^{-13} centimeters in size, about 1/100,000 of the size of an atom. Nuclei are a few times bigger than a neutron or proton, depending upon how many of these particles they contain. But the nuclei are still not much bigger than 10^{-13} centimeters. The sizes of nuclei, neutrons and protons are too small to be found by looking directly at the particles; they must be measured by indirect methods.

When one comes to an elementary particle such as a quark or an electron, there is a yet smaller scale. By indirect means the sizes of quarks and electrons are known to be less than 10^{-16} centimeters – less than 1/1000 of the size of neutron or proton. Indeed there is no evidence that these particles have any size at all, they may be thought of as points of matter occupying no space. Thus elementary particle physics is also the physics of the smallest objects in nature, Fig. 2.

C. High-Energy and Elementary Particles

Elementary particle physics, the physics of the very small, is also called high-energy physics. The term high-energy refers to the energies of the particles used to produce particle reactions; high-energy means that the kinetic energy (energy of motion) of a particle is much higher than its rest mass energy. In experimenting with elementary particles high-energy is needed for two reasons.

First, kinetic energy can be converted into mass and mass can be converted into kinetic energy according to the Einstein equation

$$E = Mc^2 \quad . \tag{1.1}$$

Here E is the kinetic energy which can be converted into mass M, and c is the velocity of light. Therefore to produce new particles, a large amount of energy, E, is needed.

The second reason for needing high-energy particles is that one investigates a particle size and structure by bombarding it with other particles. And the deeper one wishes to penetrate into a particle, the higher must be the energy of the bombarding particles.

The Heisenberg uncertainty principle also leads to the conclusion that the investigation of small distances requires high-energies. To measure small distances very precisely, there must be a large uncertainty in the momentum associated with that measurement. A large uncertainty in momentum can only be accommodated by a large initial momentum which requires high-energies.

The principal way in which we give high-energy to a particle is to accelerate it by the force of an electric field on the particle's charge, in a large device called an accelerator (Sec. VI.). A convenient unit for measuring both energy and mass is the electron-volt (eV). This is the energy acquired by an electron or proton passing through an electric potential with a total voltage of 1 volt. Larger units are

$$MeV = 10^{+6}\ eV = 1 \text{ million electron-volts}$$
$$GeV = 10^{+9}\ eV = 1 \text{ billion electron-volts}$$
$$TeV = 10^{+12}\ eV = 1 \text{ trillion electron-volts}$$

The significance of these energy units can be appreciated by looking at some particle masses expressed in electron-volts:

(1) The electron mass is about 0.5 MeV.

(2) The proton mass is about 1 GeV.

(3) The heaviest known particle, the Z^0, has a mass of about 100 GeV = 0.1 TeV. The highest effective particle energies produced by existing accelerators are in the range of several hundred GeV.

In this article, to simplify the units, we express mass in terms of the equivalent from Eq. 1.1, rather than use the conventional unit eV/c^2.

D. The Properties and Types of Elementary Particles

Each kind of elementary particle is distinguished by the intrinsic properties of the particle, mass and spin; and by how the particle connects with the basic forces.

Table I gives the masses and spins of the well established elementary particles. The masses have a vast range of values, the photon's mass is 0, the Z^0's mass is about 93 GeV. More massive elementary particles may exist; there have not yet been comprehensive searches for these more massive particles because of the energy limitations of existing accelerators.

Some particles have a permanent angular momentum called spin angular momentum. In classical physics one can think of spin angular momentum as being due to a particle permanently rotating or spinning about an axis through its center. However this picture can't be used quantitatively in elementary particle physics because such particles may have zero size. The spin angular momentum can be expressed as $sh/2\pi$ where h is Plank's constant ($h = 6.63 \times 10^{-27}$ erg-sec) and s is called the spin of the particle. General quantum mechanical principles limit s to the values 0, 1/2, 1, 3/2, 2, ... (Particles having half-integer spin 1/2, 3/2, ... are called fermions, those with integer spin 0, 1, ... are called bosons.) The known elementary particles have spin 1/2 or 1.

Besides its mass and spin each kind of particle is distinguished by how it connects with the four basic forces: gravitation, electromagnetism, strong force, and weak force. (These forces are described in the next section). For example, particles can interact with the electromagnetic force through their electric charge. Table I gives the electric charge in units of the magnitude of the charge of the electron $q = 1.6 \times 10^{-19}$ coulombs. The photon has zero electric charge but it itself carries the electromagnetic field.

All the established elementary particles fall into three types of classes according to how they connect with the basic forces:

Leptons:	do not connect with the strong force but connect with the three other forces.
Quarks:	connect with all four forces.
Force-carrying Particles:	carry the forces.

Other properties of a particle such as its lifetime are determined by its mass, its spin, and how it connects with the forces. Most non-zero mass particles are unstable, they spontaneously decay according to the experimental law.

$$P = e^{-t/\tau}$$

Here P is the probability that a particle still exists a time t after it was formed and τ is the particle lifetime.

Roman or Greek letters are used as symbols of each particle as shown in Table I.

E. Particles and Antiparticles

For each of the known elementary particles, Table 1, there exists a related particle, of the same mass but opposite electric charge, called its antiparticle. Consider first the charged particles. Thus the electron, which has negative charge, has a related particle called the antielectron or positron, which has positive charge. This same relation applies to the quarks. For example, the bottom quark has a charge of −1/3; the bottom antiquark has the same mass but has a charge of +1/3. Hadrons as well have their antiparticles. The most famous example is the antiproton, the antiparticle of the proton. Indeed, relativistic quantum theory dictates that every charged particle must have an antiparticle of the opposite charge. An antiparticle is indicated by a bar over the particle symbol. Thus

$$e = \text{electron} \quad , \quad \bar{e} = \text{positron}$$
$$b = \text{bottom quark} \quad , \quad \bar{b} = \text{bottom antiquark}$$
$$p = \text{proton} \quad , \quad \bar{p} = \text{antiproton}$$

Sometimes e^- is used for the electron, e^+ is used for the positron and so forth.

With respect to neutral particles, theory and experiment show that a particle may have a different neutral antiparticle or it may be its own antiparticle. For example each neutrino has an antiparticle which is different from itself, but the photon is its own antiparticle. The operation which transforms a particle into its antiparticle and vice-versa is called charge conjugation, and is denoted by C. Thus, $Ce = \bar{e}$, $Cp = \bar{p}$, etc.

F. Hadrons

Hadrons are subnuclear particles, but they are not elementary particles. To the best of our knowledge, hadrons (Sec. VII) are made of either three quarks or one quark and one antiquark bound together by the strong force. Table II lists a few of the known hadrons. The first hadrons to be discovered were the proton and neutron, now more than a hundred types of hadrons are known.

Although hadrons are not in themselves elementary particles, they are nevertheless very important in elementary particle physics research. First, we do not know how to isolate quarks, so to do experiments on quarks one must use the quarks in hadrons. Second, hadrons are a fascinating form of matter, and it is interesting to study them in their own right.

G. Reactions of Elementary Particles and Hadrons

Reactions involving elementary particles or hadrons are represented in the same fashion as are chemical reactions. For example

$$e^- + p \rightarrow \nu_e + n$$

means that an electron (e^-) interacts with a proton (p) to form an electron neutrino and a neutron. In

$$e^- + p \rightarrow e^- + \mu^+ + \mu^- + p$$

an electron and proton interact to form four particles. When the two particles in the final state are the same as those in the initial state,

$$e^- + p \rightarrow e^- + p$$

and

$$e^- + \mu^- \rightarrow e^- + \mu^-$$

for example, it is called an elastic reaction or elastic scattering. All other reactions are called inelastic.

The decay of a single particle is similarly represented:

$$\mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e$$

shows how the muon decays; and

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

is the most frequent way the π^- hadron decays.

Reaction and decay processes occur through the various basic forces discussed in Sec. II. The reaction equation does not directly indicate which forces are taking part in the reaction.

H. Conservation Laws

All reactions and decays of elementary particles and hadrons obey a set of laws called conservation laws. The term conservation here means that some quantity does not change, that is, this quantity is conserved, in a reaction. The simplest example of a conserved quantity is the total energy.

In a reaction, say

$$a + b \rightarrow c + d + e + f$$

the initial total energy is the sum of the kinetic energies of particles a and b and of the rest energies of a and b. (The rest energy of a particle is mc^2 where m is the particle mass.) The final total energy is the sum of the kinetic energies and rest energies of particles c through f. The law of conservation of energy states that the final total energy is equal to the initial total energy. If particles c through f have a total mass greater than the masses of particles a plus b, then some initial kinetic energy is converted into mass in the reaction.

In a decay, say

$$a \rightarrow b + c + d$$

some of the mass of a goes to produce the masses of the particles b through d and the rest gives kinetic energy to the particles.

Two other conserved quantities are the total linear momentum and the total angular momentum. The conservation of total angular momentum leads to the rule that the sum of the spins of the final particles much be integer or half integer according to whether the sum of the spins of the initial particles is integer or half integer.

The total electric charge is also conserved. For example

$$\pi^- + p \rightarrow \pi^- + \pi^+ + p$$

does not occur. Other conservation laws, such as lepton conservation are discussed later in this article.

II. THE BASIC FORCES AND THE GAUGE BOSONS

A. The Four Basic Forces

Elementary particles interact with each other through four basic forces, Table III. Two of these have been known for hundreds of years: the forces of electromagnetism and of gravitation. The other two forces were discovered in the twentieth century. One is the strong or nuclear force that holds the atomic nucleus together, and the other is the weak force that operates in many forms of radioactivity. The forces are described and distinguished from each other by their strengths, by the distance or range over which they act, and by the precise manner in which they act on particles. Here their strength and range properties are described; the precise manner in which the forces act is discussed later in the sections devoted to each force.

The most powerful of the four forces is called the strong force (Sec. VII). However, the strong force is not felt directly in everyday phenomena, since it does not extend beyond a distance of about 10^{-13} centimeters from the elementary particle. Quarks connect with each other through the strong force, in fact the force is so powerful that the quarks are held together forming small, but non-elementary, particles called hadrons. The proton and neutron are the best known examples. The distance limitation or range of about 10^{-13} cm determines the size of the proton or neutron, their radii are about 10^{-13} cm. Protons and neutrons in turn are held together by residual effects of the strong force, making nuclei. Thus the strong force is sometimes called the nuclear force, but it is more useful to think of the nuclear force as being a manifestation of the strong force. Atoms and molecules are 10^{-8} cm or larger in size, and electrons are not affected by the strong force, hence there is no direct effect of the strong force on the level of atomic or molecular physics. These are some small, indirect effects due to the size and structure of nuclei. The present theory of the strong force is called quantum chromodynamics.

The electromagnetic force (Sec.VIII) between elementary particles follows the same laws as the electromagnetic force used in modern technology, such as in motors, generators, and electronic equipment. The elementary particles simply behave as very small particles with electric charge. If the particle has non-zero spin it will also behave as a very small magnet in relation to the electromagnetic force. (The strength of the equivalent magnetic properties of a particle is expressed by its magnetic moment.) Unlike the strong force, the electromagnetic force extends out to very large distances. The strength of the electromagnetic coulomb force F_{coul} exerted by a particle of charge Q does weaken as the distance from the particle increases.

$$F_{coul} = \frac{Q^2}{R^2} \quad .$$

But there is no sharp cutoff as in the strong force. Hence the range of the electromagnetic force is said to be infinite. The electrodynamics force determines the structure and behavior of atoms and molecules. The theory of the electromagnetic force is called quantum electromagnetics.

The weak force (Sec. VIII) acts over very small distances – less than about 10^{-16} centimeters – and it is much less powerful than the strong force. Yet the weak force is not negligible. In a certain sense it is more pervasive than the strong force. Some elementary particles such as leptons and the $W^{\pm}$ and Z^0, are not affected by the strong force but are affected by the weak force. The radioactive decay of the neutron and of nuclei, as well as the decays of many of the elementary particles, occur through the weak force. Since the range of the weak force is so small, the force is not seen directly in atomic or human scale phenomena.

The gravitational force is important in human-scale and astronomical phenomena because of the immense mass of the earth, the planets and stars. But the gravitational force exerted by one elementary particle is very small compared with the three other forces that can be exerted by that particle. Indeed, present day experimental methods in particle physics are not sufficiently sensitive to detect the gravitational force exerted by one elementary particle.

The strengths of the electromagnetic, strong, and weak forces are described by a quantity called the coupling constant, defined later.

Since the 1920's physicists have speculated about the possibility that different forces can be unified into one general theory. That is, are the seemingly different forces simply different manifestations of one general force? First thoughts were about unifying the gravitational and electromagnetic forces; that has not been done, and we do not know if it can be done. But within the last fifteen years, a significant unification of the electromagnetic and weak forces has been made (Sec. VIII), and has been experimentally verified.

B. The Force-Carrying Particles and Gauge Bosons

It is a basic principle of quantum mechanics that a force has a dual nature: it can be transmitted through a wave or through a particle. The clearest example is the electromagnetic force, which can be treated in some situations as being carried by an electromagnetic wave (radio waves, light waves, etc.) and in other situations as being carried by a particle (the photon). The question then arises whether the other forces also obey quantum mechanics in this sense, and thus can be thought of as being carried by particles. Table III summarizes our present knowledge.

As already noted the electromagnetic force is carried by the photon. Photons are the particles in a ray of visible light or in an X-ray beam. At high energies they are sometimes called gamma rays, hence the usual symbol for a photon is the Greek letter γ (gamma). The photon has either zero mass or close to zero mass, it has spin 1, it has zero electric charge, and it is stable. Photons comprising an electromagnetic wave of frequency f Hz have an energy per photon of

$$E_\gamma = h\,f$$

where h is Planck's constant. The photon does not interact in any direct way with the weak or strong force. It does interact with the gravitational force according to general relativity, the force being proportional to E_γ.

The weak force is carried by three different, recently discovered, particles called the W^+,W^- and Z^0. They all have masses close to 90 GeV (Table I), and they have spin 1. The W^+ and W^- have one unit of positive or negative electric charge, hence they interact with the electromagnetic force; the Z^0 being electrically neutral, does not interact electrically. The W^+,W^- and Z^0 interact with the gravitational force, but not with the strong force.

Experiment and theory strongly indicate that the strong force is carried by particles called gluons (Sec. VII) and symbolized by g. However, unlike the photon, $W^\pm$ and Z^0 particles, the gluon has not been isolated experimentally and directly studied. Indeed, most forms of the current theory of the strong force, quantum chromodynamics, state that gluons cannot be isolated. Gluons like quarks are said to be confined to being inside hadrons, a subject discussed later. Indirect experimental evidence and current theory give the gluon a zero mass, a spin 1, and zero electric charge. It does not interact with the electromagnetic or weak forces. Inside a hadron, the gluon carries some part of the hadron's energy, say E_g, and the gravitational force interacts with the gluon in proportion to E_g.

The particle conjectured to carry the gravitational force has been called the graviton, and ascribed a spin of 2; but such a particle has not yet been discovered, and there is no experimental evidence for its existence. Because of the feebleness of the gravitational interaction among elementary particles, its detection would be extraordinarily difficult. Furthermore there is no successful application of quantum theory to general relativity at present. Therefore the nature of the particle carrying the gravitational force, or even if there is such a particle, is an open question.

The mathematical theories which describe the strong, electromagnetic and weak forces obey a general principle called a gauge symmetry, hence they are called gauge theories (Sec. VII). The gluon, photon, $W^\pm$ and Z^0 particles are intrinsic to those theories and are called gauge bosons; the boson term indicating that their spins are integers.

III. THE LEPTON FAMILY OF ELEMENTARY PARTICLES

A. Definition of a Lepton

The lepton family of elementary particles is defined by two properties:

(1) Leptons are affected by the gravitational, electromagnetic, and weak forces, but not by the strong force.

(2) Leptons cannot be arbitrarily created or destroyed; all reactions involving leptons follow a principal called lepton generation conservation or just lepton conservation.

Table IV shows the six known leptons. The tau neutrino, ν_τ, has not been detected but there is a great deal of indirect evidence for its existence and properties. The leptons come in pairs formed according to the lepton conservation principle; each pair consisting of one charged lepton and one neutral lepton, called a neutrino. Each pair is called a generation, and in each generation the mass of the neutrino is much less than the mass of the charged lepton. The generation pairs are formed according to the lepton conservation principle. The usual representation for the lepton pairs is

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \ , \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad , \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

Each pair has an antiparticle pair, respectively

$$\begin{pmatrix} \bar{\nu}_e \\ e^+ \end{pmatrix} \ , \quad \begin{pmatrix} \bar{\nu}_\mu \\ \mu^+ \end{pmatrix} \quad , \quad \begin{pmatrix} \bar{\nu}_\tau \\ \tau^+ \end{pmatrix}$$

B. Lepton Conservation

The charged lepton and neutrino in each pair show a unique property, called lepton number with the symbols n_e, n_μ, n_τ. For example the τ^- and ν_τ have

$$n_e = 0, \quad n_\mu = 0, \quad n_\tau = 1$$

Their antiparticles, τ^+ and $\bar{\nu}_\tau$ have

$$n_e = 0, \quad n_\mu = 0, \quad n_\tau = -1$$

Table V gives the complete scheme. Quarks and hadrons have all the n's equal to zero.

All experiments so far done show that a reaction involving leptons can occur only if the separate sums of $n_e, n_\mu,$ and n_τ do not change in a reaction. For example, the reaction

$$e^- + p \rightarrow \nu_e + p$$

occurs with $\Sigma n_e = 1,\ \Sigma n_\mu = 0,\ \Sigma n_\tau = 0$ before and after the reaction. But the reactions

$$e^- + p \rightarrow \mu^- + p \quad \text{or} \quad e^- + p \rightarrow \nu_\mu + p$$

do not occur since Σn_e and Σn_μ change during the reaction. In reactions with several leptons:

$$e^- + e^+ \rightarrow \mu^- + \mu^+ \quad \text{and} \quad e^- + e^+ \rightarrow \tau^+ + \tau^-$$

occurs since the $\Sigma n_e = 0, \Sigma n_\mu = 0$, and $\sum n_\tau = 0$ before and after. But

$$e^- + e^+ \rightarrow \mu^- + e^+$$

does not occur.

The lepton conservation law holds for the three forces with which the leptons interact: the electromagnetic, the weak, and the gravitational. Present theory does not explain the nature of the property in each lepton pair which gives it a unique lepton number, nor does present theory explain why the sums of the lepton numbers cannot change in a reaction. In the last few years there has been speculation, but as yet no evidence, that the proton might very rarely decay to a lepton plus hadrons. If that turns out to be true, lepton conservation would not hold in this process.

C. Muon and Tau Lepton Decays

The muon and the tau lepton are unstable, but their decay process obeys lepton conservation. Indeed, studies of these decay processes are one of the proofs of the lepton conservation law. The muon has only one decay mode, for the μ^-

$$\mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e \quad ,$$

and for the μ^+

$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

Since the second process just involves all the antiparticles of the first process, there is no need to write the second decay out.

The tau lepton has much more mass than the muon, hence it can decay in more ways. Table IV lists the main decay modes. Note that the τ^- always decays to a ν_τ plus other particles, an example of tau lepton conservation.

IV. THE QUARK FAMILY OF ELEMENTARY PARTICLES

A. Definition of a Quark

The quark family of elementary particles Table VI is defined by two properties:

(1) Quarks are affected by all four basic forces. Because they are affected by the strong force (Sec. VII), quarks act very differently from the leptons in many situations. In particular, it is either impossible or very difficult to isolate quarks, whereas leptons can easily be isolated.

(2) Quarks obey a conservation law similar to, but, more complicated than the lepton conservation law.

A very peculiar property of the quarks is that they have electric charges of 2/3 or 1/3 of the unit of electric charge carried by the electron. All other particles, elementary or not, have either zero or integral charges. This fractional charge property of the quarks is an intrinsic part of the present standard theory of how hadrons are composed of quarks. For example, the proton with charge +1 is composed of 2 up quarks with charge $+\frac{2}{3}$ each and of one down quark with charge $-\frac{1}{3}$ (Table II). The total quark charge is

$$\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=+1$$

On the other hand the neutron is composed of one up and two down quarks, giving it a total charge

$$\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$$

The four smallest mass quarks are arranged in generation pairs

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad , \quad \begin{pmatrix} c \\ s \end{pmatrix}$$

Each pair has a $+\frac{2}{3}$ charge quark and a $-\frac{1}{3}$ charge quark.

Five quarks have been well established. Most particle physicists believe that there is a sixth quark with a $+\frac{2}{3}$ charge, called the t or top quark, which will complete the third generation pair:

$$\binom{t}{b}$$

As this article is being written there is some preliminary evidence for the existence of the t quark. As with the leptons each quark has an antiquark of opposite electric charge.

There is an important unanswered question concerning quarks. Can a single quark be isolated from all other matter so that it exists all by itself as a free particle? We know from experiment that all the leptons can exist as free particles. But can the quarks be free? At present most physicists believe that quarks are always confined in the more complicated hadrons. This belief is based on the failure of almost all experiments which have tried to make or find free quarks. We say *almost all* because there has been one series of experiments which have indicated that free quarks might exist. In the end this is a question which can only be resolved with more experiments. In the meantime, most versions of the theory of how quarks interact with the strong force (Sec. VII) assume that the strong force always confines the quarks to stay inside hadrons. The same theories also assure that the gluons which carry the strong force are also confined to make hadrons.

B. Quark Conservation Laws

Quark conservation laws are more complicated than the lepton conservation law for two reasons: there is an additional force, the strong force; and quark types are almost but not exactly conserved when they interact with the weak force.

Under the strong, electromagnetic, or gravitational force each quark type (u, d, c, s, b, t) can be created or destroyed only when its antiparticle is credited or destroyed. For example

$$e^+ + e^- \rightarrow u + \bar{u}$$

can occur but

$$e^+ + e^- \rightarrow u + \bar{c}$$

cannot occur through the electromagnetic force. The strong force process of proton-antiproton annihilation can occur because the u and d quarks in the proton can combine with and annihilate the $\bar{u}$ and $\bar{d}$ quarks respectively in the antiproton.

Under the weak force each generation pair is mostly conserved within its own generation. For example the u and d quarks when interacting through the weak force mostly interact with each other. The major decay modes of the c quark through the weak force are

$$c \rightarrow s + u + \bar{d}$$
$$c \rightarrow s + \ell^+ + \nu_\ell$$

Here ℓ^+ means e^+, μ^+ or τ^+. But about 5% of the time the c decays to the d quark which is in a different generation. Then

$$c \rightarrow d + u + \bar{d}$$
$$c \rightarrow d + \ell^+ + \nu_\ell$$

This is discussed quantitatively in Sec. VIII.

V. THE QUANTITATIVE DESCRIPTION OF PARTICLE INTERACTIONS

A. Reactions and Feynman Diagrams

Elementary particles and hadronic particles are too small to be directly studied. We study them indirectly by colliding two particles together, and then determining what particles come out of the reactions. Each time there is a collision a number of different reactions can happen. This is illustrated in Fig. 3, a time sequence of two protons colliding. In (a) the protons are about to collide, and in (b) they have just collided to form a complicated concentration of mass and energy. This concentration of mass and energy is unstable, and it can change again into particles in many different ways. Thus in (c) two protons may come out again, or a large number of hadrons may come out of the collision, or other kinds of particles not shown here may be produced. There are many possibilities. By studying the different reactions and the different particles produced, the behavior of the basic forces and elementary particles is explored, and in addition searches for new particles or new basic forces can be made.

It is clumsy to draw time sequences such as Fig. 3. Instead, one uses a kind of shorthand in which the collision process is pictured in a single diagram. Thus Fig. 4 shows the collision diagram for two protons going into two protons, and also the process for two protons going into many hadrons – the same two processes shown in Fig. 3. (This article uses the convention in which time advances from left to right.)

The concentration of mass and energy in Figs. 3 and 4 represents the crux of how particles interact through the basic forces. Often we know enough about that concentration region to explain it in simple terms. For example, the reaction

$$e^+ + e^- \to \mu^+ + \mu^-$$

occurs as diagrammed in Fig. 5b. These pictures are of great assistance in making calculations, and in this context they are called Feynman diagrams after their inventor. As time advances (i.e., moving to the right in the figure), the electron and positron collide; the collision annihilates the electron and positron and produces a highly excited photon, which contains all of the collision energy. This photon is extremely unstable and quickly decays into a muon and an antimuon. The photon could alternatively produce a quark-antiquark pair, or another electron-positron pair.

Figure 6a shows another example: the reaction

$$e^- + p \rightarrow \nu_e + n$$

which occurs through the weak force and the exchange of a W^- particle. Decays can also be represented by Feynman diagrams, Fig. 6b shows the decay.

$$\mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e$$

which occurs through the weak force.

In calculations, the mathematical expression corresponding to the exchanged force-carrying particle is called the propagator. In the simplest situations the propagator is given by

$$\frac{1}{q^2 - M^2}$$

where q^2 is the square of the four-momentum transferred by the force carrying particle and M is the mass of the force-carrying particle.

B. Coupling Constants

In Figs. 5 and 6 the diagrams have parts called vertices in which two leptons or two quarks or two hadrons join with one force-carrying particle such as a photon or a W. In the quantum mechanical picture these vertices represent the emission or absorption of a force-carrying particle by a lepton or quark. The strength with which the force interacts with the leptons or quarks is represented by a parameter called the force's coupling constant. The coupling constant provides a measure of the strength of the force, but it is not the complete measure of that strength. The strength may also depend on the energy of the particle involved in the vertex. This is discussed in later sections. The strong force has the largest coupling constant by far.

C. Reaction Cross Section

In a reaction, say

$$a + b \rightarrow c + d + e$$

there are many properties of the final particle which can be studied, for example: the angles at which the particles emerge from the reaction and how they divide up the available kinetic energy. One reaction property is of particular importance: the cross section, σ, measures the probability that particles $c+d+e$ are produced when a and b collide. The units of σ are area, such as cm^2. This can be understood through a classical picture, the larger the area occupied by a and b, the greater the probability of collision and hence reaction.

The strong force has the largest cross sections

$$\sigma_{strong} \lesssim 10^{-24}\ cm^2$$

($\lesssim$ means approximately equal to or less than.) The weak force has the smallest cross sections

$$\sigma_{weak} \lesssim 10^{-37}\ cm^2$$

The electromagnetic force has in between size cross sections,

$$\sigma_{electromagnetic} \lesssim 10^{-28}\ cm^2$$

But all three forces can also produce rare processes with very small cross sections; there is no lower limit to the size of a cross section; at present it is very difficult to study reactions whose cross sections are less than 10^{-40} cm^2.

The small size of cross sections when expressed in cm^2 has led to the unit

$$1\ barn = 10^{-24}\ cm^2$$

The usual metric prefixes, milli-, micro-, nano-, and pico- denote smaller cross section units. For example 1 microbarn = 10^{-30} cm^2.

D. Higher Order Feynman Diagrams

So far we have discussed only the simplest Feynman diagram for a reaction. However, as illustrated in Fig. 7 for the reaction

$$e^+ + e^- \rightarrow \mu^+ + \mu^-$$

there are other diagrams Figs. 7b – 7c in addition to the simplest diagram. The more complicated diagrams have additional photons being exchanged by the leptons, hence they have more vertices. The number of vertices is called the order of the diagram, Fig. 7a is order 2, Figs. 7b is order 4, and Fig. 7c is order 6.

At each of these vertices there is a coupling constant for the electromagnetic force, thus higher order diagrams have more coupling constants. The size of the reaction cross section for a diagram depends in part on the product of all the coupling constants. Since the coupling constant for the electromagnetic force is much smaller than 1, the higher order diagrams have much smaller reaction cross sections than the simplest diagram, Fig. 7a. Therefore in calculating reaction cross sections for processes carried out through the electromagnetic force the simplest diagram is usually sufficiently accurate. If more accuracy is required, then the next highest order diagrams are used to calculate the additions to the reaction cross section from the diagrams.

The use of the simplest diagram, and the next higher order diagram, when necessary, is called a perturbation calculation. Such calculations can also be used for reactions involving the weak force, since the weak force coupling constant is also much smaller than 1. The relative simplicity of perturbation calculations has allowed complete comparisons of experiment with theory in reactions involving the electromagnetic and weak forces. This has allowed the physicist to gain a deep understanding of these forces.

Perturbation calculations cannot be used in most reactions involving the strong force (Sec. VII). This is because the strong force coupling constant is larger than 1, hence higher order diagrams are as important as lower order diagrams, and a very large number of diagrams contribute to a reaction cross section. At present we know how to use strong force perturbation calculations in a limited range of strong force reactions. These are reactions in which large amounts of momentum are transferred to or from a quark, as discussed in Sec. VII.

VI. EXPERIMENTAL TECHNIQUES IN ELEMENTARY PARTICLE PHYSICS

A. Experimental Techniques

The purpose of experiments in elementary particle physics is to study the behavior of the basic forces and elementary particles, and to look for new types of particles and forces. But few of these studies and searches can be carried out using the apparatus found in the usual physics laboratory. For example, elementary particles are too small to be seen using a visible light microscope or even an electron microscope. Furthermore, many elementary particles have very short lifetmes; they do not exist for a long enough time to be studied directly. A final example is that the search for new particles usually requires that other particles collide together at high-energies to produce the new particles.

The primary experimental method in elementary particle physics involves the collision of two particles at high-energy and the subsequent study of the reactions that occur and the particles produced. There are two methods as shown in Fig. 8: fixed target experiments at accelerators; and experiments using colliding-beams accelerators.

An example of a fixed target experiment using an accelerator is shown in Fig. 9. A beam of protons is accelerated to high-energy by a proton accelerator. The beam of protons leaves the accelerator and passes into a mass of material called a target, which is fixed in position. The collisions occur between the protons in the beam and the material in the target. The simplest material to use for the target is hydrogen, because the hydrogen atom consists of a single electron moving around the single proton that forms the nucleus of the hydrogen atom, but other materials such as deuterium and heavy elements are used. In order to determine what has happened, one needs an apparatus that can detect the particles coming out of the collision, called a particle detector. Particle detectors cannot "see" particles directly, but they can determine their energies, directions of motion, and the nature of the particles.

In fixed target experiments the useful energy for the collision does not increase nearly as fast as the energy of the primary beam increases. Quantitatively the useful energy is the total energy in the center-of-mass of the colliding particles

$$E_{cm} \approx \sqrt{2E_{beam}\,M_{target}}$$

In this high-energy approximation, E_{beam} is the kinetic energy of a particle in the accelerator beam and M is the mass of a particle in the target. The alternative is to collide two beams of particles moving in opposite directions, as shown in Figs. 8b and 10. In this case the useful energy is actually the sum of the energy of each of the two beams (if the two beam energies are equal):

$$E_{cm} = 2\,E_{beam}$$

Particle colliders now produce the highest useful energy of any of our machines. Since there is no fixed target in a particle collider, the particle detector must look directly at the region where the opposing beams of particles collide. Figure 10 shows how this is done in a circular collider where the beams of particles move in opposite directions around two circles. In this simple example the beams collide at just one point. In a real collider, the beams would be arranged to collide at several different points, providing the opportunity to carry out several experiments at once.

Some experiments in elementary particle physics are carried out without using accelerators. Some use particles from fission reactors or from cosmic rays. Others look for new particles, such as free quarks or magnetic monopoles, in ordinary matter. Still others study with great precision the properties of the stable or almost stable particles, testing, for example, the equality of the size of the electric charge of the electron and the proton.

B. Particle Accelerators and Colliders

Figure 11 shows how an accelerator works. A bunch of electrically charged particles, either electrons or protons, passes through an electric field. The particles gain energy because they are accelerated by the electric field, hence the name accelerator. The energy gained by each particle is given by the voltage across the electric field. Thus an electron passing through a voltage of 1 volt gains an energy of 1 electron-volt (1 eV). And an electron passing through 1 million volts gains an energy of 1 million electron-volts (1 MeV). Since protons have the same electric charge as electrons, a proton passing through a million volts also gains an energy of 1 MeV.

Accelerators are either linear or circular, Fig. 12. In the linear accelerator the particle is propelled by very strong electromagnetic fields, gaining all of its energy in one pass through the machine. In the circular accelerator, the particles are magnetically constrained to circulate many times around a closed path or orbit, and the particle energy is increased on each successive orbit by an accelerating electric field. High energy accelerators and colliders are large and expensive machines. Thus few are built, and these are used as intensively as possible.

The machines under construction are all colliders because they can achieve the largest useful, that is center-of-mass, energy. Another simplified example of a particle collider is shown in Fig. 13a. In a circular machine, a bunch of electrons and a bunch of positrons circulate in opposite directions, the particle bunches being held in the machine by a magnetic guide field. (These machines are also called storage rings.) At two opposite places in the machine, the bunches collide head on. When the bunches come together, most of the particles in one bunch simply pass through the other bunch without actually colliding. Thus they continue to rotate around the storage ring. The bunches may rotate for hours or even days, making thousands or even millions of rotations per second. The following combinations of particles are now used or will be used in colliders: $e^+ + e^-$, $p + p$, $p + \bar{p}$, $e^- + p$, $e^+ + p$. A critical property of colliders is the luminosity, L which is a measure of the rate at which particle collisions occur. Since particle collisions are the essence of particle experiments, the more collisions per second, the more useful the collider. Quantitatively

$$\text{Collisions per second} = \sigma\, L$$

where σ is the cross section. Existing colliders have luminosities in the range of 10^{29} to 10^{32} cm^{-2} sec^{-1}.

An alternative to storage rings for particle colliders is the use of colliding beams produced by linear accelerators, Fig. 13b, a linear particle collider. The colliding bunches of particles pass through each other just once. Much denser bunches must be used to compensate for the absence of repeated collisions.

C. Particle Detectors

Electrically charged high-energy particles such as electrons and pions are detected through the ionization of the material through which they pass. This ionization leaves free electrons and ions along the particle's path. There are various ways to find the positions of the ions or electrons, and therefore to indirectly detect the high-energy particle.

The bubble chamber provides the classic example. The liquid in a bubble chamber is heated above its boiling point, but it is prevented from boiling by high pressure in the chamber. If that pressure is released for a very short time and then reapplied, the liquid still does not boil. However, if a charged particle passes through the chamber while the pressure is released, the resulting ionization leads to the formation of a string of bubbles along the path of a particle. This string of bubbles is then photographed to produce a picture of the paths or "tracks" taken by the charged particles in their passage through the chamber.

The drift chamber is the most common way to detect the paths or "tracks" of charged particles. Here thin metal wires are arranged in parallel rows in a gas such as argon. The wires are at permanent high voltage, adjacent wires having opposite voltages. When a high-energy particle passes through the gas, the electrons from the ionization path drift to the positive voltage wires, inducing electrical signals in the wires nearest the particle path. These signals are then processed electronically, and the path of the particle is determined.

Ionization produced by a charged particle is used in other ways by other types of particle detectors. In a semiconductor detector, the charged particle ionizes the semiconductor; in a scintillator the ionization produces visible light which is detected by a phototube. A few charged particle detectors, such as Cerenkov radiation detectors, do not use ionization.

Electrically neutral high-energy particles are detected by their interaction with matter through the strong or electromagnetic forces. Through the strong force a neutron can produce protons or charged pions, which in turn are detected by their ionization. Photons interact with matter through the electromagnetic force producing electrons and positrons; these produce ionization and the point where they appear is the point where the photon was before it interacted.

The energy of a high-energy particle is measured in two principal ways. If the particle is charged it will have a circular path in a magnetic field of radius r. The particle's momentum p is

$$p = qBr$$

where B is the magnetic field strength, and q is the particle charge. For a particle of mass m the energy is

$$E = \sqrt{p^2 + m^2}$$

The other principal way to measure a particle's energy is to allow it interact in matter so that all its energy is converted into ionization energy in a device called a calorimeter.

VII. THE QUARK MODEL OF HADRONS AND QUANTUM CHROMODYNAMICS

A. Evidence for the Quark Model

The concept that hadrons are bound states of more fundamental particles of fractional charge and half-integer spin was invented by M. Gell-Mann and G. Zweig in 1964. Gell-Mann and Zweig proposed that hadrons were made out of either a quark and an antiquark (a meson) or three quarks (a baryon). Their quark model explained why hadrons with certain combinations of quantum numbers were observed while hadrons with other combinations were not. For example, mesons in S-states (0 orbital angular momentum) were observed with total spin J, parity P, and charge conjugation C in the combinations $J^{PC} = 0(^{-+}), 1(^{--})$, but were not observed in the combinations $J^{PC} = 0(^{--}), 1(^{-+})$. The first set of quantum numbers is allowed when combining a spin 1/2 particle and a spin 1/2 antiparticle, but the second is not allowed.

At the time the quark model was proposed, it could account for the quantum numbers of the known hadrons, but it could do little else. There in fact appeared to be a glaring discrepancy with experiment in that no fractionally charged particles had ever been observed. Despite the fact that there still has been no independently confirmed observation of free quarks, the evidence for quarks today is incontrovertible.

The evidence for quarks since 1964 has taken several forms:

1) As new hadrons have been discovered, they have continued to fit into the quark model scheme of hadron spectroscopy. The measurements of the mass spectra of mesons made of a charm quark and a charm antiquark (charmonium states) and of a bottom quark and a bottom antiquark (bottomonium states) have been particularly revealing. Energy level diagrams of these states look very much like the energy level diagram for positronium (a bound state of an electron and a positron). Indeed, the charmonium and bottomonium states can be quantitatively accounted for by non-relativistic potential models of bound

fermion-antifermion pairs.

2) Hadron-hadron, lepton-hadron, and lepton-lepton scattering experiments have all been consistent with, and have lent great support to, the quark model of hadrons. One of the most striking pieces of evidence for the existence of quarks comes from e^+e^- annihilation into hadrons. The process proceeds through the Feynman graph shown in Fig. 14b. The electron and positron annihilate through a virtual photon which couples to the charges of the final state quark antiquark pair. As the quark and antiquark move away from each other they exert an attractive force on each other. Potential energy is thereby built up and it eventually becomes energetically favorable to create additional quark-antiquark pairs. The quarks and antiquarks so produced combine with each other and with the original quarks to form hadrons. What one sees in the laboratory are two back-to-back "jets" of hadrons, oriented in the direction of the original quark-antiquark pair (Fig. 14a). The angular distribution of the jets is precisely that expected from pointlike objects with spin 1/2.

B. The Color Degree of Freedom

Quarks have a degree of freedom not shared with the other family of fundamental fermions, the leptons. This degree of freedom is called color and it is intimately associated with the strong force felt by quarks. The color degree of freedom was first proposed as a means to make the wave function of baryons anti-symmetric under the interchange of any two constituent quarks, as required by the Pauli exclusion principle. It's easiest to see the need for an extra degree of freedom in the case of the doubly charged baryon Δ^{++} with spin $J = 3/2$. The state consists of three up quarks with their spins aligned. The total wave function of such a state is symmetric under the interchange of any two quarks. If quarks are given an additional tri-valued degree of freedom then the baryon wave function can be totally anti-symmetric.

Quarks come in three colors. They can be denoted R, Y, B for red, yellow, and blue. Antiquarks come in three anticolors: $\bar{R}$, $\bar{Y}$, and $\bar{B}$, or anti-red, anti-yellow, and anti-blue. All hadrons are colorless. If the c quark in a D^+ pseudoscalar meson has the color red, then the $\bar{d}$ quark will have the color anti-red. A baryon will always contain one red quark, one yellow quark, and one blue quark. It is said to be colorless because it is invariant under unitary transformations in the space spanned by the three color eigenstates.

The rate of production for the process

$$e^+ + e^- \to \text{hadrons}$$

corresponds to what one would expect from quark pair-production, once the color degree of freedom is included. This is illustrated in Fig. 15 where the value

$$R = \frac{\sigma(e^+ + e^- \to \text{hadrons})}{\sigma(e^+ + e^- \to \mu^+ + \mu^-)} \tag{7.1}$$

is plotted as a function of e^+e^- center-of-mass energy. The rate for the process

$$e^+ + e^- \to f + \bar{f}$$

is proportional to the square of the fermion's charge ($f \neq e$). Thus

$$\begin{aligned} R &= \frac{4}{9} && \text{(red up quark only)} \\ R = \frac{4}{9} + \frac{4}{9} + \frac{4}{9} &= \frac{4}{3} && \text{(all up quarks)} \\ R &= \sum_q 3 \cdot e_q^2 && \text{(all quarks above threshold)} \quad . \end{aligned} \tag{7.2}$$

For center-of-mass energies above 11 GeV (above $b\bar{b}$ threshold)

$$R = 3 \cdot \left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9} + \frac{4}{9} + \frac{1}{9} \right) = \frac{11}{3} \quad . \tag{7.3}$$

Among the fundamental fermions, only quarks feel the strong force. It is no coincidence that they are also the only fundamental fermions with the color degree of freedom. Color is the "electric charge" of the strong force. To understand how color generates the strong force, some background in a class of quantum field theories called quantum gauge fields theories is necessary.

C. Gauge Field Theories

The theories that describe the strong, electromagnetic, and weak interactions are all gauge field theories. In gauge field theories, interactions are a consequence of the requirement that the Lagrangian for free matter fields be invariant under a set of transformations called local gauge transformations. The Lagrangian for a free fermion field has the form

$$\mathcal{L} = \bar{\psi}\,(i\,\gamma^\mu \partial_\mu - m)\,\psi \tag{7.4}$$

where ψ is the fermion field (an electron, for example), m is the mass of the fermion and γ^μ are matrices. The term $\gamma^\mu \partial_\mu$ represents the sum

$$\sum_{\mu=0}^{3} \gamma^\mu \partial_\mu \quad .$$

Repeated indices will always indicate a sum, unless otherwise indicated.

The first known quantum gauge field theory was quantum electrodynamics (QED), the fundamental theory of electromagnetic interactions. In QED, the local gauge transformation is a phase rotation of the fermion field:

$$\psi(x) \rightarrow e^{i\,q\theta(x)}\psi(x) \tag{7.5}$$

The phase transformation varies from point to point in space-time x. This is what is meant by a local gauge transformation. If the same phase rotation is applied at all points in space-time, then the transformation is called a global gauge transformation.

If the Lagrangian describing the fermion field ψ is to be invariant under arbitrary local phase rotations, then the derivative ∂_μ must be redefined to be

$$\partial_\mu \rightarrow D_\mu \equiv \partial_\mu + i\,q\,A_\mu(x) \tag{7.6}$$

where A_μ is a new field called the gauge field. The gauge field is in fact the scalar and vector potentials of classical electrodynamics (i.e., the electromagnetic field) and the constant q is the charge of the fermion field ψ. If the gauge field A_μ undergoes the transformation

$$A_\mu(x) \rightarrow A_\mu(x) - \partial_\mu \theta(x) \tag{7.7}$$

when the fermion undergoes the transformation (7.5), then the Lagrangian (7.4) with the redefined derivative (7.6) will be invariant under local phase rotations. Gauge transformations of the form (7.7) are familiar from classical electrodynamics.

The set of phase rotations (7.5) forms the mathematical group U(1). A gauge group is said to be Abelian when the product of two successive gauge transformations is independent of the order in which the transformations are made. The U(1) gauge group is Abelian.

D. Quantum Chromodynamics

The strong force results from requiring that the free quark Lagrangian be invariant under local rotations in the space spanned by the three color eigenstates. The resulting quantum gauge field theory is called quantum chromodynamics (QCD). The gauge group is $SU(3)_{color}$ where the subscript is a reminder that the gauge transformations are rotations in the space spanned by the three color eigenstates of the quarks. SU(3) is a non-Abelian group, so QCD is a non-Abelian gauge field theory. In QCD (or strictly speaking perturbative QCD) massless vector gauge bosons called gluons are exchanged by colored quarks, much as massless photons are exchanged by charged particles in QED.

QCD has a richer structure than QED, due to the fact that it is a non-Abelian gauge theory. There are eight kinds of gluons, compared to only one photon. Furthermore, the gluons themselves are colored (i.e., color charged) whereas the photon carries no electric charge. A red quark might interact with a yellow quark, for example, by exchanging a red-antiyellow gluon, as shown in Fig. 16a. Because the gluons are themselves colored, they can interact with each other, and Feynman graphs such as those shown in Fig. 17 are possible.

Such interactions are not found in QED. Self-interacting gauge boson fields are a feature non-Abelian gauge field theories.

E. The QCD Running Coupling Constant

An important property of QCD is the running coupling constant of perturbative QCD. The lowest order Feynman diagram for the scattering of two quarks through virtual gluon exchange is shown in Fig. 16a. Such a diagram is called a Born diagram. When higher order diagrams such as those shown in Fig. 16b are calculated, the results can be expressed as a modification to the coupling constant used in the Born diagram calculation. The modified coupling constant will in general depend on the momentum transferred between the two quarks. The momentum transfer is usually expressed in terms of q^2, the square of the invariant mass of the virtual gluon exchanged by the two quarks. The dependence of α_S, the strong force coupling constant, on q^2 has the form

$$\alpha_S(q^2) = \alpha_S(q_0^2)\left[1 + \frac{\alpha_S(q_0^2)}{12\pi}\log\left(\frac{-q^2}{q_0^2}\right)(2n_f - 33) + \ldots\right] \tag{7.8}$$

where $\alpha_S(q_0^2)$ is the strong force coupling constant at a reference value of $q^2 = q_0^2$, and n_f is the number of quarks with masses $M^2 < q^2$.

Running coupling constants are common to all quantum field theories. Higher order corrections to the QED Born diagram, for example, lead to a q^2 dependent QED coupling constant of the form:

$$\alpha(q^2) = \alpha(q_0^2)\left[1 + \frac{\alpha_S(q_0^2)}{3\pi}\log\left(\frac{-q^2}{q_0^2}\right) + \ldots\right] \tag{7.9}$$

where again $\alpha(q_0^2)$ is the coupling constant at a reference q^2. The importance of the QCD running coupling constant lies in the coefficient $(2n_f - 33)$ of the logarithm term. As Fig. 18 illustrates, the running coupling constant $\alpha_S(q^2)$ decreases with increasing q^2 (or, equivalently, with smaller distances), so that for large enough q^2, $\alpha_S << 1$. This behavior is known as asymptotic freedom. It implies that perturbative QCD calculations will be meaningful for large enough q^2.

Asymptotic freedom also implies that as q^2 decreases (i.e., as larger distances are probed) α_S grows. For small enough q^2, α_S exceeds unity so that perturbative QCD is no longer valid. The growth of the strong coupling constant with distance provides hope that QCD can someday explain the apparent confinement of color (i.e., the confinement of quarks and gluons inside hadrons).

Asymptotic freedom plays an important role in the interpretation of high momentum transfer collisions between leptons and hadrons. When a lepton scatters off a hadron by transferring a large amount of momentum to the hadron, the process is termed deep inelastic lepton-hadron scattering. The leptons can be electrons, muons, or neutrinos. The hadrons are typically protons and neutrons. During deep inelastic lepton-hadron collisions, the leptons appear to scatter off pointlike, quasi-free, approximately massless spin 1/2 objects. These objects are, of course, the quarks, but it wasn't until the discovery of asymptotic freedom that the quasi-free nature of the quarks inside hadrons was understood. If quarks felt the same strong force at high q^2 as they do at low q^2, then the quark constituents of hadrons would not appear to be quasi-free. They would instead appear to be rigidly attached to the hadrons during deep inelastic collisions, and the energy-angular distributions of the scattered leptons would be modified accordingly. The discovery of the q^2 dependence of α_S given by (7.8) helped resolve the apparent paradox that while the quarks acted like quasi-free objects during deep inelastic collisions, they were nevertheless permanently confined inside hadrons.

F. Experimental Evidence for Gluons

Have gluons ever been observed? Like quarks, gluons have never been observed as free particles. Gluons carry color, and the only free objects observed in high energy physics laboratories so far have been colorless objects. There is nevertheless strong experimental support for the existence of gluons.

One of the things experimentalists can do in deep inelastic lepton-nucleon scattering is to measure the momentum distribution of quarks inside the nucleon. Both electron-nucleon and neutrino-nucleon scattering give the same quark momentum distributions. (This is yet another piece of evidence for the quark model of hadrons.) Both types of deep inelastic scattering experiments indicate that quarks can only account for about half of the nucleon's momentum. The other half of the nucleon's momentum is carried by constituents which are blind to the electromagnetic and weak forces. These extra constituents are the gluons that bind the quarks together inside the nucleon. The gluons also produce virtual quark-antiquark pairs so that there is an observable antiquark component in nucleons.

While lepton-hadron scattering experiments provided the first experimental evidence for gluons, the most dramatic and convincing piece of evidence for gluons has come from e^+e^- annihilation. Recall that when an electron and positron annihilate and form two back-to-back jets, the angular distribution and rate strongly reflect the underlying fundamental process

$$e^+ + e^- \to q + \bar{q} \quad .$$

For large enough e^+e^- center-of-mass energies (greater than about 25 GeV or so), the momenta of the quark and antiquark are large enough that perturbative QCD is applicable. Perturbative QCD predicts that one of the quarks will sometimes radiate a gluon, with a probability proportional to the strong coupling constant (Fig. 19b). If the gluon is radiated at a large angle with respect to the quark, then three jets of hadrons will be formed. Such three-jet events are indeed observed (Fig. 19a).

The rate of three-jet events produced in e^+e^- annihilation is a measure of the strong coupling constant α_S. However, a measurement of α_S based on the rate of three-jet events produced in e^+e^- annihilation is difficult to make because the fragmentation of quarks and gluons into jets of hadrons cannot be calculated from first principles and must be modeled. Nevertheless, we know that at center-of-mass energies of about 30 GeV, the value of α_S appears to be in the neighborhood of 0.2.

VIII. THE ELECTROMAGNETIC AND WEAK INTERACTIONS

One of the great achievements of 20th century physics has been the understanding that the electromagnetic and weak forces are really manifestations of the same force, today called the electroweak force. In this chapter we present an overview of the fundamental SU(2) × U(1) gauge theory of electroweak interactions, and discuss electroweak phenomenology and experimental evidence for the electroweak theory.

A. Left-handed and right-handed fermions

A prerequisite for a discussion of the SU(2) × U(1) theory is the concept of left-handed and right-handed fermions. Relativistic fermions are governed by the Dirac equation. A Dirac fermion (sometimes called a Dirac spinor) contains four components:

$$\psi(x) = \begin{pmatrix} \psi_1(x) \\ \psi_2(x) \\ \psi_3(x) \\ \psi_4(x) \end{pmatrix} \quad . \tag{8.1}$$

The Dirac equation is actually a set of four coupled differential equations which can be represented in matrix notation by

$$(i\gamma^\mu \partial_\mu - m)\psi = \emptyset \tag{8.2}$$

where γ^μ, $\mu = 0, 1, 2, 3$, are 4×4 matrices. (Recall from Sec. VIIC that repeated indices indicate a sum over the indices.) These matrices can take the form

$$\gamma^0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad , \quad \gamma^i = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix} \tag{8.3}$$

where the 2×2 σ^i matrices are the Pauli matrices familiar from non-relativistic quantum mechanics:

$$\sigma^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad ,\sigma^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad ,\sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad . \tag{8.4}$$

The spin degree of freedom is contained in the Dirac fermion wave function. An electron at rest with its spin oriented in the $+z$ direction would have the wave function

$$\psi = e^{-imt} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad . \tag{8.5}$$

An electron at rest with its spin pointing in the $-z$ direction would have the wave function

$$\psi = e^{-imt} \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} \quad . \tag{8.6}$$

An alternate quantization axis for the fermion's spin is the direction of motion of the fermion. The spin eigenstates along such a quantization axis are called helicity eigenstates. A fermion in a helicity eigenstate with the spin pointing parallel (anti-parallel) to the direction of motion is said to be right-handed (left-handed).

For a Dirac fermion state ψ, the right-handed and left-handed states ψ_R and ψ_L are defined by

$$\begin{aligned} \psi_R &\equiv \frac{1}{2}(1+\gamma_5)\,\psi \\ \psi_L &\equiv \frac{1}{2}(1-\gamma_5)\,\psi \qquad\qquad \gamma_5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3 \quad . \end{aligned} \tag{8.7}$$

The states ψ_R and ψ_L are so named because they are right-handed and left-handed helicity eigenstates in the limit of zero fermion mass.

The decomposition of fermions into right-handed and left-handed components is important in the SU(2) $\times$ U(1) theory because the left and right-handed components transform differently under SU(2) $\times$ U(1) gauge transformations. The difference between the transformation properties of right-handed and left-handed fermions leads ultimately to the phenomenon of parity violation in the weak interactions. A parity transformation inverts the x, y, z cartesian coordinates for a system. This makes the left-handed component of a fermion right-handed and vice versa. Parity violation occurs when a system is not invariant under parity transformations.

B. Introduction to the SU(2) $\times$ U(1) Gauge Theory

The SU(2) $\times$ U(1) electroweak theory is a quantum gauge field theory, just like QED and QCD. (QED is actually contained in the SU(2) $\times$ U(1) theory, as we shall see.) An SU(2) $\times$ U(1) local gauge transformation is a product of a local rotation in weak isospin space, and a local phase rotation with a constant of proportionality given by a quantity called the weak hypercharge. The group of rotations in weak isospin space is SU(2) and the group of phase rotations is U(1); hence the electroweak gauge group is SU(2) $\times$ U(1).

Weak isospin rotations, when applied to leptons, mix left-handed charged leptons with the left-handed neutrino of the same generation. Weak isospin rotations have no effect on right-handed leptons. The left-handed leptons therefore form weak isospin doublets:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \quad . \tag{8.8}$$

The right-handed charged leptons form weak isospin singlets:

$$e^-_R, \quad \mu^-_R, \quad \tau^-_R \quad . \tag{8.9}$$

If a neutrino is massless (Table IV), then the left-handed neutrino is the entire neutrino spinor, and the right-handed neutrino doesn't exist. We'll assume that the three neutrinos ν_e, ν_μ, ν_τ are exactly massless, so that there are no right-handed neutrino weak isospin singlets. The left and right-handed leptons are eigenstates of T^3, the third component of weak isospin, with eigenvalues given in Table VII.

The weak hypercharge Y of a particle is given by its charge Q in units of the magnitude of the electron charge, and its third component of weak isospin T^3:

$$Y = 2(Q - T^3) \quad . \tag{8.10}$$

Note that because T^3 is different for the left and right-handed components of a fermion, the hypercharge will also be different for the two components. The weak hypercharges for the left and right-handed components of leptons are summarized in Table VII.

The SU(2) $\times$ U(1) local gauge invariant Lagrangian for leptons is given by

$$\mathcal{L} = i\bar{\psi}\gamma^\mu D_\mu \psi - \frac{1}{4}F^i_{\eta\rho}F^{i\eta\rho} \tag{8.11}$$

where D_μ is the gauge covariant derivative

$$D_\mu = \partial_\mu + i\,gW^i_\mu T^i + ig'B_\mu \frac{Y}{2} \tag{8.12}$$

and $-\frac{1}{4}\,F^i_{\eta\rho}F^{i\eta\rho}$ is a kinetic energy term for the gauge boson fields. The operators T^i are called the generators of SU(2), and are given by

$$T^i = \frac{1}{2}\sigma^i \qquad i = 1,\ 2,\ 3 \tag{8.13}$$

in the case of SU(2) doublets and

$$T^i = 0 \qquad i = 1,\ 2,\ 3 \tag{8.14}$$

for SU(2) singlets. T^3 is the third component of weak isospin operator. The fields $W^i_\mu = 1,\ 2,\ 3$ are the gauge boson fields associated with SU(2) transformations and B_μ is the gauge boson field associated with weak hypercharge U(1) transformations.

We now study the lepton interaction term

$$\bar{\psi}\, i\,\gamma^{\mu}\,(D_{\mu}-\partial_{\mu})\psi=\bar{\psi}_L\, i\,\gamma^{\mu}(D_{\mu}-\partial_{\mu})\psi_L+\bar{\psi}_R\, i\,\gamma^{\mu}(D_{\mu}-\partial_{\mu})\psi_R \quad . \tag{8.15}$$

For the case

$$\psi_L=\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L \text{ and } \psi_R=e_R \tag{8.16}$$

the lepton interaction term is given explicitly by

$$\begin{aligned}\bar{\psi}\, i\gamma^{\mu}\,(D_{\mu}-\partial_{\mu})\,\psi &= -\bar{e}_L\,\frac{g}{2}\,(W_{\mu}^{1}+i\,W_{\mu}^{2})\,\nu_e-\bar{\nu}_e\,\frac{g}{2}\,(W_{\mu}^{1}-i\,W_{\mu}^{2})\,e_L\\ &-\bar{\nu}_e\left(g\gamma^{\mu}W_{\mu}^{3}T^{3}+g'\gamma^{\mu}B_{\mu}\frac{Y}{2}\right)\nu_e-\bar{e}_L\left(g\gamma^{\mu}W_{\mu}^{3}T^{3}+g'\gamma^{\mu}B_{\mu}\frac{Y}{2}\right)e_L\\ &-\bar{e}_R\,g'B_{\mu}\frac{Y}{2}e_R \quad .\end{aligned} \tag{8.17}$$

Charged Current Interactions

The terms

$$\bar{e}_L\,\frac{g}{2}\,(W_{\mu}^{1}+i\,W_{\mu}^{2})\,\nu_e \quad \text{and} \quad \bar{\nu}_e\,\frac{g}{2}\,(W_{\mu}^{1}-i\,W_{\mu}^{2})\,e_L \tag{8.18}$$

represent the absorption of a positively and negatively charged gauge boson respectively, an example of which is shown in Fig. 6b. We write

$$W_{\mu}^{\pm}=\frac{W_{\mu}^{1}\mp i\,W_{\mu}^{2}}{\sqrt{2}} \tag{8.19}$$

and call $W^{\pm}$ the charged W gauge bosons. Interactions mediated by the charged W bosons are called charged current interactions. The parameter g is the coupling constant for charged current interactions. Note that the W bosons couple only to left-handed leptons, so that charged current interactions are manifestly parity-violating in the SU(2) $\times$ U(1) theory.

Neutral Current Interactions

The terms

$$\bar{\nu}_e\Big(g\gamma^\mu W_\mu^3\,T^3 + g'\gamma^\mu\,B_\mu\frac{Y}{2}\Big)\nu_e \quad , \quad \bar{e}_L\Big(g\gamma^\mu W_\mu^3\,T^3 + g'\gamma^\mu\,B_\mu\frac{Y}{2}\Big)e_L$$
$$\text{and} \quad \bar{e}_R\, g' B_\mu \frac{Y}{2}\, e_R \tag{8.20}$$

represent neutral current interactions. Notice that there are two gauge boson fields involved here: W_μ^3 and B_μ. Some linear combination of these fields should be the photon A_μ, and so we write

$$A_\mu = \sin\theta_W W_\mu^3 + \cos\theta_W B_\mu \tag{8.21}$$

and call the orthogonal combination Z_μ:

$$Z_\mu = \cos\theta_W\, W_\mu^3 - \sin\theta_W B_\mu \quad . \tag{8.22}$$

Rewriting the neutral current terms (8.20) in terms of the fields A_μ and Z_μ,

$$-\bar{\nu}_e\left[\gamma^\mu A_\mu\Big(g\sin\theta_W\,T^3 + \frac{1}{2}\,g'\cos\theta_W Y\Big) + \gamma^\mu Z_\mu\Big(g\cos\theta_W\,T^3 - \frac{1}{2}\,g'\sin\theta_W Y\Big)\right]\nu_e$$
$$-\bar{e}_L\left[\gamma^\mu A_\mu\Big(g\sin\theta_W\,T^3 + \frac{1}{2}\,g'\cos\theta_W Y\Big) + \gamma^\mu Z_\mu\Big(g\cos\theta_W\,T^3 - \frac{1}{2}\,g'\sin\theta_W Y\Big)\right]e_L$$
$$-\bar{e}_R\Big(\gamma^\mu\,A_\mu\,\frac{g'}{2}\cos\theta_W Y - \frac{1}{2}\,\gamma^\mu Z_\mu\,g'\sin\theta_W Y\Big)e_R \tag{8.23}$$

we can identify A_μ with the photon if

$$g\sin\theta_W = g'\cos\theta_W = e \tag{8.24}$$

where e is the magnitude of the electron's charge. The angle θ_W that determines the mixing of the W_μ^3 and B_μ fields is called the Weinberg angle. Equation (8.24) gives a relation between the strength of the electromagnetic force and the strength of the charged weak force.

The gauge boson Z_μ is called the Z^0 gauge boson. The coupling of the Z^0 to fermions can be read off of (8.23) and it is

$$g \cos\theta_W \, T^3 - \frac{1}{2} g' \cos\theta_W Y \ . \tag{8.25}$$

Expressing g and g' in terms of e and θ_W, the Z^0 coupling can be written

$$\frac{e}{\sin\theta_W \, \cos\theta_W} \left[T^3 - Q \sin^2\theta_W\right] \quad . \tag{8.26}$$

Values for $T^3 - Q\sin^2\theta_W$ are summarized in Table VII. Processes mediated by the Z^0 gauge boson are called weak neutral current interactions.

Although the neutrinos are electrically neutral and therefore do not couple to the photon, they nevertheless experience neutral current interactions through their nonzero coupling to the Z^0.

$$\nu_\mu + e \rightarrow \nu_\mu + e$$

is an example of a reaction that can only be mediated by the Z^0 (Fig. 20).

The Z^0 couples to both left and right-handed charged leptons, as does the photon. Unlike the photon, the Z^0 couples with different strengths to right-handed and left-handed charged leptons, and the neutral current interactions mediated by the Z^0 are therefore parity violating.

C. The Higgs Mechanism

Although our development of the SU(2) × U(1) theory has so far been correct, it nonetheless has been incomplete. The problem is that, in the theory presented so far, the gauge bosons are massless. Because of the short-range nature of the weak force, we know that the $W^\pm$ and Z^0 gauge bosons cannot be massless. Therefore, to be phenomenologically successful, something in the SU(2) × U(1) theory must give a lot of mass to the $W^\pm$ and Z^0. Furthermore, for technical reasons mass must be given to the $W^\pm$ and Z^0 without breaking the local SU(2) × U(1) gauge invariance of the Lagrangian.

An explicit mass term in a Lagrangian for a gauge boson X_μ has the form

$$\frac{M^2}{2} X_\mu X^\mu \qquad (8.27)$$

where M is the mass of the gauge boson. An explicit mass term for a fermion f takes the form

$$m(\bar{f}_R f_L + \bar{f}_L f_R) \qquad (8.28)$$

where m is the fermion mass. Explicit gauge boson mass terms break the SU(2) $\times$ U(1) local gauge symmetry and must therefore be absent from the Lagrangian.

Scalar (spin 0) fields can be added to the SU(2) $\times$ U(1) locally gauge invariant Lagrangian (8.11) without spoiling the gauge invariance. If we add a pair of complex fields ϕ^+ and ϕ^0, and put them in a weak isospin doublet

$$\Phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad (8.29)$$

then the following terms can be added to (8.11) without destroying the gauge invariance:

$$(D^\mu\Phi)^\dagger(D_\mu\Phi) - V(\Phi^\dagger\Phi) - G\left[\psi_R(\Phi^\dagger\psi_L) + (\bar{\psi}_L\Phi)\psi_R\right] \quad . \qquad (8.30)$$

The superscripts of ϕ^+ and ϕ^0 indicate the charge of the scalar fields. The only restriction on the potential V is that it not contain powers of $\Phi^\dagger\Phi > 2$. We let the potential $V(\Phi^\dagger\Phi)$ take the form

$$V(\Phi^\dagger\Phi) = \mu^2(\Phi^\dagger\Phi) + |\lambda|(\Phi^\dagger\Phi)^2 \quad . \qquad (8.31)$$

The potential $V(\Phi^\dagger\Phi)$ is plotted in Fig. 21 for the cases $\mu^2 > 0$ and $\mu^2 < 0$.

The Lagrangian

$$\mathcal{L} = \mathcal{L}_{lepton} + \mathcal{L}_{scalar} \qquad (8.32)$$

with the terms $\mathcal{L}_{lepton}$ and $\mathcal{L}_{scalar}$ given by (8.11) and (8.30) respectively is the complete electroweak SU(2) $\times$ U(1) locally gauge invariant Lagrangian which today so successfully describes electroweak phenomena. However the true nature of the Lagrangian is hidden from us when it is expressed in such a form. To ascertain the true nature of the Lagrangian (8.32) we must study the lowest energy state of the system, called the vacuum state. The field Φ corresponding to the lowest energy state is called the vacuum expectation value of Φ, denoted by $\langle\Phi\rangle_0$. From Fig. 21 we see that if $\mu^2 > 0$, the vacuum expectation value of Φ is simply $\langle\Phi\rangle_0 = 0$. However if $\mu^2 < 0$, the lowest energy of the system corresponds to

$$V = -\frac{|\mu|^4}{4|\lambda|} \quad . \tag{8.33}$$

The vacuum expectation value of Φ is then any state $\langle\Phi\rangle_0$ with

$$\langle\Phi\rangle_0^\dagger \langle\Phi\rangle_0 = -\frac{\mu^2}{2|\lambda|} \quad . \tag{8.34}$$

It turns out that nature has chosen $\mu^2 < 0$.

The true behavior of the Lagrangian (8.32) is revealed when the scalar field Φ is assumed to deviate only slightly from its nonzero vacuum expectation value $\langle\Phi\rangle_0$. To this end we choose

$$\langle\Phi\rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \quad , \quad v \equiv \sqrt{\frac{-\mu^2}{|\lambda|}} \tag{8.35}$$

and write

$$\Phi(x) = \langle\Phi\rangle_0 + \begin{pmatrix} 0 \\ \eta(x)/\sqrt{2} \end{pmatrix} + \sum_{j=1}^{3} i\,\frac{\xi^j(x)}{v}(T^j\langle\Phi\rangle_0) \tag{8.36}$$

where ξ^j and η are small-valued functions of the space-time coordinates x. After a carefully chosen SU(2) $\times$ U(1) local gauge transformation, the scalar term of the Lagrangian (8.32) will then contain the terms

$$\frac{1}{2}(\partial^\mu\eta)(\partial_\mu\eta) - \mu^2\eta^2 + \frac{g^2v^2}{8}\left[|W_\mu^+|^2 + |W_\mu^-|^2\right]$$
$$+\frac{v^2}{8}\left[(gW_\mu^3 - g'B_\mu^3)^2\right] - \frac{Gv}{\sqrt{2}}(\bar{e}_R e_L + \bar{e}_L e_R) \quad , \tag{8.37}$$

where we've taken ψ_R and ψ_L to be

$$\psi_R = e_R \qquad \text{and} \qquad \psi_L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad . \tag{8.38}$$

The term

$$\frac{g^2v^2}{8}\left[|W_\mu^+|^2 + |W_\mu^-|^2\right] \tag{8.39}$$

looks like a mass term for the $W^\pm$ gauge bosons. The term

$$\frac{v^2}{8}\left[(g\,W_\mu^3 - g'B_\mu^3)^2\right] = \frac{v^2\,e^2}{8\sin^2\theta_W\cos^2\theta_W}\left[(\cos\theta_W W_\mu^3 - \sin\theta_W B_\mu^3)^2\right] \tag{8.40}$$

is a mass term for the linear combination of W_μ^3 and B_μ corresponding to the Z^0 gauge boson (8.21). There is no mass term for the orthogonal combination corresponding to the photon A_μ.

When the field Φ is expanded about a non-zero vacuum expectation value $\langle\Phi\rangle_0$, and only low order terms are kept, the Lagrangian is no longer gauge-invariant. The symmetry is said to be spontaneously broken by the nonzero vacuum expectation value. The method by which the gauge bosons of gauge field theories acquire mass through spontaneous symmetry breaking is called the Higgs mechanism. S. Weinberg and A. Salam were the first to realize that the Higgs mechanism could be applied to a gauge theory of the electromagnetic and weak interactions to give mass to the weak force gauge bosons.

The term

$$\frac{1}{2}(\partial^\mu\eta)(\partial_\mu\eta) - \mu^2\eta^2 \tag{8.41}$$

in (8.37) can be identified with the kinetic energy term of a scalar particle with mass $\sqrt{2}|\mu|$. Of the four real fields

$$\xi^1, \; \xi^2, \; \xi^3, \; \eta \tag{8.41}$$

in our expression (8.36) for the weak isospin doublet Φ, three have disappeared as three gauge bosons have acquired mass, while one remains. The remaining scalar particle has 0 charge, is called the neutral Higgs boson, and is denoted by H^0. The mass of the H^0 is a free parameter of the SU(2) $\times$ U(1) theory. The H^0 particle has never been observed.

D. Electroweak Coupling of Quarks

Like the leptons, the left-handed components of quarks mix under weak isospin rotations, and the right-handed components of quarks remain unaltered. Left-handed quarks form the following weak isospin doublets:

$$L_u \equiv \begin{pmatrix} u \\ d' \end{pmatrix}_L, \quad L_c \equiv \begin{pmatrix} c \\ s' \end{pmatrix}_L, \quad L_t \equiv \begin{pmatrix} t \\ b' \end{pmatrix}_L \tag{8.43}$$

where the primed quantities d', s', b', are mixtures of the left-handed components of d, s, and b quarks:

$$\begin{pmatrix} d'_L \\ s'_L \\ b'_L \end{pmatrix} = \begin{pmatrix} c_1 & -s_1c_3 & -s_1s_3 \\ s_1c_2 & c_1c_2c_3 - s_2s_3e^{i\delta} & c_1c_2c_3 + s_2c_3e^{i\delta} \\ s_1s_2 & c_1s_2c_3 + c_2s_3e^{i\delta} & c_1s_2s_3 - c_2c_3e^{i\delta} \end{pmatrix} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} \quad , \tag{8.44}$$

where $c_i = \cos\theta_i$ and $s_i = \sin\theta_i$ for $i = 1, 2, 3$. The matrix (8.44) is called the Kobayashi-Maskawa or K-M matrix. The angles θ_1, θ_2, θ_3, δ are called the Kobayashi-Maskawa angles. The components of the matrix have the values

$$\begin{pmatrix} 0.9705 \text{ to } 0.9770 & 0.21 \text{ to } 0.24 & 0. \text{to } 0.014 \\ 0.21 \text{ to } 0.24 & 0.971 \text{ to } 0.973 & 0.036 \text{ to } 0.070 \\ 0. \text{ to } 0.024 & 0.036 \text{ to } 0.069 & 0.997 \text{ to } 0.999 \end{pmatrix} \tag{8.45}$$

so that the d' state is mostly d_L, the s' state is mostly s_L, and the b' state is mostly b_L. The right-handed quark states are each weak isospin singlets:

$$u_R,\ d_R,\ s_R,\ c_R,\ b_R,\ t_R \quad . \tag{8.46}$$

The weak isospin eigenvalues T^3 and hypercharges Y for left-handed and right-handed quarks are given in Table VII.

The mixing of different generation quarks in the same weak isospin doublet comes about because nature has taken full advantage of the most general SU(2) $\times$ U(1) locally gauge invariant coupling between the Higgs scalar Φ and fermions. This coupling can be written as

$$\begin{aligned}
&- G_1\left[\left(\bar{L}_u\bar{\Phi}\right)u_R + \bar{u}_R\left(\bar{\Phi}^\dagger L_u\right)\right] - G_2\left[\left(\bar{L}_u\Phi\right)d_R + \bar{d}_R\left(\Phi^\dagger L_u\right)\right]\\
&- G_3\left[\left(\bar{L}_u\Phi\right)s_R + \bar{s}_R\left(\Phi^\dagger L_u\right)\right] - G_4\left[\left(\bar{L}_c\bar{\Phi}\right)c_R + \bar{c}_R\left(\bar{\Phi}^\dagger L_c\right)\right]\\
&- G_5\left[\left(\bar{L}_c\Phi\right)d_R + \bar{d}_R\left(\Phi^\dagger L_c\right)\right] - G_6\left[\left(\bar{L}_c\Phi\right)s_R + \bar{s}_R\left(\Phi^\dagger L_c\right)\right]
\end{aligned} \tag{8.47}$$

plus analogous terms involving L_t, b_R and t_R. The G_i are arbitrary constants called Yukawa coupling constants. The same Higgs mechanism that gave mass to the $W^\pm$ and Z^0 gauge bosons will also lead to the terms

$$\begin{aligned}
&-\frac{G_1 v}{\sqrt{2}}\left(\bar{u}_R u_L + \bar{u}_L u_R\right) - \left(\frac{G_2 v}{\sqrt{2}}\cos\theta_1 + \frac{G_5 v}{\sqrt{2}}\sin\theta_1\cos\theta_2\right)\left(\bar{d}_R d_L + \bar{d}_L d_R\right)\\
&-\left(\frac{G_6 v}{\sqrt{2}}\left(\cos\theta_1\cos\theta_2\cos\theta_3 - \sin\theta_2\sin\theta_3 e^{i\delta}\right) - \frac{G_3 v}{\sqrt{2}}\sin\theta_1\cos\theta_3\right)\left(\bar{s}_R s_L + \bar{s}_L s_R\right)\\
&-\frac{G_4 v}{\sqrt{2}}\left(\bar{c}_R c_L + \bar{c}_L c_R\right) + \text{terms involving } b_L,\ b_R,\ t_L \text{ and } t_R\ ,
\end{aligned} \tag{8.48}$$

where v is related to the Higgs vacuum expectation value (8.35). These terms look like fermion mass terms (recall eq. 8.28). The d quark, for example, has a mass

$$\frac{G_2 v}{\sqrt{2}}\cos\theta_1 + \frac{G_5 v}{\sqrt{2}}\sin\theta_1\cos\theta_2 \quad . \tag{8.49}$$

If $G_3 = G_5 = 0$, then the weak eigenstates d', s', are the left-handed components of the mass eigenstates, and there is no mixing of weak eigenstates and mass eigenstates. If G_3 and G_5 are nonzero then there will be mixing.

Weak Neutral Coupling of Quarks

The term in the SU(2) × U(1) Lagrangian that corresponds to the weak neutral current coupling of quarks is

$$\frac{e}{\sin\theta_W \cos\theta_W}\left[\bar{L}_u\gamma^\mu Z_\mu\left(T_3 - Q\sin^2\theta_W\right)L_u + \bar{L}_c\gamma^\mu Z_\mu\left(T_3 - Q\sin^2\theta_W\right)L_c\right.$$
$$\left.-\sin^2\theta_W\left(\bar{u}_R\gamma^\mu Z_\mu Q\, u_R + \bar{d}_R\gamma^\mu Z_\mu Q\, d_R + \bar{s}_R\gamma^\mu Z_\mu Q\, s_R + \bar{c}_R\gamma^\mu Z_\mu Q\, c_R\right)\right] \tag{8.50}$$

where we've neglected b and t quarks. Expanding the left-handed coupling, we have

$$\bar{L}_\mu\,\Gamma\, L_u + \bar{L}_c\,\Gamma\, L_c = \bar{u}_L\,\Gamma\, u_L + \bar{d}'_L\,\Gamma\, d'_L + \bar{s}'_L\,\Gamma\, s'_L + \bar{c}_L\,\Gamma\, c_L \tag{8.51}$$

where

$$\Gamma \equiv \gamma^\mu Z_\mu(T^3 - Q\sin^2\theta_W) \quad . \tag{8.63}$$

Expanding the terms for d_L and s_L, we have

$$\begin{aligned}\bar{d}'_L\,\Gamma\, d'_L &= \cos^2\theta_1 \bar{d}_L\,\Gamma d_L + \sin^2\theta_1 \bar{s}_L\,\Gamma\, s_L \\ &\quad - \sin\theta_1\cos\theta_1\left(\bar{s}_L\,\Gamma d_L + \bar{d}_L\,\Gamma\, s_L\right)\end{aligned} \tag{8.53}$$

and

$$\begin{aligned}\bar{s}'_L\,\Gamma\, s'_L &= \sin^2\theta_1 \bar{d}_L\,\Gamma\, d_L + \cos^2\theta_1 \bar{s}_L\,\Gamma\, s_L \\ &\quad + \sin\theta_1\cos\theta_1\left(\bar{s}_L\,\Gamma\, d_L + \bar{d}_L\,\Gamma\, s_L\right)\end{aligned} \tag{8.54}$$

where we've set $\theta_2 = \theta_3 = 0$.

At the time Weinberg and Salam proposed their SU(2) × U(1) theory, the charm quark had not been discovered, so that L_c and hence the term $\bar{s}'_L\,\Gamma\, s'_L$ in (8.51) didn't exist. This meant that the term

$$-\sin\theta_1\cos\theta_1(\bar{s}_L\,\Gamma\, d_L + \bar{d}_L\,\Gamma\, s_L) \tag{8.55}$$

in the expression (8.53) for $\bar{d}'\Gamma d'_L$ was left uncancelled. Such an interaction term would lead to decay processes such as

$$K^+ \rightarrow \pi^+ + \nu + \bar{\nu} \tag{8.56}$$

which, in the quark model view, is the decay

$$\bar{s} \rightarrow \bar{d} + \nu + \bar{\nu} \quad . \tag{8.57}$$

The predicted rate for such a strangeness-changing neutral current decay was eight orders of magnitude larger than the measured limit. S. Glashow, J. Iliopoulos, and L. Maiani demonstrated in 1970 that a fourth quark would lead to the cancellation of terms in the Lagrangian responsible for strangeness-changing neutral currents. Higher order diagrams would still lead to strangeness-changing neutral currents, even with a fourth (charm) quark present, and in order to suppress again the decay rate of (8.56) it was predicted that the charm quark mass must be less than a few GeV. In 1974 the J/Ψ particle, a meson consisting of a charm quark and a charm antiquark, was discovered simultaneously in hadron-hadron collisions at Brookhaven and in e^+e^- collisions at SLAC with a mass of 3 GeV. This gave a charm quark mass of about 1.5 GeV. The discovery of the J/Ψ meson therefore provided support, not only for the quark model of hadrons, but also for the SU(2) $\times$ U(1) electroweak theory.

E. Electroweak Phenomenology

Muon decay (Fig. 6b) proceeds through the charged vector boson W^-. The amplitude for the decay rate is proportional to

$$\frac{g^2}{M_W^2} \quad . \tag{8.58}$$

This is because each vertex in Fig. 6b contributes a factor g, while the W^- propagator contributes a factor

$$\frac{1}{(q^2 - M_W^2)} \quad , \tag{8.59}$$

where q^2 is the square of the momentum transferred by the W^- in the decay.

For muon decay, $|q|^2 << M_W^2$, so that the muon decay amplitude is simply proportional to (8.58).

Hadrons can also decay through the $W^\pm$. For example, a meson with a $\bar{u}$ and b quark that cannot decay by any other means will decay eventually through the charged weak coupling (Fig. 22). The decay rate amplitude for a particular final state will be proportional to the product of g^2/M_W^2 and the two $K-M$ matrix elements associated with the two vertices in Fig. 22. By comparing the charged weak decays of many particles (both leptons and hadrons) the mixing angles of the Kobayashi-Maskawa matrix (8.44) can be measured.

Three independent parameters determine the coupling of the SU(2) $\times$ U(1) gauge bosons to quarks and leptons. These can be taken to be the magnitude of the charge of the electron, e, the Weinberg angle, θ_W, and a quantity called the Fermi constant, G_F. G_F is defined to be

$$G_F = \frac{g^2}{4\sqrt{2}\,M_W^2} \quad . \tag{8.60}$$

Notice that experiments involving low q^2 $W^\pm$ exchange, such as muon decay and charged current neutrino scattering experiments, measure G_F, but they do not measure g and M_W separately. G_F is measured to be $G_F = 1.16632 \pm 0.00004 \times 10^{-5}$ GeV^{-2}.

From (8.24) we have the relation

$$g = \frac{e}{\sin\theta_W} \tag{8.61}$$

so that the mass of the $W^\pm$ can be expressed as

$$M_W^2 = \frac{e^2}{4\sqrt{2}\,G_F \sin^2\theta_W} \tag{8.62}$$

According to (8.40) the Z^0 mass is

$$M_Z^2 = \frac{e^2 v^2}{4\sin^2\theta_W \cos^2\theta_W} \tag{8.63}$$

where v is (from 8.39)

$$v^2 = \frac{4M_W^2}{g^2} = \frac{1}{\sqrt{2}\,G_F} \tag{8.64}$$

so that

$$M_Z^2 = \frac{M_W^2}{\cos^2\theta_W} \quad . \tag{8.65}$$

When Weinberg and Salam proposed their SU(2) $\times$ U(1) theory in 1967, the charge of the electron, e, was of course known, and the Fermi coupling constant, G_F, had also been measured. However, the Weinberg angle θ_W was an unknown quantity, and hence there was no estimate of the $W^{\pm}$ and Z masses.

When neutral weak current events were observed in the early 1970's, physicists got their first look at the magnitude of θ_W. Fig. 20 shows the Born diagram for the neutral weak current process

$$\nu_\mu + e \to \nu_\mu + e \quad .$$

As usual we represent the amplitude for this process by mutiplying together the couplings at the two vertices and the propagator. The neutrino vertex is

$$\frac{e}{2\sin\theta_W\cos\theta_W} \quad , \tag{8.66}$$

the propagator contributes

$$\frac{1}{M_Z^2} \quad , \tag{8.67}$$

and we represent the electron vertex as the square root of the sum of squares of the left and right-handed contributions:

$$\left(\frac{e}{2\sin\theta_W\cos\theta_W}\right)\left(\frac{1}{4} - \sin^2\theta_W + 2\,\sin^4\theta_W\right)^{\frac{1}{2}} \quad . \tag{8.68}$$

Combining the three terms, the amplitude for elastic muon-neutrino electron scattering is proportional to

$$\frac{e^2}{4\,\sin^2\theta_W\cos^2\theta_W}\,\frac{1}{M_Z^2}\,\left(\frac{1}{4} - \sin^2\theta_W + 2\,\sin^4\theta_W\right)^{\frac{1}{2}} \quad . \tag{8.69}$$

We have neglected effects due to angular momentum conservation and the relative spins of the neutrino and the electron. When these are included the relative contribution of the right-handed electron is reduced by 66%. The important point is that the neutral current cross section is sensitive to θ_W. Once θ_W had been measured, in experiments such as muon-neutrino electron, electron-neutrino electron, and neutrino hadron scattering, the mass of the $W^\pm$ and Z^0 gauge bosons could be predicted.

The measured value of θ_W is usually expressed in terms of $\sin^2\theta_W$. $\sin^2\theta_W$ is about 0.2. Thus the mass of the $W^\pm$ boson should be about 84 GeV, and the mass of the Z^0 should be about 94 GeV. Direct observations of the $W^\pm$ and Z^0 bosons did not take place until 1983 when the $W^\pm$ and Z^0 bosons were produced in proton-antiproton collisions at 540 GeV center-of-mass energy at CERN. Recalling the quark composition of the proton (Table II), the fundamental processes leading to $W^\pm$ production are

$$\begin{aligned} u + \bar{d} &\rightarrow W^+ \\ d + \bar{u} &\rightarrow W^- \end{aligned} \tag{8.70}$$

and the fundamental processes leading to Z^0 production are

$$\begin{aligned} u + \bar{u} &\rightarrow Z^0 \\ d + \bar{d} &\rightarrow Z^0 \quad . \end{aligned} \tag{8.71}$$

The $W^\pm$ are observed through their decay to $\nu_e + e^+$ or $\bar{\nu}_e + e^-$, and the Z^0 is observed through its decay to an e^+e^- or $\mu^+\mu^-$ pair. The measured masses of the $W^\pm$ and Z^0 gauge bosons (Table I) are as predicted by (8.62) and (8.65).

IX. CURRENT ISSUES IN ELEMENTARY PARTICLE PHYSICS

Research efforts in elementary particle physics today can be broadly classified into two categories:

1) continued tests of the standard model

and

2) experimental searches for, and theoretical models of, physics beyond the standard model By "standard model" we mean the description of elementary particle physics presented in this article: three generations of quarks and leptons which interact through the SU(2) × U(1) theory of the electroweak force and the $SU(3)_{color}$ theory of the strong force.

A. Continued tests of the standard model

All high energy physics phenomena appear to fit the standard model. There are, however, many aspects of the standard model that have yet to be tested. Firstly, almost all experiments sensitive to the electroweak force have involved the exchange of gauge bosons with invariant-mass squared values, q^2, of $|q^2| << M_W^2, M_Z^2$. The one (very notable) exception is the observation of W and Z gauge bosons at the CERN proton-antiproton collider. Will the standard model continue to stand up under close scrutiny at $|q^2| > M_W^2, M_Z^2$? Secondly, most experiments involving the strong force have taken place at energies where the strong coupling constant, α_S, was greater than 1. It is very difficult to quantitatively test quantum chromodynamics under conditions where perturbative calculations cannot be made. It is hoped that as experiments are performed at higher energies, there will be a greater opportunity to quantitatively compare QCD predictions with experiment. Thirdly, there are two particles predicted by the standard model that have yet to be seen: the top quark and the neutral Higgs boson. The standard model does not predict the masses of these two particles, but it does predict that they must exist at some mass.

The standard model parameters that experimental physicists measure are:

a) the mass of the Z^0 gauge boson, M_Z

b) the mass of the W gauge boson, M_W

c) the mixing angles of the Kobayashi-Maskawa matrix, θ_1, θ_2 and θ_3

d) upper limits on the masses of the electron-neutrino, muon-neutrino, and tau-neutrino

e) the QCD coupling constant α_S, evaluated at a particular q^2

f) the couplings of the quarks and leptons to the γ, W and Z gauge bosons.

All of these quantities have been measured to some degree of accuracy already. Many of them will be measured to a greater accuracy at $q^2 = M_Z^2$ in the late 1980's at the SLC e^+e^- linear collider at SLAC and at the LEP e^+e^- storage ring at CERN. The cross-section for

$$e^+ + e^- \rightarrow Z^0 \rightarrow \text{ anything}$$

has a sharp peak at center-of-mass energies equal to the mass of the Z^0, so that many Z^0 bosons will be produced at SLC and LEP, even if the luminosities at these machines are in a certain sense average or below-average. Other experiments at lower q^2 will continue to provide better values for the mixing angles of the Kobayashi-Maskawa matrix and better upper limits on the masses of the neutrinos.

There are some standard model parameters that are not known at all. These are the top mass, the neutral Higgs boson mass, and the phase angle, δ, of the Kobayashi-Maskawa matrix. Actually, we do know a little bit about these parameters. We know, since hadrons containing top quarks have not been produced at the PETRA e^+e^- collider at DESY, that the top quark mass must be greater than 22.5 GeV. The neutral Higgs boson mass is constrained through theoretical considerations to be between 7 GeV and 1000 GeV.

B. CP Violation

The phase angle δ (Eq. 8.44) is of great interest because a non-zero δ can produce "CP violation" in weak interactions. CP represents the combined operations of parity transformation, P, and charge conjugation, C. CP violation occurs when the operation CP is not a symmetry of the Lagrangian. The mass eigenstates of a system that violates CP are not eigenstates of CP.

CP violation shows up experimentally in the decays of neutral K mesons. The neutral K meson mass eigenstates K_S^0 and K_L^0 are linear combinations of the strange quark eigenstates $|K^0> = |\bar{d}s>$ and $|\bar{K}^0> = |d\bar{s}>$:

$$
\begin{aligned}
|K_S^0> &= a_{11}\,|K^0> + a_{12}\,|\bar{K}^0> \\
|K_L^0> &= a_{21}\,|K^0> + a_{22}\,|\bar{K}^0> \;; \\
\begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} &\approx \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{pmatrix} \quad .
\end{aligned}
$$

It was once thought that $|K_S^0>$ and $|K_L^0>$ were eigenstates of CP, but in 1964 J. Cronin and V. Fitch discovered a decay mode of the $|K_L^0>$ state which indicated that $|K_S^0>$ and $|K_L^0>$ were not quite eigenstates of CP.

The standard SU(2) $\times$ U(1) weak interaction with only two generations of fermions will not have a complex phase, $e^{i\delta}$ (the K.M. matrix is parameterized in such a case by only 1 angle). Such a Lagrangian will violate parity and charge conjugation separately, but will conserve the combined operation of CP. In 1973 M. Kobayashi and T. Maskawa demonstrated that in the standard SU(2) $\times$ U(1) theory with three generations of quark doublets, a complex phase $e^{i\delta}$ arises in the matrix describing the mixing of weak and mass quark eigenstates. This phase will lead to a violation of CP in the SU(2) $\times$ U(1) Lagrangian.

Although we know today that there are three generations of fundamental fermions, we don't know if the complex phase in the Kobayashi-Maskawa matrix can explain the observed CP violation in the $K^0\bar{K}^0$ system. The amount by which CP is violated is very small, and quantitative predictions of $K^0\bar{K}^0$ CP violation in terms of δ, θ_1, θ_2, θ_3, and the quark masses are difficult to make because non-perturbative QCD effects are very important. Nevertheless, thanks to recent improved experimental measurements of θ_1, θ_2, θ_3, physicists have been able to place tight limits on the allowed values of the phase angle δ. New, more sensitive $K^0\bar{K}^0$ CP violation experiments are planned for the mid to late 1980's, and these may tell us whether or not the standard model can account for $K^0\bar{K}^0$ CP violation.

There is a general result from quantum field theory which states that the combined operations of charge conjugation, parity transformation, and time reversal (CPT) should be a symmetry of any Lagrangian. CP violation therefore implies time reversal violation. Time reversal violation should show up as a small electric dipole moment in the neutron. Experimental limits on the electric dipole moment of the neutron continue to improve; if ever a non-zero value is found it will add substantially to the understanding of CP violation.

B. Physics beyond the standard model

Even if all predictions of the standard model were to be confirmed to the umpteenth decimal place, few physicists would be satisfied with the standard model. Perhaps the biggest problem with the standard model is the multitude of fundamental constants and fundamental fields. The standard model contains eighteen fundamental parameters: three coupling constants (α, α_S, $\sin^2\theta_W$), the neutral Higgs boson mass, the Higgs vacuum expectation value, and 13 Yukawa couplings, corresponding to 4 Kobayashi-Maskawa angles, 3 charged lepton masses, and 6 quark masses. The standard model has nothing to say about these parameters. Should the fundamental theory of elementary particle physics contain so many arbitrary constants? The number of fermion generations, three, is also arbitrary (there may even be more generations at higher masses – we will have to determine this from experiment).

Other questions left unanswered by the standard model are the following. Why are fermions in the representations they are in: left-handed quarks and leptons in SU(2) doublets, right-handed quarks and leptons in SU(2) singlets, all leptons in $SU(3)_{color}$ singlets, and all quarks in $SU(3)_{color}$ triplets? Why do the fundamental fermions have the hypercharges and hence the electric charges that they have? (Why is the charge of the electron precisely three times the charge of the down quark?) Why are neutrinos massless or at least nearly massless? Where does the form of the Higgs scalar potential come from and why do the constants describing this potential have the values that they have? Is the Higgs scalar a fundamental particle or is it composite? Are quarks and leptons composite objects? (The repetition of quark-lepton generations with higher mass fermions in successive generations certainly suggests such a possibility.)

There are many ideas for physics beyond the standard model. Each attempts to deal with one or more of the above questions. These ideas include:

a) grand unified gauge theories of the electroweak and strong forces

b) dynamical symmetry breaking

and

c) supersymmetric gauge theories .

Grand unified gauge theories

Grand unified gauge theories attempt to combine the $SU(3)_{color}$ and SU(2) $\times$ U(1) gauge theories into a single gauge theory with one gauge group and one coupling constant. Such theories reduce the number of fundamental coupling constants from three to one and explain why leptons and quarks have the electric charge ratios that they do. The development of grand unified gauge theories has been motivated by the success of the $SU(3)_{color}$ and SU(2) $\times$ U(1) gauge theories, the striking similarity between quarks and leptons, and the fact that the running coupling constants of the electromagnetic, weak, and strong forces appear to converge at some very large energy (Fig. 18).

The simplest grand unified gauge theory is based on the group SU(5). In this theory all the quarks and leptons in one generation are placed in the same SU(5) multiplet. Such an assignment produces simple algebraic relations between the electric charges of quarks and leptons which explain the observed ratios of quark and lepton charges and the fact that the sum of electrical charges over fermions in the same generation is zero.

Another consequence of placing quarks and leptons in the same gauge group multiplet is that there will be gauge bosons, called X and Y gauge bosons, which mediate transistions between quarks and leptons and which therefore induce baryon number and lepton number violating interactions. It is presumed that some Higgs mechanism breaks the SU(5) symmetry to $SU(3)_{color} \times SU(2) \times U(1)$, and in the process imparts very large masses to the X and Y gauge bosons. This first level of spontaneous symmetry breakdown leaves the $SU(3) \times SU(2) \times U(1)$ gauge bosons massless, and the $W^{\pm}$ and Z^0 gauge bosons then acquire mass in a second spontaneous symmetry breakdown in a manner analogous to the process described in Sec. VIIIC.

The X and Y gauge bosons induce proton decay (Fig. 23), and in order for the proton lifetime to be extended to values greater than the current lower limit of 10^{32} year, the masses of the X and Y gauge bosons must be greater than about 10^{15} GeV. The X and Y gauge boson masses are further constrained by the requirement that they be roughly equal to the energy at which the running weak and strong coupling constants converge. Applying the boundary condition that these two running coupling constants are equal at some unification energy, it's possible to obtain relations between the electromagnetic and strong coupling constants. Substituting known low energy values for these coupling constants, the unification energy is found to be about 10^{15} GeV. The current limits on proton decay are therefore very close to the values predicted by some grand unified theories; in fact the SU(5) grand unified theory appears to be excluded by present experimental limits.

Although proton decay is not observed at the rate predicted by the the SU(5) grand unified theory, the theory does do an admirable job of predicting $\sin^2 \theta_W$ at present day energies. Requiring that the weak and strong coupling constants be equal at a unification energy leads to an expression for $\sin^2\theta_W\,(q^2)$ in terms of $\alpha(q^2)$ and the unification energy. Using a known low energy value for α, and 10^{15} GeV for the unification energy, $\sin^2\theta_W$ is predicted to be 0.21 at 100 GeV.

Dynamical symmetry breaking

The standard model doublet of complex scalar fields Φ is a set of four fundamental scalar fields. Some physicists find fundamental scalar fields objectionable. The problem is that the mass of the neutral Higgs boson (or the mass of any other fundamental scalar field) is overly sensitive to details of the electroweak theory at very high energies. It is often said that there is no "natural" way for the Higgs boson mass to be less that 1000 GeV because small variations in parameters describing the electroweak theory at large energies cause enormous variations in the Higgs boson mass. Fundamental fermions do not have this problem.

Models have been proposed in which the standard model fundamental scalar fields are replaced by composite scalar fields made of new fundamental fermions. Such models are called dynamical symmetry breaking models.

One well-known dynamical symmetry breaking model is technicolor. In technicolor there are new fundamental fermions called techniquarks which interact and form bound states of technihadrons through a new force called technicolor. Techniquarks and the technicolor force are entirely analogous to quarks and the $SU(3)_{color}$ force; the major difference between the two systems is that the technicolor mass scale is 1 TeV, compared to 1 GeV for ordinary $SU(3)_{color}$.

Technicolor is relevant to the question of fundamental scalar fields because the pions of the technicolor sector (technipions) can be used instead of fundamental scalar fields to give mass to the $W^\pm$ and Z^0 gauge bosons. When the $SU(2) \times U(1)$ symmetry is broken by technipions, the $W^\pm$ and Z^0 gauge bosons acquire masses which are in the same ratio as in the standard model. A technicolor mass scale of 1 TeV will produce $W^\pm$ and Z^0 masses on the order of 100 GeV.

The problem with dynamical symmetry breaking is that there is no known way to construct a phenomenologically acceptable model which gives mass to the quarks and leptons. Recall that the single complex Higgs doublet of the standard model gave mass not only to the $W^{\pm}$ and Z^0 gauge bosons, but also to quarks and leptons.

Supersymmetric gauge field theories

All quarks and leptons have spin 1/2, all gauge bosons (photon, gluon $W^{\pm}$ and Z^0) have spin 1, and the neutral Higgs scalar has spin 0. Some physicists believe that there exist as yet unseen quarks and leptons with spin 0, and gauge bosons and Higgs scalars with spin 1/2. Such particles are predicted by a class of gauge field theories called supersymmetric gauge field theories. Supersymmetric theories predict that for every fundamental particle with spin s, there is another particle, called the supersymmetric partner, with a spin that differs from s by 1/2 unit. The transformation that changes a particle's spin by 1/2 unit is called a supersymmetry transformation. The Lagrangians of supersymmetric theories are invariant under supersymmetry transformations.

Supersymmetric theories are considered attractive for a number of reasons. Firstly, in supersymmetric theories the masses of fundamental scalar fields are no longer overly sensitive to details of the theory at very high energies. Secondly, theorists find that supersymmetric quantum field theories are "better behaved" than other quantum field theories. Thirdly, in locally supersymmetric theories there is a connection between supersymmetry transformations and space-time transformations. This implies that it may be possible to use locally supersymmetric theories to unify the gravitational force with the strong and electroweak forces.

To date there is no experimental evidence for supersymmetry. If there are supersymmetric partners of the known quarks, leptons, and gauge bosons, then their masses must be greater than about 20 GeV.

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Table I. Properties of the established elementary particles. The masses are given in terms of equivalent energy in MeV, or GeV units. The constituent quark masses are given, these are calculated from hadron masses, the quarks being the constituents of the hadrons. The electric charge is expressed in units of the magnitude of the electron's charge, 1.602 $\times 10^{-19}$ coulomb.

Family	Name	Symbol	Mass	Spin	Electric Charge	Antiparticle Symbol
Leptons	electron	e^- or e	0.511 MeV	1/2	−1	e^+ or $\bar{e}$
	muon	μ^- or μ	105.7 MeV	1/2	−1	μ^+ or $\bar{\mu}$
	tau	τ^- or τ	1784. ± .3 MeV	1/2	−1	τ^+ or $\bar{\tau}$
	electron neutrino	ν_e	< 0.000046 MeV	1/2	0	$\bar{\nu}_e$
	muon neutrino	ν_μ	< 0.50 MeV	1/2	0	$\bar{\nu}_\mu$
	tau neutrino	ν_τ	< 125. MeV	1/2	0	$\bar{\nu}_\tau$
Quarks	up	u	about 350 MeV	1/2	+2/3	$\bar{u}$
	down	d	about 350 MeV	1/2	−1/3	$\bar{d}$
	strange	s	about 500 MeV	1/2	−1/3	$\bar{s}$
	charm	c	about 1500 MeV	1/2	+2/3	$\bar{c}$
	bottom or beauty	b	about 5000 MeV	1/2	−1/3	$\bar{b}$
Gauge Bosons	photon	γ	0.0	1	0	γ
	W^+ boson	W^+	80.8 ± 2.7 GeV	1	+1	W^-
	W^- boson	W^-	80.8 ± 2.7 GeV	1	−1	W^+
	Z^0 boson	Z^0	92.9 ± 1.6 GeV	1	0	Z^0
	gluon	g	assumed 0	1	0	g

Table II. Properties of some hadrons. The mass and charge units are defined in Table I. The final column gives the quark composition of the hadron.

Name	Symbol	Mass in GeV	Charge	Quarks in the hadrons
proton	p	0.938	+1	uud
antiproton	$\bar{p}$	0.938	−1	$\bar{u}\bar{u}\bar{d}$
neutron	n	0.940	0	udd
antineutron	$\bar{n}$	0.940	0	$\bar{u}\bar{d}\bar{d}$
positive pion	π^+	0.140	+1	$u\bar{d}$
negative pion	π^-	0.140	−1	$\bar{u}d$
neutral pion	π^0	0.135	0	$u\bar{u}$, $d\bar{d}$
positive kaon	K^+	0.494	+1	$u\bar{s}$
negative kaon	K^-	0.494	−1	$\bar{u}s$
neutral kaon	K^0	0.498	0	$d\bar{s}$, $\bar{d}s$
D^+ charm meson	D^+	1.869	+1	$c\bar{d}$
D^- charm meson	D^-	1.869	−1	$\bar{c}d$
D^0 charm meson	D^0	1.865	0	$c\bar{u}$, $\bar{c}u$
psi or J	ψ/J	3.097	0	$c\bar{c}$
upsilon	Υ	9.460	0	$b\bar{b}$

Table III. The four basic Forces.

Type of Force	Strong or Nuclear	Electromagnetic	Weak	Gravitational
Behavior over distance	Limited to less than about 10^{-13}	Extends to very large distances	Limited to less than about 10^{-16}	Extends to very large distances
Strength relative to strong force at a distance of 10^{-13}	1	10^{-2}	10^{-13}	10^{-38}
Particle which carries the force	Gluon The gluon has been identified indirectly but it has not, and perhaps cannot, be isolated	Photon	W^+, W^- and Z^0 Intermediate bosons	Not discovered, but in proposed theories called graviton

Table IV. Properties of the known Leptons.

Lepton Generation	Lepton	Symbol	Mass (MeV)	Charge	Lifetime (seconds)	Major Decay Modes
1	electron	e^-	0.511	–1	stable*	none
1	electron neutrino	ν_e	< 0.00003	0	stable*	none
2	muon	μ^-	105.7	–1	2.197×10^{-6}	$\nu_\mu + e^- + \bar{\nu}_e$
2	muon neutrino	ν_μ	< 0.5	0	stable*	none
3	tau	τ^-	$1784. \pm 3.$	–1	3.4×10^{-13}	$\nu_\tau + e^- + \bar{\nu}_e$, 16.5% $\nu_\tau + \mu^- + \bar{\nu}_\mu$, 18.5% $\nu_\tau + \pi^-$, 10.3% $\nu_\tau + \rho^-$, 22.1% $\nu_\tau + \rho^0 + \pi^-$, 5.4%
3	tau neutrino	ν_τ	$< 100.$	0	stable*	none

*Stability based partly on measurement and partly on present theoretical expectations.

Table V. The lepton conservation numbers.

Particle	n_e	n_μ	n_τ
e^-, ν_e	+1	0	0
e^+, $\bar{\nu}_e$	−1	0	0
μ^-, ν_μ	0	+1	0
μ^+, $\bar{\nu}_\mu$	0	−1	0
τ^-, ν_τ	0	0	+1
τ^+, $\bar{\nu}_\tau$	0	0	−1
all other particles and all hadrons	0	0	0

Table VI. Properties of the established quarks. Constituent quark masses are given.

Quark Generation	Quark	Symbol	Mass (GeV)	Charge	Known Decay Modes of Heavier Quarks
1	up	u	about 350.	$+\frac{2}{3}$	
1	down	d	about 350.	$-\frac{1}{3}$	
2	charm	c	about 1500.	$+\frac{2}{3}$	$c \rightarrow s$ + other particles $c \rightarrow d$ + other particles
2	strange	s	about 500.	$-\frac{1}{3}$	$s \rightarrow u$ + other particles
3	bottom or beauty	b	about 5000.	$-\frac{1}{3}$	$b \rightarrow c$ + other particles

Table VII. Third component of weak isospin, weak hypercharge, and Z^0 coupling of the first generation quarks and leptons. The values for the 2nd and 3rd generation quarks and leptons are the same as for the corresponding 1st generation fermions.

fermion	3rd component of weak isospin T^3	weak hypercharge Y	Z^0 coupling $\lvert T^3 - Q\sin^2\theta_W \rvert$
ν_e	1/2	−1	0.5
e_L	−1/2	−1	0.28
e_R	0	−2	0.22
u_L	1/2	1/3	0.35
d_L	−1/2	1/3	0.43
u_R	0	4/3	0.15
d_R	0	−2/3	0.07

Figure Captions

1. Many basic objects in nature are made up of yet simpler objects. For example, molecules are made up of atoms, and atoms are made up of electrons moving around a nucleus. To the best of our present knowledge, the elementary particles, electrons and quarks, are not made up of simpler particles.

2. The different subfields of physics study parts of nature that are very different in size. Elementary particle physics studies the smallest objects in nature, objects that are smaller than 10^{-13} centimeters.

3. In (a) two protons are about to collide head-on. When they collide in (b), their mass and energy are concentrated in a small region of space. That concentration of mass and energy is unstable and very quickly breaks up into new particles as in (c). Sometimes just two particles come out of the collision. But at high-energies usually many particles come out of the collisions, and none of them need be the original protons.

4. The collisions of particles can be represented succinctly in a diagram in which time advances from left to right. For example, the lower figure shows two protons going into a collision producing a concentration of mass and energy, which then breaks up into six particles.

5. The collision of an electron and a positron can lead to the production of a positive muon and a negative muon. The electron and positron actually disappear; the technical term is that they annihilate each other. A sketch of how that interaction occurs is shown in (a). A more detailed description of the interaction is given in (b).

6. Feynman diagrams for (a) $e^- + p \to \nu_e + n$ and (b) $\mu^- \to \nu_\mu + e^- + \bar{\nu}_e$.

7. Feynman diagrams for $e^+ + e^- \to \mu^+ + \mu^-$ of order: (a) two, (b) four, and (c) six.

8. (a) In fixed target experiments, a beam of high-energy particles collides

with particles at rest in a target. (b) In colliding beam experiments, two beams of high-energy particles collide head-on.

9. In a fixed-target experiment a beam of high-energy particles, for example protons, is produced by an accelerator. The beam of particles interacts with the target producing new particles. The particles are detected and their properties studied using an apparatus called a particle detector. In (a) the entire experiment is sketched. In (b) the interaction of the particle itself is shown: a proton in the beam interacts with a proton in the target and produces four particles.

10. In the simplest form of colliding beam facilities, two beams of particles rotate in the same direction in circles which are tangent at just one point. The beams collide at that point.

11. Accelerators work by exerting an electric force on a charged particle. In the example here a negative plate repels the bunch of electrons and a positive plate attracts them. The electrons thus gain energy in moving from the negative plate to the positive plate. By the time they reach the positive plate they are traveling so quickly that they pass through the hole in the plate.

12. Very high energies cannot be obtained by using just one pair of plates, as in Fig. 11. There are two ways to solve this problem. In the linear accelerator, many pairs of plates are lined up, and the particles being accelerated are given more and more energy as they pass through each pair of plates. In a circular accelerator, only one pair of plates is used, but the particles are made to travel in a circle, thus passing through that pair of plates again and again. Each time they pass through the pair of plates they are given more energy.

13. (a) A colliding beam storage ring accelerator has two bunches of particles moving in opposite directions. The bunches collide at the two interaction points. Even though the bunches collide, most of the particles in the bunch

pass right through the other bunch; therefore the bunches continue to rotate again and again around the orbits.

(b) In a linear colliding beam accelerator the two bunches collide only once. To make full use of that single collision the bunches have to be much denser than in a circular collider.

14. e^+e^- annihilation into two jets of hadrons: (a) as observed in a particle detector and (b) the Feynman diagram for the underlying fundamental process $e^+ + e^- \to q + \bar{q}$.

15. $R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$ as a function of e^+e^- center-of-mass energy.

16. Feynman diagrams for gluon exchange by two quarks: (a) the Born diagram and (b) higher order diagrams.

17. Feynman diagrams for gluon self-interactions.

18. Evolution of the electromagnetic, weak and strong coupling constants (α, $\frac{\alpha}{\sin^2\theta_W}$, and α_s respectively); q^2 is the square of the energy scale at which a particular interaction takes place.

19. e^+e^- annihilation into three jets of hadrons: (a) as observed in a particle detector and (b) the Feynman diagram for the underlying fundamental process $e^+ + e^- \to q + \bar{q} + g$.

20. The Feynman diagram for the weak neutral current process $\nu_\mu + e^- \to \nu_\mu + e^-$.

21. The Higgs scalar potential $V(\Phi^\dagger\Phi) = \mu^2(\Phi^\dagger\Phi) + |\lambda|(\Phi^\dagger\Phi)^2$: (a) $\mu^2 > 0$ and (b) $\mu^2 < 0$.

22. Diagram for the decay of the B^- meson.

23. Diagrams for the decay of the proton through the SU(5) X and Y gauge bosons.

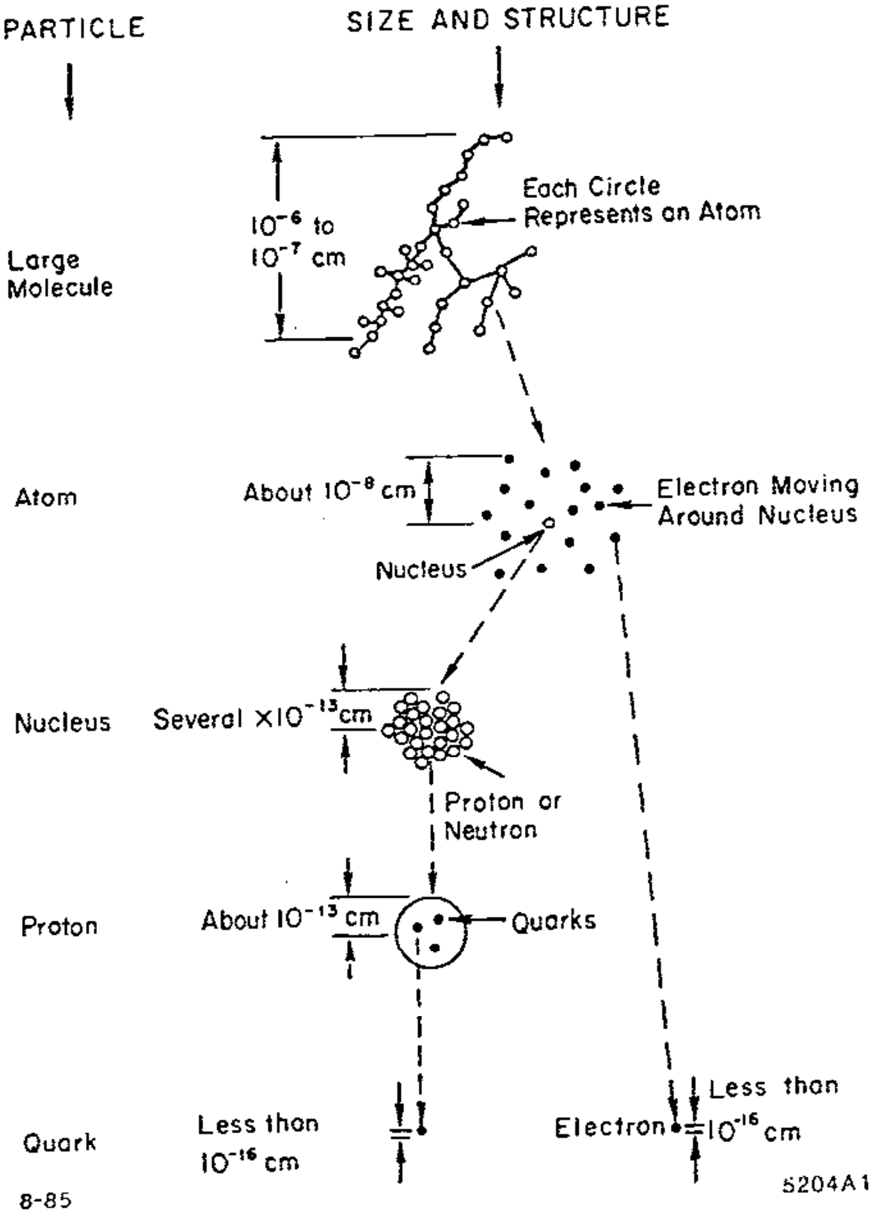
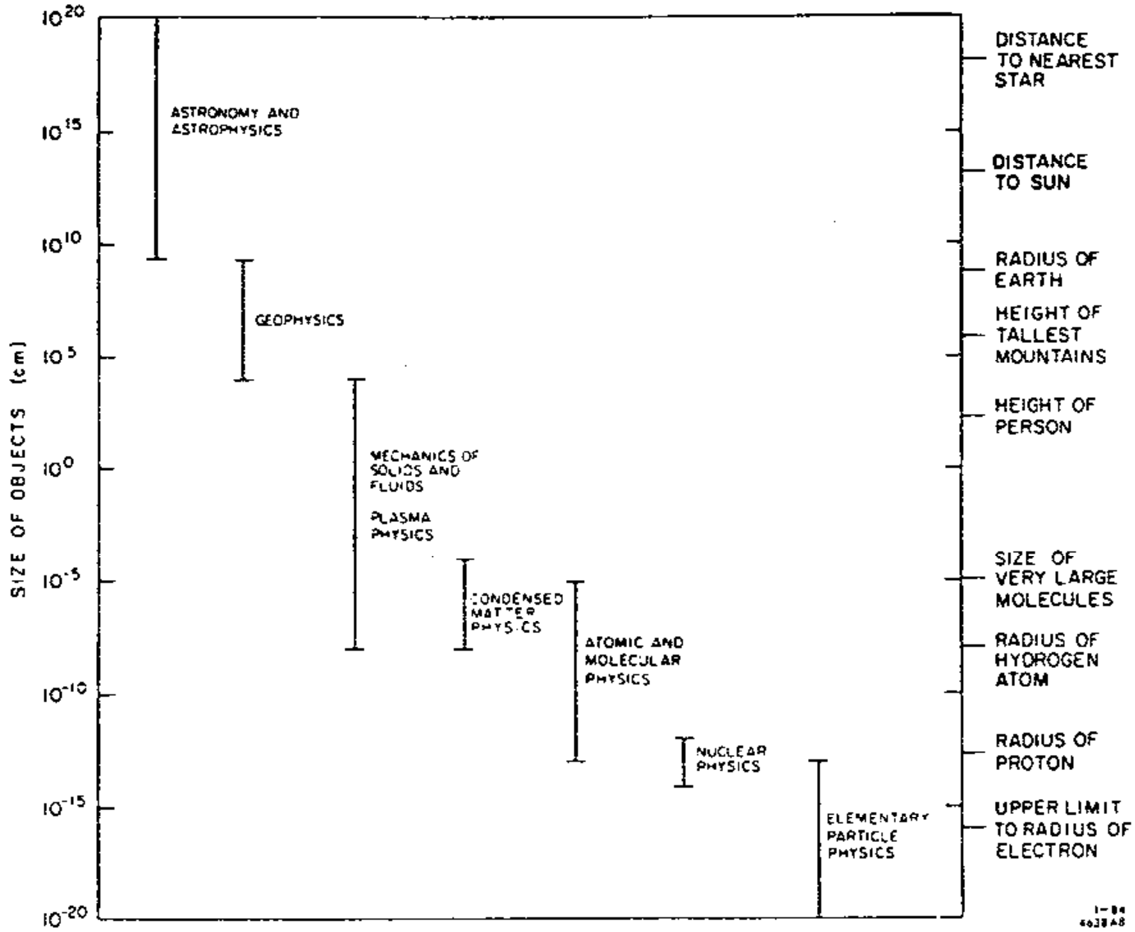
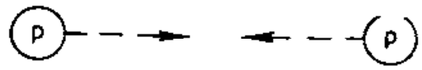

PARTICLE
SIZE AND STRUCTURE
Large Molecule
10⁻⁶ to 10⁻⁷ cm
Each Circle Represents an Atom
Atom
About 10⁻⁸ cm
Electron Moving Around Nucleus
Nucleus
Nucleus
Several ×10⁻¹³ cm
Proton or Neutron
Proton
About 10⁻¹³ cm
Quarks
Quark
Less than 10⁻¹⁶ cm
Electron
Less than 10⁻¹⁶ cm
8-85
5204A1

Fig. 1



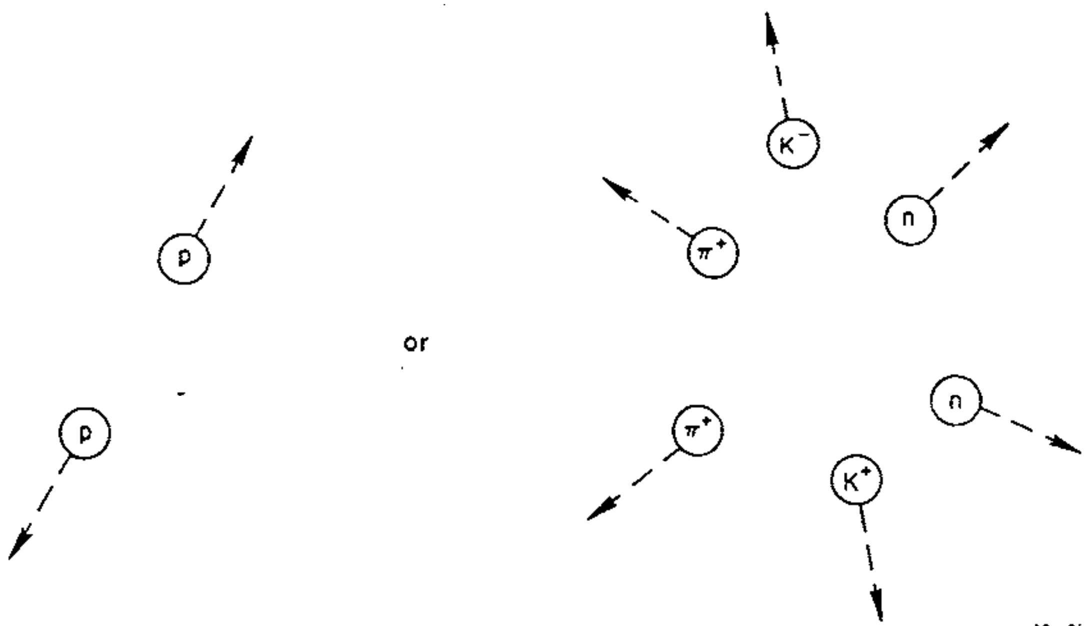
SIZE OF OBJECTS (cm)
10^{20}
10^{15}
10^{10}
10^{5}
10^{0}
10^{-5}
10^{-10}
10^{-15}
10^{-20}
ASTRONOMY AND ASTROPHYSICS
GEOPHYSICS
MECHANICS OF SOLIDS AND FLUIDS
PLASMA PHYSICS
CONDENSED MATTER PHYSICS
ATOMIC AND MOLECULAR PHYSICS
NUCLEAR PHYSICS
ELEMENTARY PARTICLE PHYSICS
DISTANCE TO NEAREST STAR
DISTANCE TO SUN
RADIUS OF EARTH
HEIGHT OF TALLEST MOUNTAINS
HEIGHT OF PERSON
SIZE OF VERY LARGE MOLECULES
RADIUS OF HYDROGEN ATOM
RADIUS OF PROTON
UPPER LIMIT TO RADIUS OF ELECTRON

Fig. 2



(a) Protons about to collide head on.

(b) Concentration of mass and energy just after protons collide.



(c) Two posibilities for what may come out of the collision.

Fig. 3

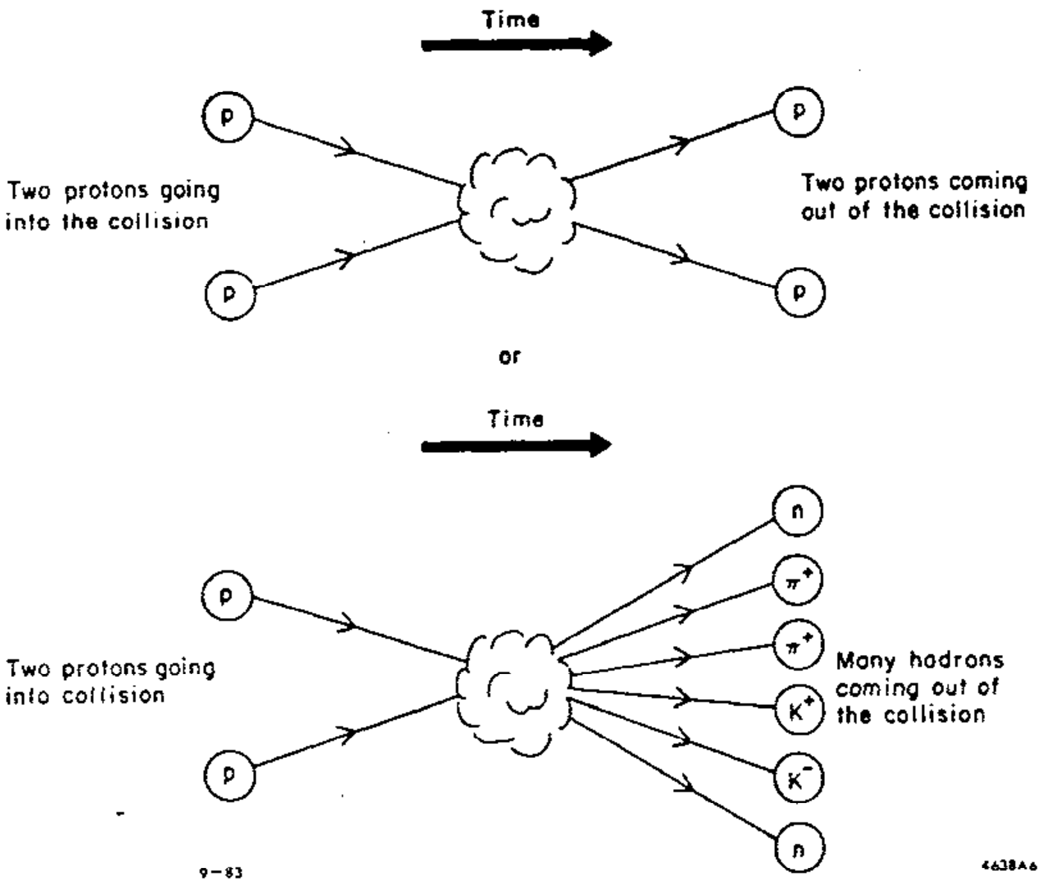

Time
p
p
Two protons going
into the collision
p
p
Two protons coming
out of the collision
or
Time
p
p
Two protons going
into collision
n
π+
π+
K+
K-
n
Many hadrons
coming out of
the collision
9-83
4638A6

Fig. 4

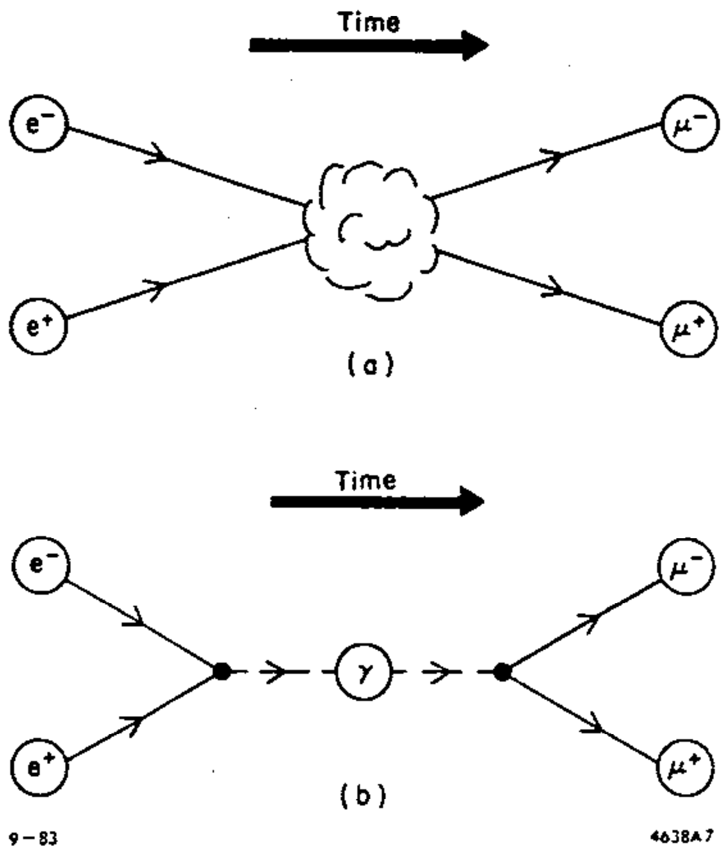
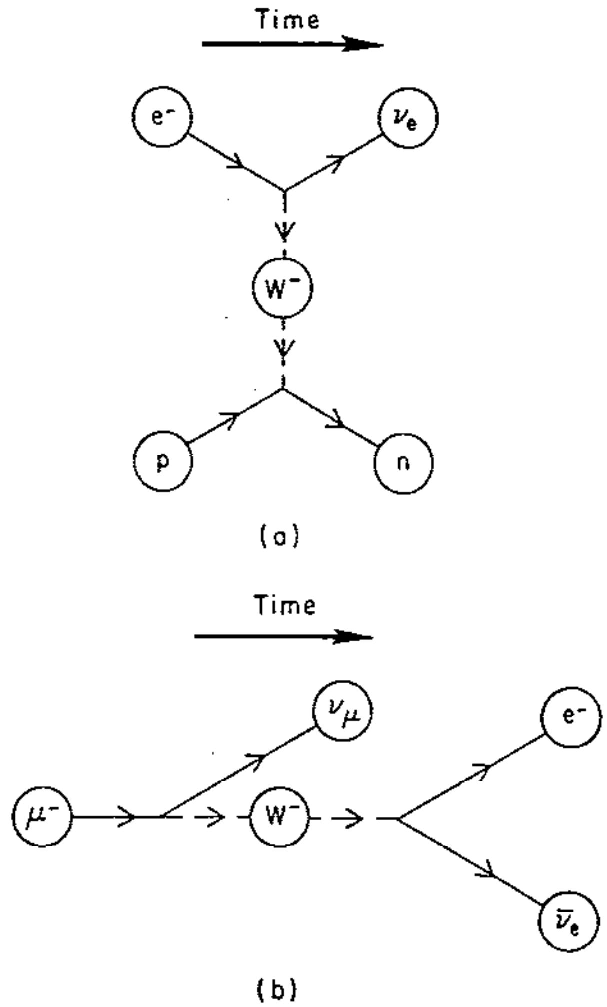


Fig. 5



8-85 5204A6

Fig. 6

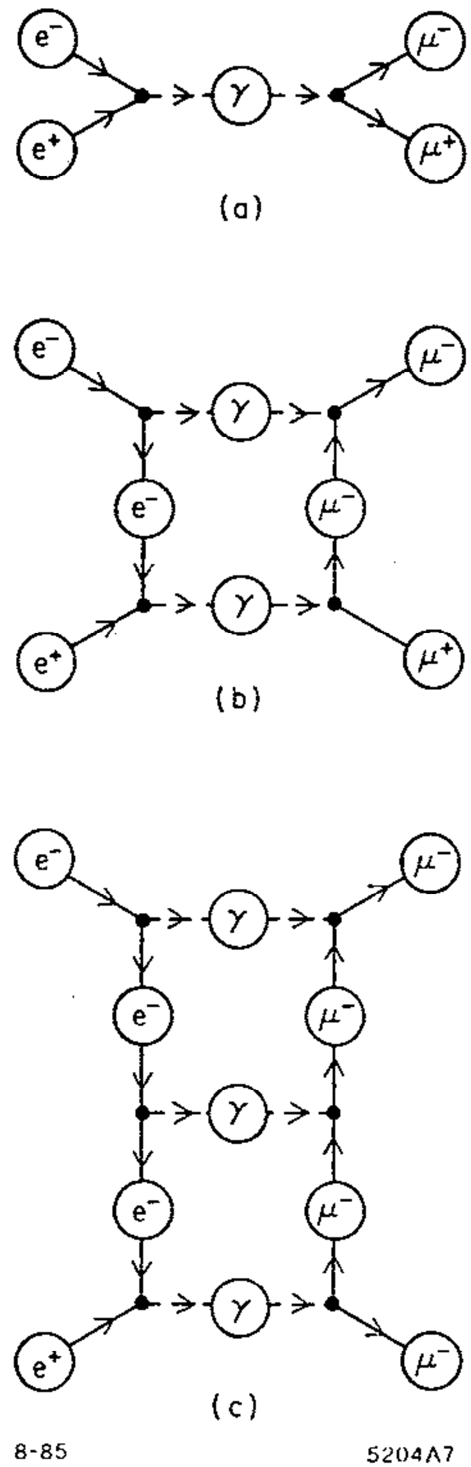


Fig. 7

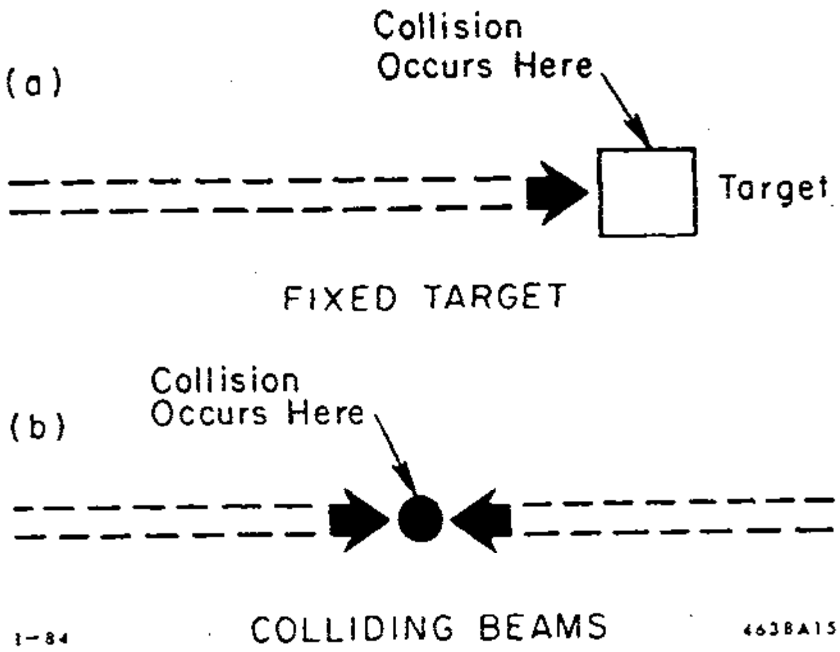

(a)
Collision
Occurs Here
Target
FIXED TARGET
(b)
Collision
Occurs Here
COLLIDING BEAMS
1-84
4638A15

Fig. 8

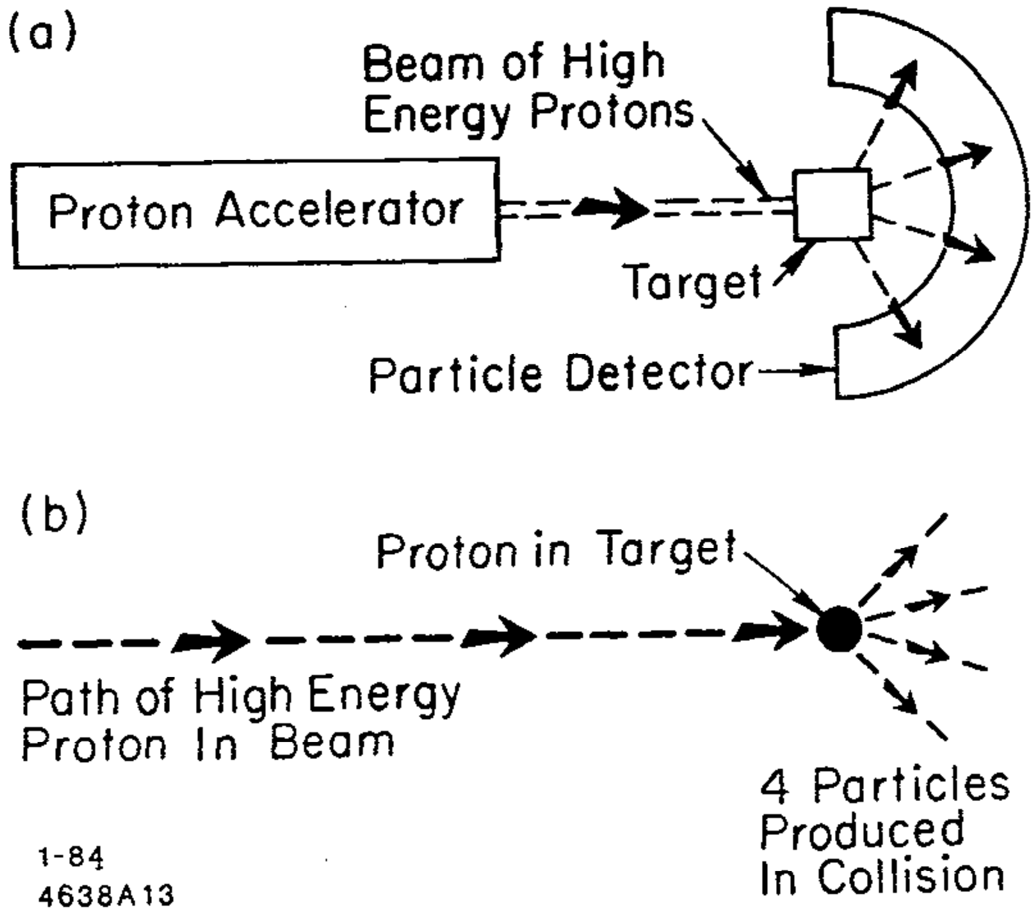

(a)
Beam of High Energy Protons
Proton Accelerator
Target
Particle Detector
(b)
Proton in Target
Path of High Energy Proton In Beam
4 Particles Produced In Collision
1-84
4638A13

Fig. 9

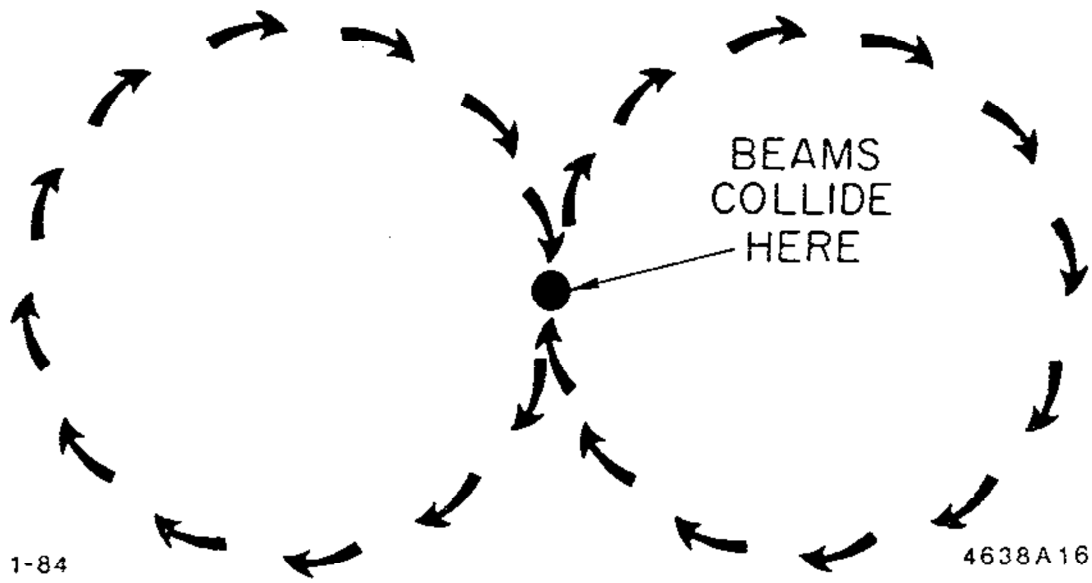


Fig. 10

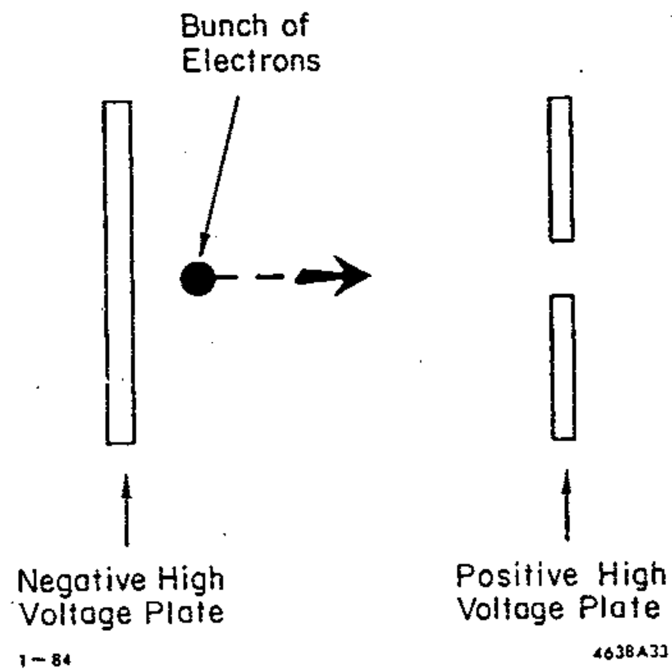
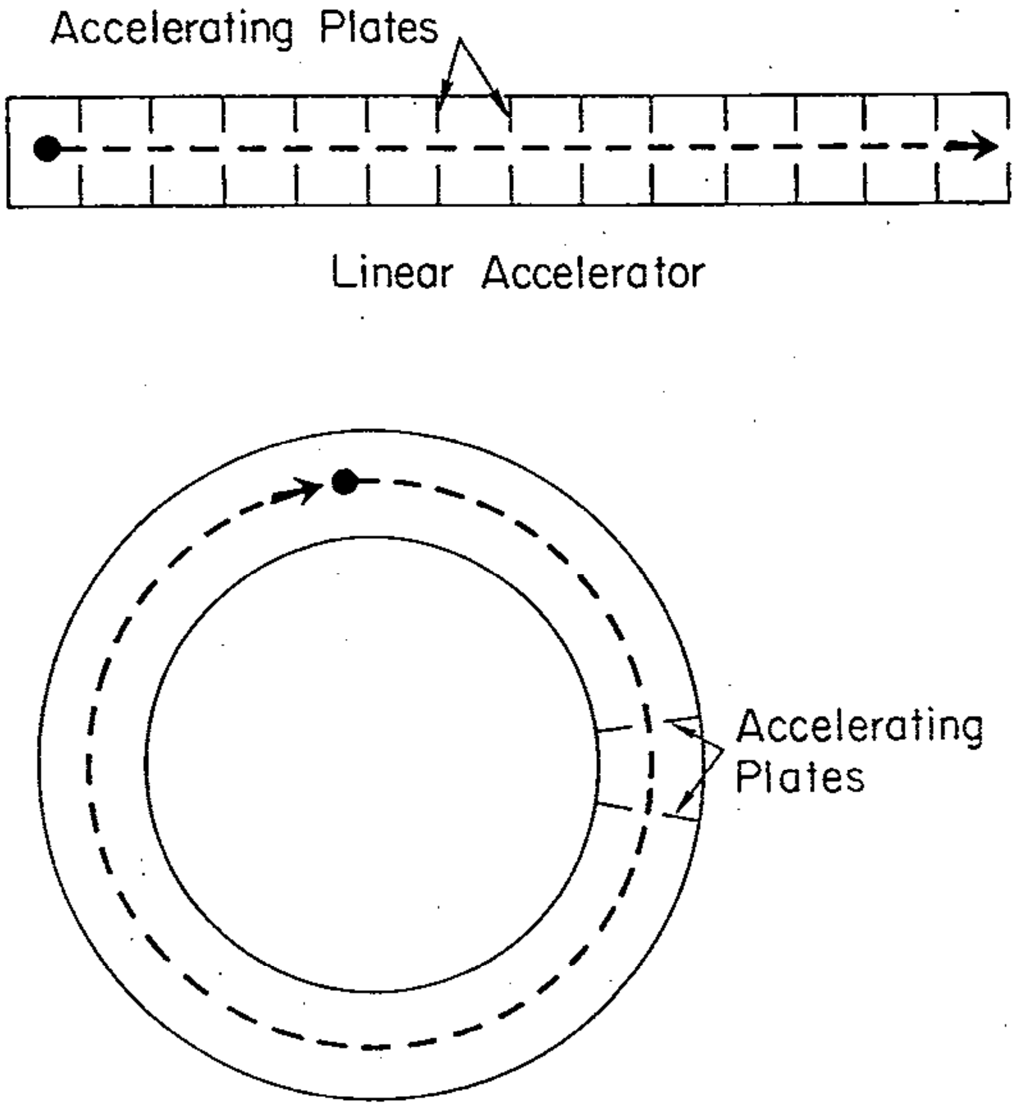
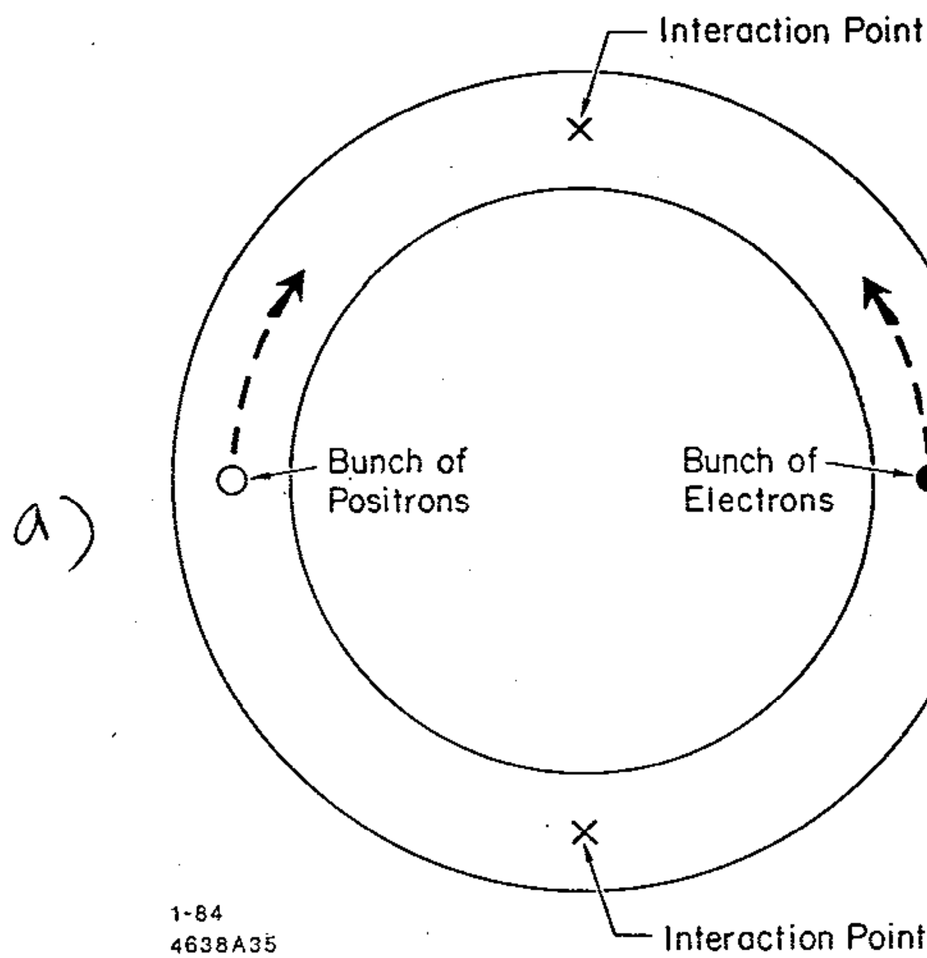

Bunch of
Electrons
Negative High
Voltage Plate
Positive High
Voltage Plate
1-84
4638A33

Fig. 11

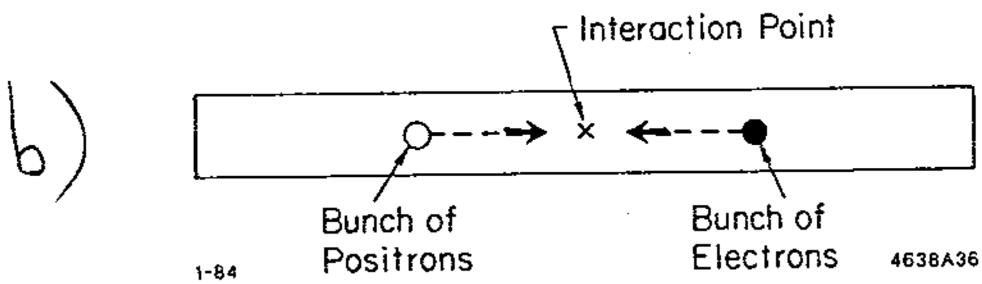


1-84 Circular Accelerator 4638A34

Fig 12



Interaction Point
Bunch of Positrons
Bunch of Electrons
Interaction Point
1-84
4638A35



Interaction Point
Bunch of Positrons
Bunch of Electrons
1-84
4638A36

Fig. 13

MARK II - SLC/PEP

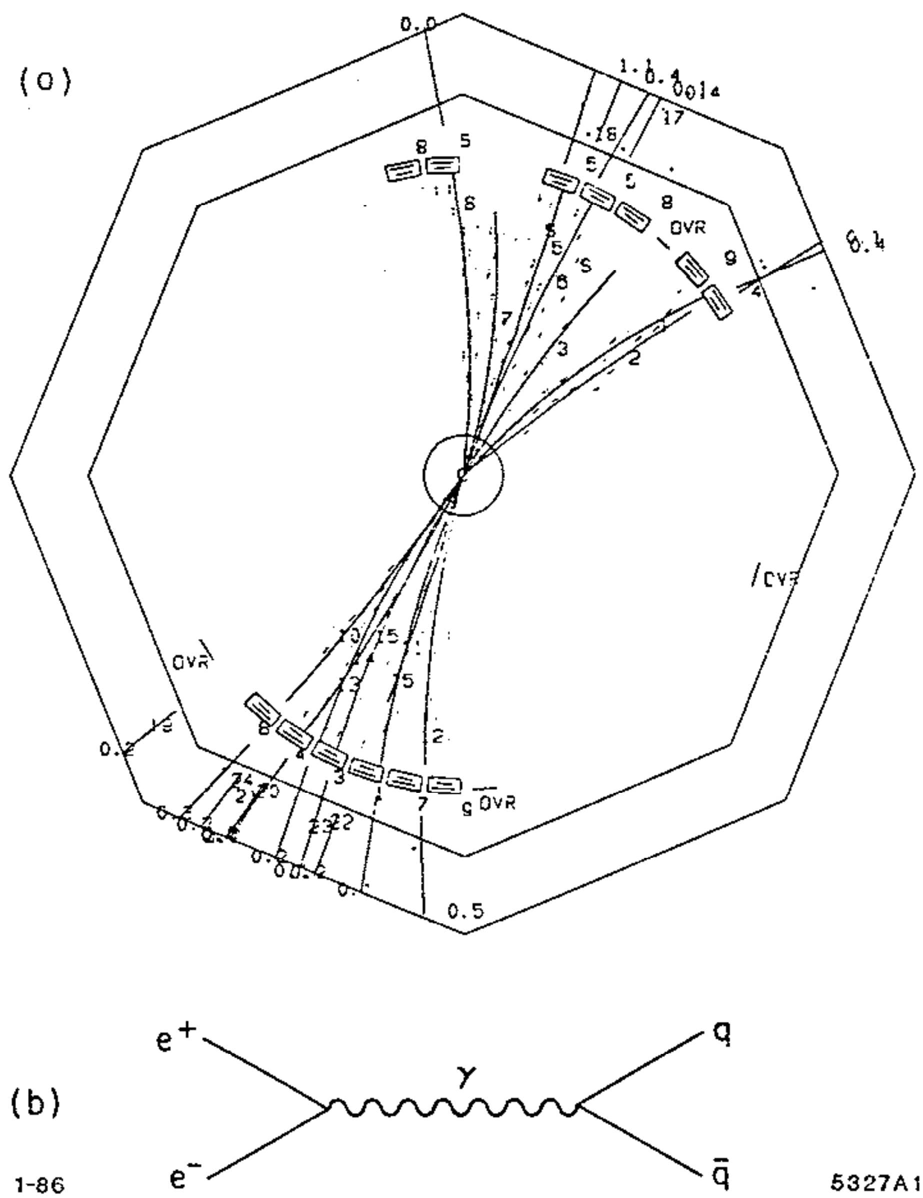
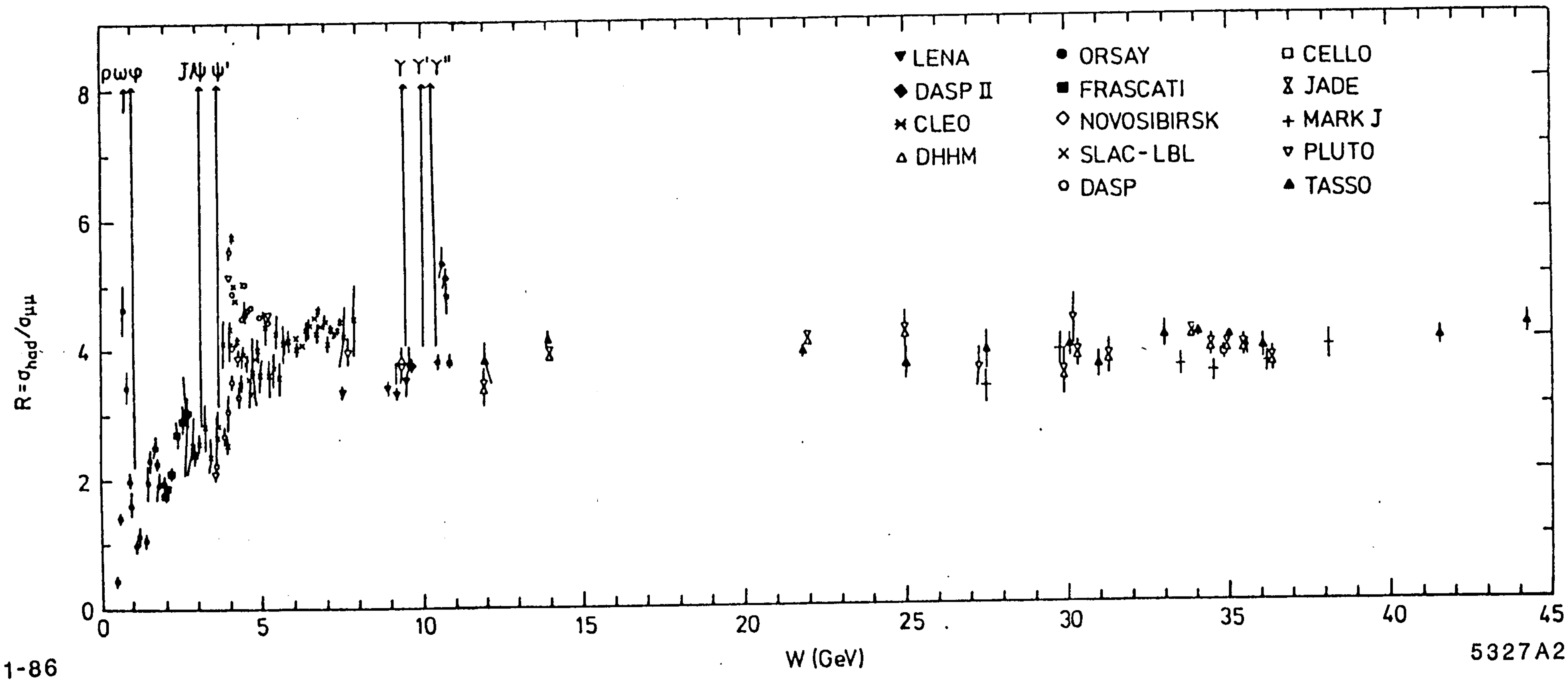
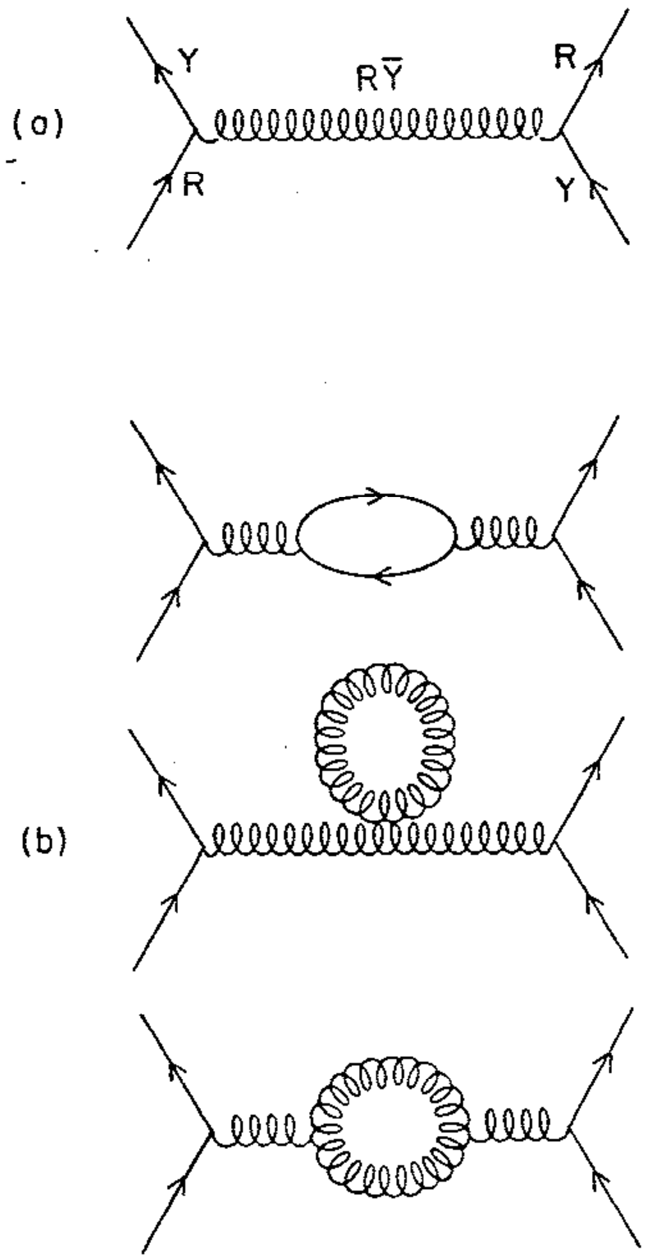


Fig. 14


ρ ω φ
J/ψ ψ'
Υ Υ' Υ''
LENA
DASP II
CLEO
DHHM
ORSAY
FRASCATI
NOVOSIBIRSK
SLAC-LBL
DASP
CELLO
JADE
MARK J
PLUTO
TASSO
R = σhad/σμμ
W (GeV)
1-86
5327A2

15

Fig.



1-86 5327A3

Fig 16

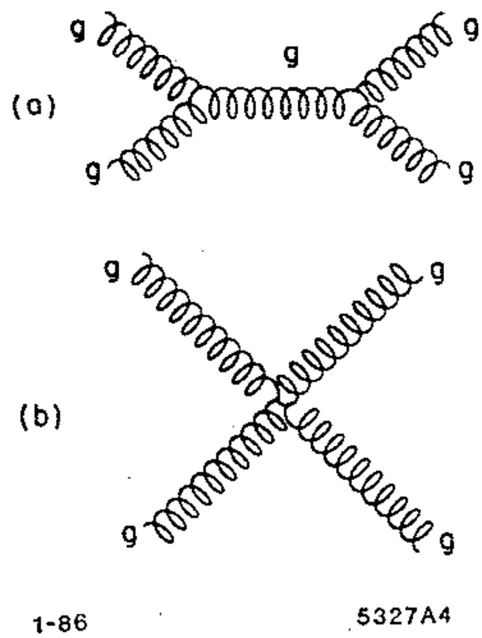


Fig. 17

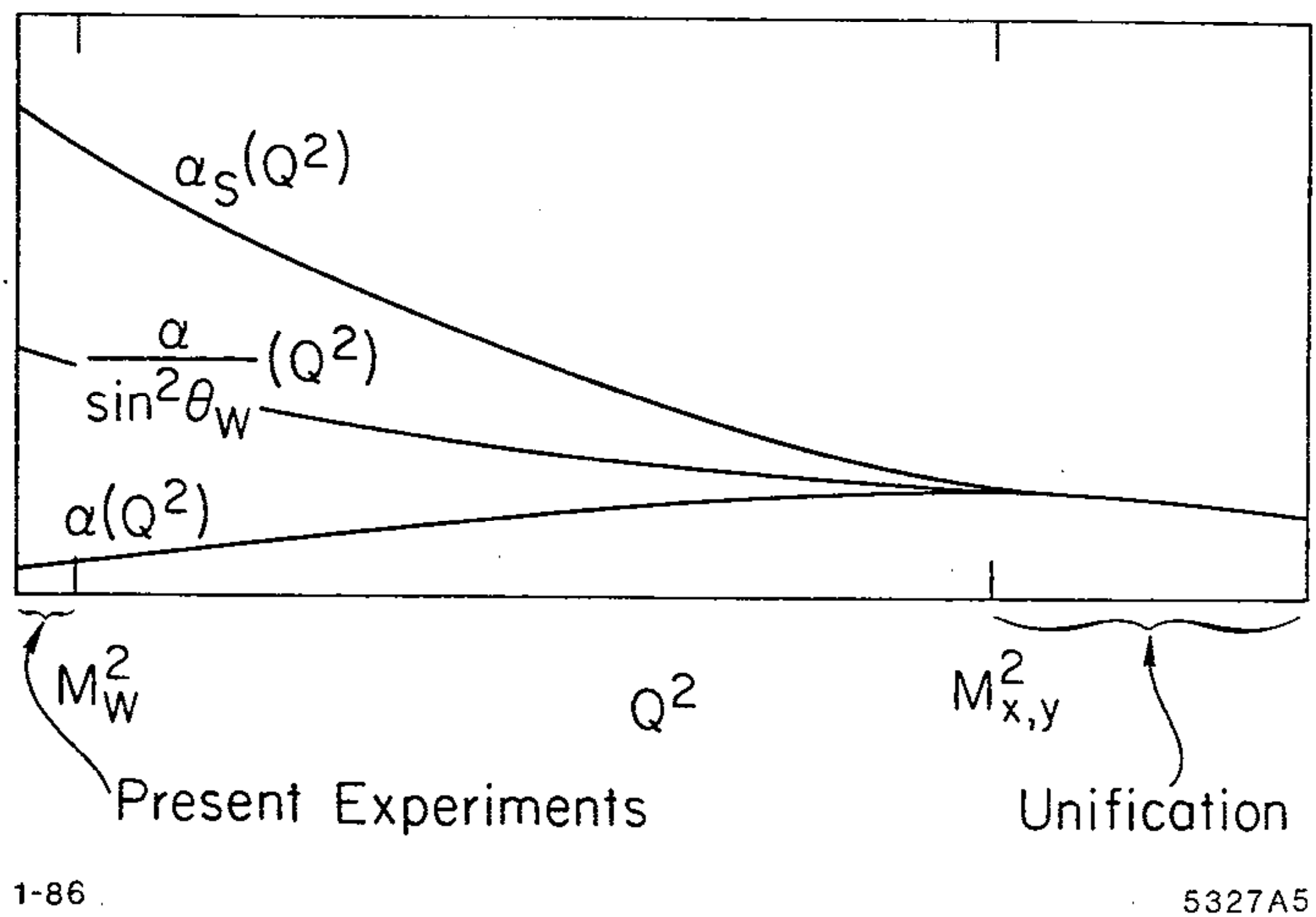

$\alpha_S(Q^2)$
$\frac{\alpha}{\sin^2\theta_W}(Q^2)$
$\alpha(Q^2)$
M_W^2
Q^2
$M_{x,y}^2$
Present Experiments
Unification
1-86
5327A5

Fig. 18

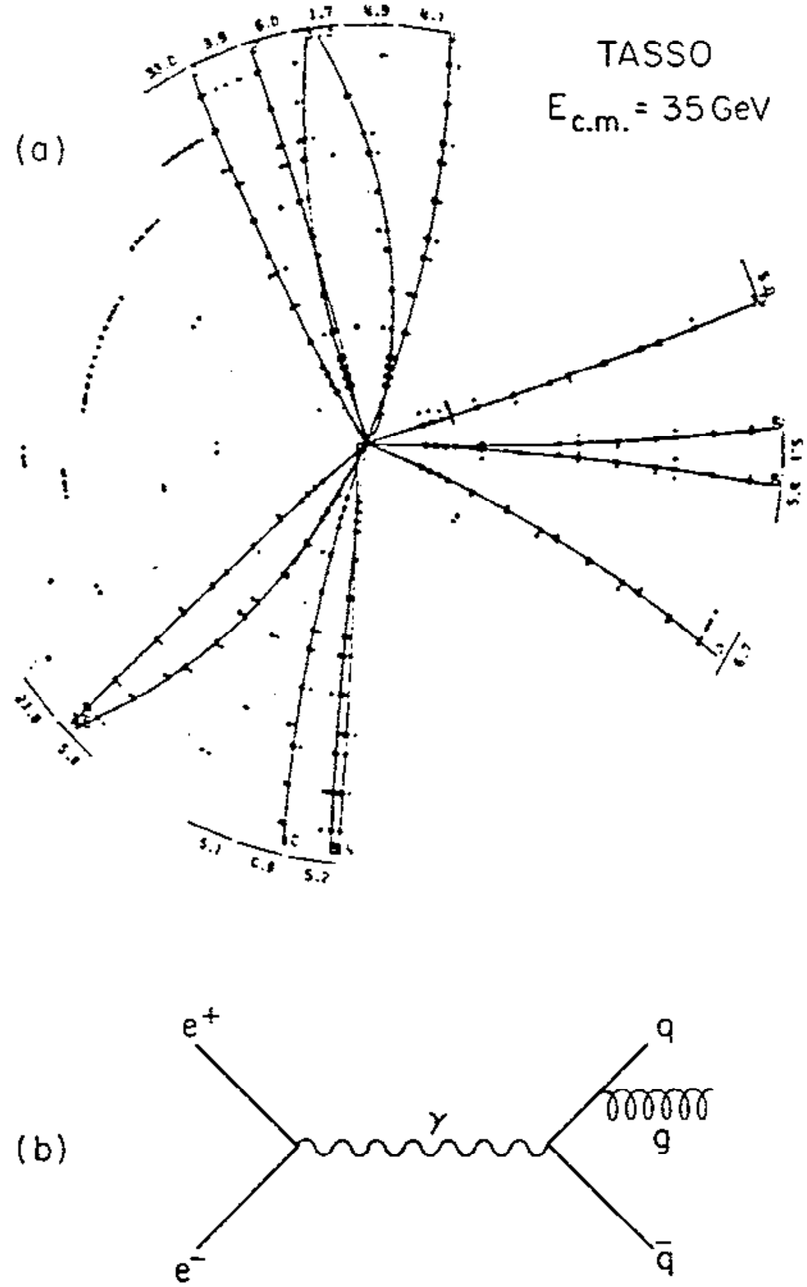


Fig 19

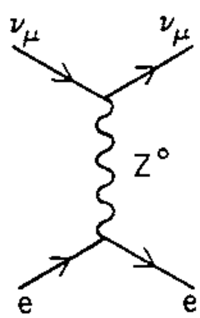


Fig. 20

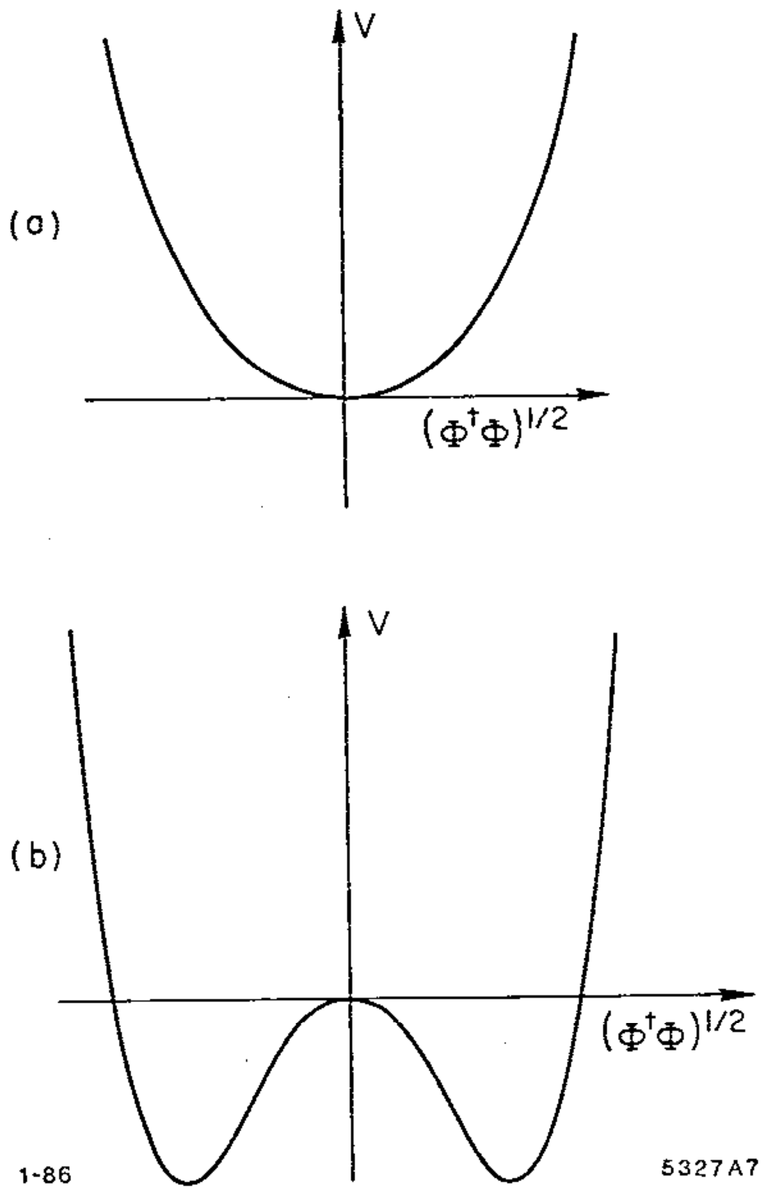


Fig. 21

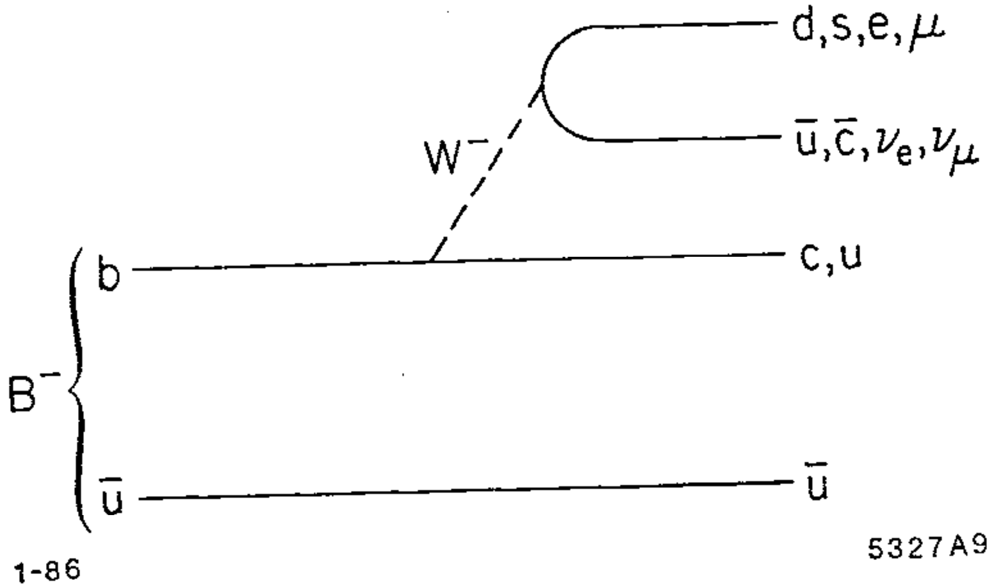
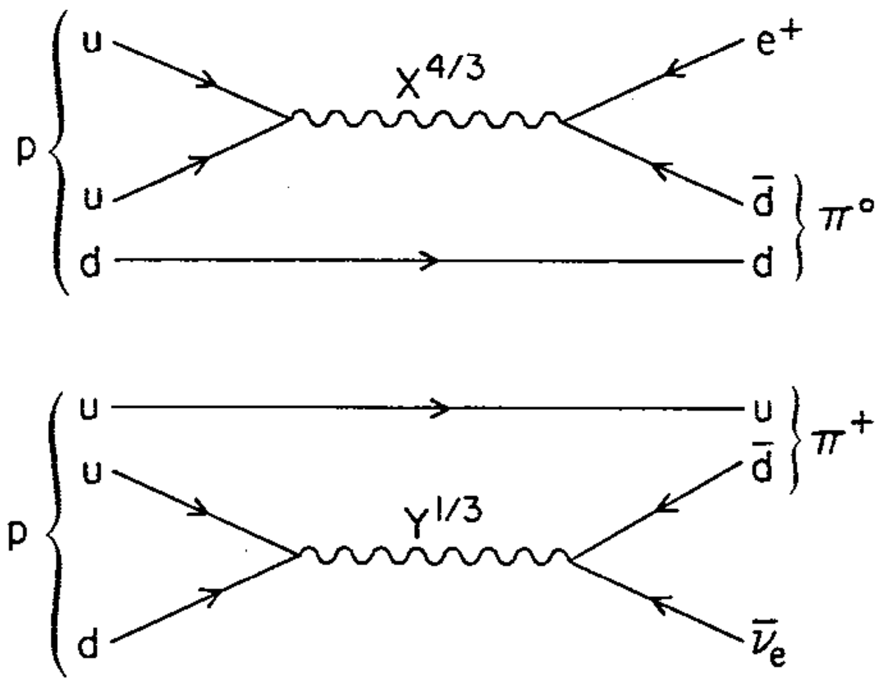


Fig. 22



1-86 5327A10

Fig. 23