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FUNDAMENTAL PARTICLES AND INTERACTIONS — A WALL CHART OF MODERN PHYSICS*

The Fundamental Particles and Interactions Chart Committee

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Enclosed with this issue of *The Physics Teacher* is a copy of a wall chart on "The Standard Model of Fundamental Particles and Interactions." This chart is designed for use in introductory physics courses at either the high school or the college level and will expose students to some of the excitement of very recent physics. In presenting this chart here we seek participants for a broad field test program for the chart and its supporting materials.

I. THE WALL CHART PROJECT

This chart has been produced by the Fundamental Particles and Interactions Chart Committee (FPICC). This committee is an outgrowth of the Conference on Teaching of Modern Physics (CTMP)[1] and resulted from a proposal made by F. Priebe.[2] The Fundamental Particles and Interactions Chart Committee was structured to achieve a balance among individuals directly involved in particle physics and those involved in introductory physics instruction at the high school and undergraduate levels.

The central goal of the FPICC is to produce a wall chart which reflects the major results of the past three decades of high energy particle physics research and which is suitable for use in introductory physics courses. Additional goals include the production of an accompanying explanatory booklet for instructors, and interactive tutorial software for users of the chart. Of equal importance is the goal of bringing about broad use of the chart, with increased exposure of introductory students to the areas of modern physics which the chart addresses.

The wall chart is designed for use in an introductory level course but also could be part of a more specific undergraduate level introduction to modern physics. It is intended for use at both the college and high school level. Display of this chart in the high school classroom is intended to serve as a stimulus and as a challenge to encourage students to explore basic physics further. The use of the "Standard Model of Fundamental Particles and Interactions" chart both in high school and college will provide physics students with a sense of continuity akin to that which chemistry students experience as they begin the study of the "Periodic Table of the Elements" in high school and appreciate it from a higher level of sophistication in their college years.

Many physics instructors are themselves unfamiliar with the terms that appear on the chart, and probably less familiar with the concepts that underlie them. The committee plans a variety of aids for those who feel they lack facility with the chart content:

• The written notes on the chart itself provide some explanations. These will be modified in succeeding versions of the chart based on the feedback we receive.

• The explanatory booklet is intended to be a resource for the instructor; it expands on the content of the chart and provides background information on related topics. The booklet, a key item in the field test process, should provide answers to many of the student questions which the chart is expected to elicit. The first three chapters of this booklet are included as the next section of this article. These chapters introduce some vocabulary and describe the components of the chart. Subsequent chapters will provide further explanation of various technical points as well as discussion of the experimental basis of the Standard Model. The booklet will also contain a bibliography of related reference material which is suitable for non-expert readers.

• Software now being developed will afford interested students the opportunity to acquire knowledge of the chart on an independent basis. The software will incorporate background information from the booklet.

• It is expected that workshops on modern physics arising from the CTMP will incorporate discussion of the chart. Workshops dealing specifically with the introduction of the chart are also proposed. Veterans from the field test phase of the chart project may wish to continue their efforts by participating in the development and production of workshops for colleagues.

To date the project has involved, to varying degrees, approximately two hundred people, ranging from particle physicists at national laboratories to high school students. Preliminary field testing has occurred in the classrooms of committee

members. We now seek further input from the broad community of physics teachers. We encourage interested teachers and professors to participate in the field test and to use this chart. After field test results are incorporated, a final version of the chart (in a sturdier format) and its supporting materials will be produced and will be available for classroom use.

II. BOOKLET EXCERPT

The following three sections are the first three chapters of the booklet which explains the chart.

1. Introduction

People have long asked "What is the world made of?" and "What holds it together?" Particle physics seeks to answer these questions. Over the past ten years a clear consensus has evolved in the field. Down to the smallest scales studied experimentally, these questions are answered by a theory which particle physicists call "the Standard Model." The purpose of this chart and the accompanying booklet is to summarize this theory in a form that can be presented to beginning students of physics.

The Standard Model is a well-established theory which represents tremendous progress in our understanding of the fundamental structure of matter. It is as basic to physics as the periodic table is to chemistry. It explains hundreds of subatomic particles and their properties by postulating a half dozen basic constituents called quarks and another six called leptons from which all matter is made. It is the product of many years of research. We believe it is a sufficiently mature and important theory that it should now be included in a introductory general physics course.

By the time most students reach a physics class they can answer the two questions ("What is it made of?" and "What holds it together?") at the level of atoms, that is down to a scale of about $10^{-10}m$. They know the atom has a positively charged nucleus surrounded by electrons which are held in place by their electrical interaction with the nucleus. They probably know that the nucleus is made of protons and neutrons. For the most part they have not yet asked

the other question: "What holds the nucleus together?" As soon as the physics student learns that like electrical charges repel one another, this question should become compelling; there must be some attractive force stronger than the electrical repulsion between the protons. It soon becomes clear that gravity is too weak. To answer this question, another interaction must be invoked. It is called the strong interaction. It acts between protons and neutrons, binding them into nuclei.

There is one more nuclear phenomenon which needs an explanation. In radioactive transitions a nucleus goes from one state to another, in the process emitting some type of radiation. The earliest experiments on radioactivity identified three different types of radiation, called α, β and γ rays. We now know that the α ray is actually a helium nucleus emitted in a spontaneous nuclear fission, a strong interaction process. The γ ray is an energetic photon emitted in a transition mediated by an electrical interaction. However the β ray cannot be explained either by strong or electrical interactions. It is an energetic electron which comes from a transition in which a neutron decays into a proton, emitting the energetic electron and, as later realized, an antineutrino. To explain this process requires yet another type of interaction. It occurs relatively slowly compared to the emission of comparable energy γ rays in electrical interactions. We call this a weak interaction, since the slow rate of the process indicates it must be due to an interaction that is weaker than the electromagnetic one.

These three interactions—strong, electromagnetic and weak—are now described by a theory called "the Standard Model" (or more technically $SU(3) \times SU(2) \times U(1)$), which satisfactorily describes all observed particle processes. It explains the structure of matter and the interactions responsible for all processes, down to a scale even finer than that of protons and neutrons, which in this theory are themselves composite objects made up of constituents called quarks.

The purpose of the wall chart and of this booklet is to describe the world in the language of this theory. Throughout this booklet whenever a statement of fact is made—such as "Electric charge is conserved"—we mean that this is true in the

Standard Model and is consistent with all experimental data at present. However the Standard Model has not answered all questions. There are many features of the data which are not explained but rather are given simply by a choice of parameters in the Standard Model. For example, a particle called the top quark has yet to be observed and the theory cannot predict what mass it should have, nor can it explain the values of any of the other quark and lepton masses. There are many deeper questions, including the possible unification of all interactions, which the Standard Model does not address. Particle physics research today seeks theories which go "beyond the Standard Model" in somewhat the same way as Einstein's theory of general relativity goes beyond Newton's theory of gravity. Because the Standard Model correctly describes so many data it will surely be a part of whatever further understanding we reach.

$SU(3) \times SU(2) \times U(1)$, the technical name of the Standard Model, denotes the parts of the theory in a mathematical language called group theory. In this booklet, we will not deal with more than the most obvious parts of the meaning of this language. However, in teaching this material it is important to stress that everything in this chart and booklet is based on an extensive mathematical structure which allows physicists not just to name and describe particles but also to predict which particles can exist and which cannot, to calculate the rates of a variety of processes, and to make quantitative predictions about the outcome of experiments. The mathematics of such calculations are well beyond the knowledge of a beginning physics student. However the student should understand that the names and descriptions are but a small part of any physical theory. In presenting this material one should stress concepts and processes rather than memorization of lists of particle names and masses. The beauty of the Standard Model lies in the fact that hundreds of particles and processes can be explained on the basis of a few types of quarks and leptons and their interactions.

One should also stress the experimental basis of particle physics. Students are familiar with the need for a microscope to see small objects. The accelerators which are the basic tools of particle physics experiments are effectively gigantic microscopes. There is an inverse relationship between the energy reached by particles in the accelerator and the sizes of objects that they can probe. This is the fundamental reason why progress in this field requires the construction of yet higher energy accelerators. At this time physicists are proposing to construct the Superconducting Super Collider (SSC) to seek answers to some of the fundamental unanswered questions. Further details on accelerators and experiments will be discussed later in this booklet.[3]

Another point to make clear is the importance of interactions as well as constituents in describing matter. The interactions explain the rules for combining the fundamental objects to make observable particles. Further, they explain the structure of the composite objects. Nothing is static; at every level we find the constituents of matter are constantly in motion. We then must explain why some objects are stable while others decay very rapidly. All of the conservation laws of physics are built into the Standard Model. It is these laws, along with the dynamics of the interactions, that explain particle lifetimes and decay patterns. In Chapter 4 of this booklet[3] we discuss a few processes to illustrate the application of the Standard Model to such questions.

2. Overview

The terminology of particle physics contains many words that are new to the student and others that have technical meanings which differ from their everyday usage. This chapter introduces some of the terminology of particle physics. In this chapter and the following one, bold face type is used to denote technical terms that are explained more fully elsewhere in this booklet.

2.1. Physics and Philology

The tendency to evolve a physics meaning for a word that is different from the everyday one is not new. Consider "force" and "work" in elementary physics: the physics meaning is related to the everyday one but is much more specialized. In the Standard Model the tendency is carried a step further. The words **"color"** and **"flavor"** have technical meanings that have nothing to do with their everyday meanings. These names were chosen to convey the idea that quarks come with a variety of properties, but those properties are not color and flavor in the usual sense. This tendency to redefine words probably happens because it is very difficult to invent a new word for a new concept without finishing up with something that sounds silly. However, there are also many entirely new words in the particle physics vocabulary which we will explain here. There is no fixed rule about how to name a new particle or a new concept. It is usually considered to be the privilege of the discoverer to choose the name for something entirely new. Once patterns have been recognized, the naming system tries to incorporate the pattern, and some standard usage evolves.

2.2. Forces and Interactions

Every force in nature (in the sense of $F = ma$) is due to one of the fundamental interactions. For example, the force of friction between two surfaces is due to electrical interactions between the electrons and atoms in the surfaces. The usage of the words "force" and "interaction" sometimes smears the distinction; one speaks of "the force of gravity" or "the strong force", meaning "a force due to the gravitational interaction" or "a force due to the strong interaction." The fundamental interactions described by the Standard Model include strong, electromagnetic and weak. Gravity is the fourth type of fundamental interaction but is not part of the Standard Model. (Occasionally claims have been made of a need for a "fifth force" to explain certain data. There is as yet no well established experimental evidence that requires more than the four interaction types.)

In the Standard Model a particle experiences an interaction if and only if it carries a charge associated with that interaction. Electric charges for all particles are given on the chart. Weak charges which are associated with quark and lepton **flavors** are explained later. The charges of the strong interaction are called **color charges** (or sometimes just colors) and are carried by **quarks** and by **gluons**. Particles which are composites do feel some residual effects of an interaction for which their constituents carry a charge, even though overall the composite may be neutral.

The Standard Model contains three parts, denoted in the technical name as a product: $SU(3) \times SU(2) \times U(1)$. The first factor represents the strong interactions. The three in $SU(3)$ is the number of different color charges for the quarks. The weak and electromagnetic interactions are described by the second two factors, $SU(2) \times U(1)$. The theory is called a unified electroweak theory because these two factors cannot be separated into one for weak and one for electromagnetic; rather, both contain parts of each interaction.

2.3. Particle Types

Spin – Bosons and Fermions.

The first major distinction in particle types is the separation of all particles into two classes - **fermions** and **bosons**. Those names honor two famous physicists: Enrico Fermi and S. N. Bose. Particles carry an intrinsic angular momentum, known as **spin**. Spin must be included in accounting for the conservation of angular momentum in particle processes. The quantum unit of angular momentum is

$$\hbar = h/2\pi = 6.58 \times 10^{-25} GeV s = 1.05 \times 10^{-34} Js.$$

It denotes the smallest possible unit of angular momentum in the usual situation of one point mass rotating around another. Remarkably it has been found that some particles carry half units of $\hbar$ as their intrinsic angular momentum. Any particle with a spin that is an odd number of half units of $\hbar$ is a fermion. Any particle with an integer number of units of $\hbar$ is a boson. The major difference between the properties of fermions and bosons is that fermions obey the **Pauli Exclusion Principle**, whereas bosons do not. The exclusion principle states that two fermions cannot occupy the same state at the same time. The most familiar example of the application of this principle is to the electron levels in an atom. It is the exclusion principle which strictly limits the possible number of electrons in each subshell.

Classes of Fermions

- Leptons and Quarks

The fundamental fermions are **leptons** and **quarks**. All matter is made from these particles. The electron is the most familiar example of a lepton. Leptons have no color charge, which means they have no strong interactions. They are particles that can be observed in isolation. Quarks have **color charge**. All color charged particles are **confined** by the strong interaction. This means they can be observed only in those combinations that are color neutral. These composite particles are called **hadrons**. Hadrons may be either fermionic, made from three quarks and called **baryons**, or bosonic, made from a quark and an **antiquark** and called **mesons**. All hadrons have **residual** strong interactions due to their quark constituents.

- Baryons

Protons and neutrons are the most familiar baryons. All hadrons consisting of three quarks have half integer spin and are called **baryons**; for example, the proton has the quark content *uud*. These are color-charge neutral combinations made from one quark of each of the three possible quark color charges. This rule is part of the mathematics called the algebra of $SU(3)$, *it cannot be explained in terms of ordinary arithmetic.* Baryons can have spin 1/2, 3/2,....

- Antiparticles

For every fermion that exists in the Standard Model there also exists another fermion which is its antiparticle. The antiparticle has an identical mass to the corresponding particle but the opposite value for all charges (color, flavor and electric). The antiparticle is usually denoted by writing a bar over the name of the particle, thus u denotes an up quark with electric charge 2/3 and $\overline{u}$ denotes an anti-up quark with charge -2/3. For charged leptons the antiparticles are simply written by noting the positive charge, thus the antiparticle of the electron (e^-) is written e^+ and called the positron. The antiparticle of the μ^- (muon or mu minus) is the μ^+ (mu plus) and the antiparticle of the τ^- (tau or tau minus) is the τ^+ (tau plus). For every baryon made of three quarks there is an antibaryon made of the corresponding three antiquarks.

Classes of Bosons

- Force Carriers

The fundamental bosons are the carriers of the fundamental interactions. The **photon** is the quantum of the electromagnetic field or the carrier of electrical interactions. The **W and Z bosons** play this same role for weak interactions. The quanta of the strong interactions are called **gluons**. All of these particles have spin 1.

The quantum of the electromagnetic field, the photon, has zero electric charge; in contrast, the gluons do carry strong interaction color charges. This important difference between strong and electromagnetic interactions is responsible for the property that color charged objects are **confined**. There are eight possible types of color charge for gluons. Gluons exist only inside composite hadrons where they provide the "glue" that holds the composite together. Most hadrons are known to be composites of quarks and gluons. In principle, in the Standard Model there can also be some particles made only from gluons. As yet there is no clear experimental evidence for such objects.

Bosons also have antiparticles of equal mass but opposite charge. Thus the W^- boson is the antiparticle of the W^+. In the special case of bosons with zero value for all charges, the particle and the antiparticle are the same object—this is true for the photon and the Z boson. Similarly there is no real distinction between gluons and antigluons; for each of the eight gluons there is some gluon among the eight that is its antiparticle.

- Mesons

Hadrons consisting of a quark and an antiquark (for example, π^+ which is $u\bar{d}$) are called **mesons**. Mesons can have any integer spin and thus they are bosons. The color charges of the quark and antiquark must be combined to a color-neutral state. The antiparticle of a meson has the roles of quark and antiquark reversed. Thus the antiparticle of the π^+ is a π^- which is $\bar{u}d$.

The following table summarizes the various particle types.

	Fermion	**Boson**
Fundamental (as far as we now know)	q = quark ℓ = lepton	g = gluon γ = photon W Z
Composite (hadron)	qqq = baryon	$q\bar{q}$ = meson

3. The Components of the Chart.

This chapter briefly explains all the tables and figures that appear on the chart.

3.1. Layout of the Chart

The chart is arranged with **fermions** on the left and **bosons** on the right. Information about the **interactions** is given in the central part of the chart. Colored backgrounds are used to emphasize related areas. For example, the top central

figure shows the area of the electron cloud in yellow. This color is used as a background for all those parts of the tables that relate to **electroweak** interactions and for the figures depicting electroweak processes. In the fermion tables there are three colors of background to delineate the three **generations** of **quarks** and **leptons**. Encourage your students to try to understand the significance of all the color coding on this chart.

3.2. The Diagram of Structure Within an Atom

If this figure were drawn to the scale given by the nucleons, then the electrons and quarks would be smaller than 0.1 mm and the entire atom would be about 10 km across.

The purpose of this figure is to try to introduce the idea of the extremely small scales that particle physics now studies. Electron and quark sizes are labelled as $\leq 10^{-18}m$ because that size is the present limit of our ability to distinguish structure. So far there is no evidence of any size or structure for these particles.

Students are familiar with the description of an atom as a nucleus surrounded by electrons. They probably also know that the nucleus consists of protons and neutrons. The new feature of this picture is the structure within the neutrons and protons; they are made of quarks. From this starting point one can relate this figure to the rest of the chart.

It should be stressed that this figure is a diagrammatic representation of the atom, *not* a picture. One cannot draw a sensible picture of the atom. Apart from the problem of scales, there is the problem that the atom is a quantum mechanical system—the proper description of such a system is in terms of a probability distribution which, for example, gives the likelihood that an electron would be found at a certain distance from the center of the atom if one were able to make an instantaneous measurement. Such a system is always in motion. The constituents at every level are moving around each other. Students are aware of the electrons' mobility;

it is important to stress that a similar description also applies to the nucleons and to the quarks within them.

3.3. Fermion Tables

The table of fundamental fermions on the upper left of the chart is divided into two groups—**leptons** and **quarks**. The basis of this separation is that quarks have **color charges** and hence experience strong interactions whereas leptons do not. Each of the tables is further subdivided by background colors into three sets called **"generations"** by physicists. Notice that each generation contains two leptons with electric charges 0 and −1, and two quarks, charges 2/3 and −1/3. The only difference between the generations is in the masses which increase as one moves to the right across the chart. This chart assumes that the top quark exists, which is strongly suggested by a variety of indirect experimental evidence but not yet directly confirmed. Each fermion has a corresponding **antiparticle** that has the same mass and spin but the opposite value for all other quantum members, such as electric charge, flavor, etc. All the hadrons observed so far are composites of quarks and antiquarks of the five known flavors. The repeating pattern of the generations and the pattern (or lack of it) of the masses of quarks and leptons is completely unexplained by the Standard Model. Mysteries such as these lead physicists to seek further theories which must encompass the Standard Model, but which can in some way go beyond it. As far as the Standard Model is concerned a single generation of quarks and leptons would be quite satisfactory. All stable matter is made from particles in the first generation. The muon, discovered in 1936, was the first particle of the second generation. It is said that the physicist, I. I. Rabi, asked "Who ordered that?" when he heard of it.[4] Today we still are trying to answer his question! Related questions are: How many more generations exist? Are there further leptons and quarks which are simply too heavy to have been produced in any experiment to date? The answers await further research.

- Leptons

Leptons are distinguished from quarks by the fact that they do not have color charge and thus do not experience strong interactions. This means that they can be isolated for observation. Except for the electron, charged leptons can decay by the weak interactions and therefore are unstable. The electron is the lightest electrically charged particle. There are no lighter charged particles into which it could decay. Since electric charge is conserved, the electron is stable.

Neutrinos are leptons that have zero electric charge. Hence they do not participate in strong or electromagnetic but only in weak (and gravitational) interactions. It is possible that neutrinos have zero mass. All we know from measurements to date is that their masses are not bigger than the values shown in the chart; they could be much smaller or even exactly zero.

There appears to be another conservation law which is obeyed in the decays of leptons. Each generation of leptons has distinct "flavor"—called electron type, muon type, etc. Each lepton flavor type is conserved. In other words, lepton flavor does not change when a Z boson or a photon is emitted or absorbed. For leptons, W-boson emission always involves a transition between a charged lepton and its own neutrino type. Thus when a muon decays to an electron it must also produce a muon-type neutrino and an anti-electron-type neutrino to maintain lepton flavor conservation.

	Before		After				
process	μ^-	$\longrightarrow$	ν_μ		e^-		$\overline{\nu}_e$
electric charge	−1	=	0	+	(−1)	+	0
muon flavor	1	=	1	+	0	+	0
electron flavor	0	=	0	+	1	+	(−1)

- Quarks

Since the 1930s approximately 200 strongly interacting particles (hadrons) have been observed and named. Various characteristics such as mass, electric charge, and angular momentum (spin) have been studied for each particle. Unsatisfied with merely counting each new species and memorizing long lists, physicists tried to find patterns in the information. In 1964 Murray Gell-Mann and George Zweig[5] suggested that hadrons might be composed of quarks. He could explain all hadrons then known with only three flavors of quarks. ("Quark" was a whimsical name taken by Gell-Mann from "three quarks for Muster Mark" in James Joyce's novel, Finnegan's Wake.) The up (u) and down (d) quarks are the constituents of all common, stable matter—that is, protons (uud) and neutrons (udd). The third quark was called strange (s). That name was already associated with the K-mesons, which contain an s- or an $\bar{s}$-quark, because when K-mesons were first discovered, their long lifetimes seemed a "strange" or unexpected property. A fourth "flavor" of quark, charm (c), was discovered in the Ψ or J particle in 1974 at the Stanford Linear Accelerator Center[6] and at Brookhaven National Laboratory.[7] The bottom quark, in a $b\bar{b}$ combination called upsilon (Υ), was first observed at Fermi National Laboratory in 1977.[8] A sixth quark, top (t), has been predicted by the theories, but particles containing this quark have not yet been observed (as of September 1988).

Quarks have non-zero color charge and hence, like gluons, they are confined objects. Each flavor type of quark comes with any of three possible color charges. The word "flavor" is used somewhat differently for quarks than for leptons. For leptons there is one flavor for each generation; for quarks each distinct mass is called a separate flavor so that the three generations give six flavors. Quark flavor is never altered in strong or electromagnetic interactions or in the neutral weak (Z boson) processes. However when a quark emits a W boson, it must change its electric charge and hence also its flavor. The predominant weak processes involve transitions between quarks shown paired on the table, that is those in the same generation, but rarer transitions occur between any $+2/3$ and any $-1/3$ charged quarks.

- Fermion Masses

The tables show masses for the charged leptons which are experimentally well measured. (All masses are here given to only a few significant figures and experimental uncertainties are not indicated.) For the neutrinos all that can be given is an experimental upper limit on the mass of each neutrino type. This means that it is possible that the neutrinos are all zero mass particles, or they could have any mass smaller than the stated limit. The Standard Model makes no prediction on this matter. There are some extensions of the standard model known as **Grand Unified Theories.** In some of these theories neutrinos have exactly zero mass, while in others they have very small masses. We do not yet know which type of theory is correct.

For quarks the columns are labelled "approximate mass." Because a quark cannot be isolated, it is very difficult to determine its mass or even to fully define what is meant by quark mass. This is especially true for the lightest generation since most of the mass of protons and neutrons does not come from quark masses but rather from the strong interaction binding. We can use the mass difference between a particle containing a heavy quark and a similar particle with that quark replaced by an up or a down quark to estimate the mass differences between the quarks. This gives an accurate estimate of heavy quark masses.

For the top quark we can only give a lower limit on its mass since it has not yet been observed. If it were lighter than this limit, particles containing top quarks would already have been produced in experiments.

3.4. Boson Table

The table on the upper right of the chart shows the fundamental bosons of the Standard Model. These are labelled "force carriers." This is an important concept to convey. Each of these particles is the **quantum** of the corresponding interaction just as the photon is the quantum of the electromagnetic field.

The masses of the W and Z boson are determined experimentally. For the photon an exactly zero mass is a consequence of a symmetry of the theory and is related to the exact conservation of electric charge. Experimentally this mass is known to be very tiny, less than $10^{-24} GeV/c^2$.

The gluons are like the quarks in that they cannot be isolated and hence their masses are difficult to define. The number of gluons in a hadron is not even a well-defined concept; it keeps changing as gluons are emitted and absorbed by the quarks within the hadrons. The $SU(3)$ symmetry of the strong interactions is an exact symmetry, and formally this requires that the gluon mass is zero in the same way that exact electric charge conservation requires that the photon mass is zero. Because of confinement, it is difficult to relate this formal definition of a gluon mass to any mass measurement. However, since this formal definition is the one used by physicists, we show the gluon mass as zero on the chart.

3.5. Hadron Tables

The two tables labelled **sample fermionic hadrons** and **sample bosonic hadrons** are just that, a small sample of the many experimentally observed particles. Any combination of three quark flavors makes a **baryon**. Baryons are color neutral. By the rules of $SU(3)$ one can make a color-neutral object by taking one quark of each of the three possible color charges and putting them together. The three quarks can have any combination of flavors.

The second way to form a color-neutral combination of quarks is to combine a quark with an antiquark; such hadrons are called **mesons**. Since the total spin of the combination is an integer, mesons are **bosons**. Any combination of flavors for the quark and antiquark makes a possible meson.

The spin of a hadron made up from the spins of the quarks it contains and in addition there can be a contribution from the orbital angular momentum of their motion around one another. One can have different hadrons with the same quark content but with different spin—for example, the π and ρ mesons shown on the table.

3.6. Properties of Interactions

The first two rows of this table are self-explanatory. The remaining rows are a summary of the *relative* strengths of the several interactions in various situations. The first lesson to be drawn from this is that there is no absolute way to compare the strengths of the interactions, since they vary with the situation. There are even extreme conditions in which the effect of gravity is as strong as that of the strong interactions, although the table shows that this is clearly not the case in the examples presented here. A second point to emphasize is the hypothetical nature of the situation "two quarks at distance ...". Quarks cannot be isolated and pinned down. The distance between them is constantly varying as they move around inside the hadrons. On the chart the smaller distance, $10^{-18} m$, is chosen to illustrate the fact that when they get very close together the weak interaction is comparable to the electromagnetic one. The strength of the weak interaction decreases exponentially with distance, d, as $e^{-mcd/\hbar}$ where m is the mass of the exchanged W or Z meson. Electromagnetic interactions fall off as only a power of distance. This is a consequence of the fact that the photon is massless. Thus, as shown on the chart, when the quarks are at a separation of $3 \times 10^{-17} m$ (still only about a tenth of their typical separation in a proton), the weak interaction is already much weaker relative to the electromagnetic. From this it becomes clear that to understand the rate of weak processes in a hadron, one needs to know the probability that the quarks are very close, because for all practical purposes one can say that certain weak processes happen only when the quarks are at distances of order $10^{-18} m$ or less. The last row of the table already includes this effect. When we discuss the interactions of two protons in a nucleus, we must take a weighted average of interaction strengths with a weighting that reflects the probability of a given separation in a typical nucleus, that is, the fraction of time that the protons will have that separation.

Another aspect of this table that needs to be explained is the separation of the strong interaction column into two parts, one for the fundamental interaction of objects which have net color charge, and another, labeled **residual strong interaction** for the strong interaction between color-neutral hadrons. This distinction is probably best explained by the analogy to the familiar electrical case. We say that particles have electrical interactions because of their electric charge. Atoms are electrically neutral objects with charged constituents. What interaction is responsible for the binding of atoms to form compounds? It is clearly an electrical effect. In chemistry it is described as being due to the sharing or the exchange of electrons between the atoms. Similarly the residual strong interaction which binds protons and neutrons to form atomic nuclei can be viewed as due to exchanges of the color-charged constituents, gluons and quarks, between the nucleons. For the longer range part of the process, the exchange takes place in the form of a meson. Thus the modern view of this interaction incorporates the older view that meson exchange is responsible for the formation of the nucleus. When nuclear physicists refer to the strong force, they mean the residual interaction. However, particle physicists mean the fundamental force. It is important to remember the distinction.

3.7. Figures

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, red lines the quark paths, and black lines the paths of leptons.

Neutron Decay

This figure represents the most familiar weak interaction process, the decay of a neutron to a proton, an electron and an electron antineutrino.

$$n \longrightarrow p\ e^-\ \overline{\nu}_e$$

In the Standard Model this decay occurs by the transition of a d quark to a u

quark and a **virtual** W^-. The W-boson then decays, creating the electron and the electron-type antineutrino.

The figure is an attempt to represent this entire process. It needs to be explained that the picture shows the history of a sequence of events. The W-boson appears as the quark changes flavor and disappears when the leptons are produced.

Electron - Positron Annihilation

This figure shows a process which happens in a **colliding-beam** experiment. In facilities such as those at the Stanford Linear Accelerator Center in California electrons and positrons are accelerated to high energy and then stored in counter-rotating bunches in a circular ring. (See Chapter 5 for a list of the colliding beam facilities around the world).[3] At various points around the ring the bunches are steered to cross one another. Thus a bunch of electrons going one way meets a bunch of positrons going equally fast in the opposite direction. Sometimes an electron and a positron will **annihilate** to form either a **virtual** photon or a **virtual** Z-boson. The virtual particle subsequently produces a quark and its corresponding antiquark. Because these particles carry all the energy of the original electron and positron, they are produced moving apart. The strong interaction between their **color-charges** creates a region of force field between them,which slows them down. The energy now in the force field creates some additional quark and antiquark pairs. The various quarks and antiquarks combine to form color-neutral hadrons. These are observed to emerge from the collision. In the diagram a particularly simple case is shown, where only one additional quark and antiquark are created, and hence only a pair of mesons emerges. In relatively low energy collisions where there is not sufficient energy to make many mesons, this will happen in a significant fraction of **events**. In higher energy collisions one most often sees many particles emerging, including sometimes baryons and antibaryons as well as mesons.

Decay of η_c

In this figure we see a possible decay of an unstable hadron. The η_c contains a charm quark and its antiquark.These can annihilate to produce gluons in much the same way as the electron and positron in the previous example annihilate to produce a photon or a Z-boson. They cannot produce a single gluon because that is forbidden by conservation of angular momentum and also by conservation of color-charge. The subsequent evolution as the color-charged gluons begin to separate is similar to that described in the previous case for separating quarks. Quark and antiquark pairs are produced in the strong field region and combine to form hadrons. Here we show one of many possible final states that could occur when an η_c decays. This process is known to occur in about 4% of such decays.[9]

III. USING THE CHART

The booklet will also contain a more detailed set of suggestions for incorporating the concepts of modern particle physics in an introductory course. Here we provide only a few brief suggestions. This chart was designed primarily for use in an introductory physics course. Typically such a course covers mechanics, heat, electricity and magnetism, optics and waves and modern physics. Clearly the introduction to particle physics which is provided by the wall chart belongs to the modern physics segment of the course and should come after the introduction of the basic concepts of quantum mechanics. However the fundamental concepts of particle physics should be introduced as early as possible in the course. For example, the idea that every force is due to one or another of the four fundamental interactions should be introduced when forces are first discussed in the mechanics portion of the course—the notion that friction is due to the electrical interactions between the atoms in the surfaces of the two materials does not immediately occur to most students. It is useful to begin referring to the quantum view as early as possible in the course; for example, the introduction of the photon as the quantum of the electromagnetic field can occur first in the section of the course on electromagnetism and reappear with the concept of an electromagnetic wave in the wave section. In discussing electron levels in atomic physics one should introduce the Pauli Exclusion principle and its crucial role in explaining the "filling" of levels.

This same concept then reappears at the nuclear level in explaining the patterns of stable isotopes and again in particle physics to explain, for example, why the proton is the lightest baryon. The process of nuclear β-decay should be included in the discussion of nuclear physics, starting from the neutron decay process shown on the chart. Finally at the smallest scale of structure we come to the quark level. One needs to make reference to the very large number of known mesons and baryons, only a few of which are shown on the chart, to see how the quark picture simplifies our understanding of particles just as the concept of protons and neutrons simplifies our understanding of the many elements.

It is important to provide more than a static picture of objects made from putting pieces together. The notion that there must be some interaction between the pieces to bind them into stable objects can first be introduced in mechanics with the example of gravity in the solar system and then carried through the atomic and nuclear levels to the quark level. The role of the four interactions in the various decays of unstable particles should also be discussed. It should be made clear to students that the Standard Model is built on the basis of hundreds of experiments in particle physics.

Although this brief outline applies to an introductory course, it is clear that at the college level the chart can also be profitably incorporated into an intermediate level course on modern physics or even an introduction to particle physics.

Another proposed use of the chart is to educate both high school and college physics teachers about modern particle physics. Workshops for teachers on the material presented in this chart will provide general background information on this subject which is important even for teachers who do not plan to incorporate the wall chart in their teaching program.

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Field Test Participation

Field testing of the chart, booklet, and computer software will be conducted during the first half of 1989. The committee will issue two hundred (200) sets of field test materials. Detailed procedures will be included with materials sent to participants. Results of the testing will be compiled in July 1989, so that work can begin to prepare final versions of the materials.

If you wish to participate, please complete the form below. Please note: At present computer software is limited to Hypercard-equipped Apple Macintosh computers. Include in your application the type of computer on which you prefer to operate the software, so you can be sent software compatible with your computer, if and when it becomes available.

Application to Receive FPICC Field Test Materials

To: Fundamental Particles and Interactions Chart Committee

Date: ____________________

Please send field test instructions and materials for the "STANDARD MODEL OF FUNDAMENTAL PARTICLES AND INTERACTIONS" Chart Project to the person listed below:

Name ____

Position ____

Address ____

____

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Level of Physics Instruction:

_____ High School

_____ Undergraduate

_____ Other (Please specify):

____

Telephone Numbers: ____

Type of Computer Available: _____________________________________

Please return this form to:

FPICC Field Test Materials
Particle Data Group
Lawrence Berkeley Laboratory
Building 50–308
Berkeley, CA 94720

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