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Teachers' Resource Book on Fundamental Particles and Interactions

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Helen R. Quinn, Jonathan Dorfan, R. Michael Barnett, Robert N. Cahn,
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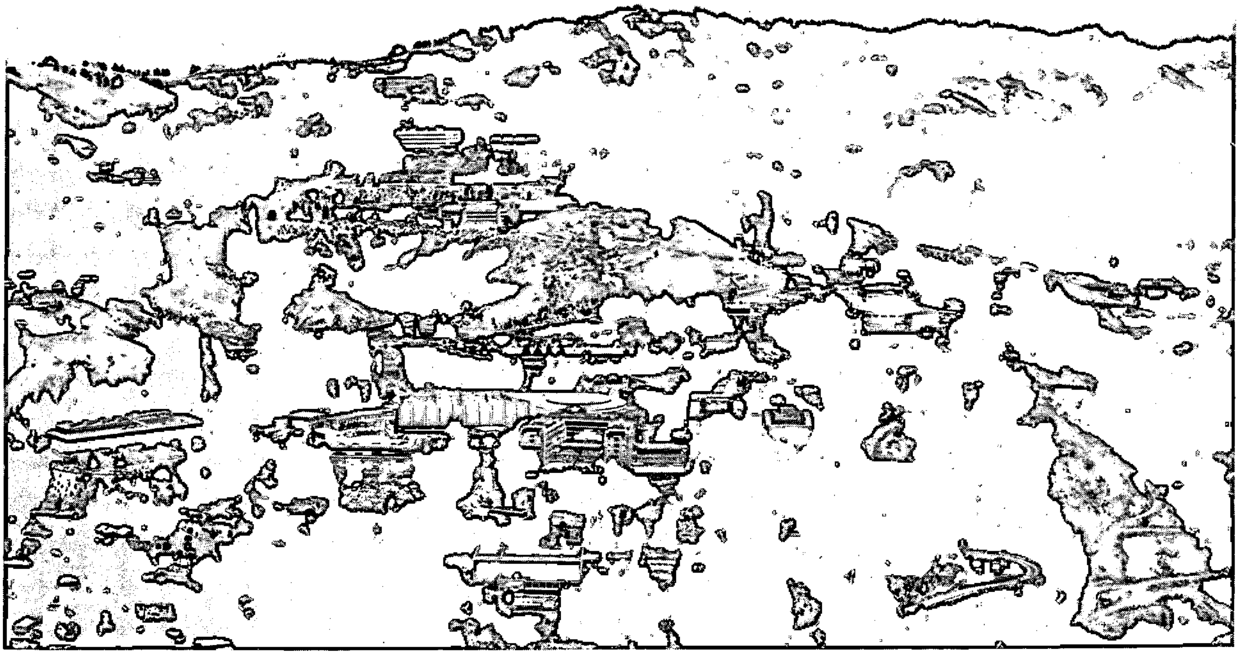
January 1989



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January 31, 1989

TEACHERS' RESOURCE BOOK ON FUNDAMENTAL PARTICLES AND INTERACTIONS[*]

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AND INTERACTIONS CHART COMMITTEE

To accompany the FPICC Wall Chart

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This is a **Preliminary Version** of the Resource Book for use in field testing.

January 1989

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Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS

The "Standard Model" is a term used to describe the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2,...

Leptons ℓ spin = 1/2 (Antileptons $\bar{\ell}$)

Electric charge	Flavor	Mass GeV/c^2	Flavor	Mass GeV/c^2	Flavor	Mass GeV/c^2
0	ν_e electron neutrino	$< 2 \times 10^{-8}$	ν_μ muon neutrino	$< 2.5 \times 10^{-4}$	ν_τ tau neutrino	$< 3.5 \times 10^{-2}$
−1	e electron	5.1×10^{-4}	μ muon	0.106	τ tau	1.784

Quarks q spin = 1/2 (Antiquarks $\bar{q}$)

Electric charge	Flavor	Approx. mass GeV/c^2	Flavor	Approx. mass GeV/c^2	Flavor	Approx. mass GeV/c^2
2/3	u up	4×10^{-3}	c charm	1.5	t top	> 41 (not yet observed)
−1/3	d down	7×10^{-3}	s strange	0.15	b bottom	4.7

Spin is the *intrinsic* angular momentum of particles. It must be included to conserve angular momentum in particle processes. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58 \times 10^{-25}$ GeV s $= 1.05 \times 10^{-34}$ J s. Particles with half-integer spin are called fermions. They obey the Pauli Exclusion Principle. This property is fundamental to the structure of all matter. Particles with integer spin are called bosons.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electron Volt (eV), the energy gained by one electron in crossing a potential difference of one Volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60 \times 10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67 \times 10^{-27}$ kg. Uncertainties in the determination of masses are not shown on this chart.

Sample Fermionic Hadrons

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω	omega	sss	−1	1.672	3/2

Matter and Antimatter

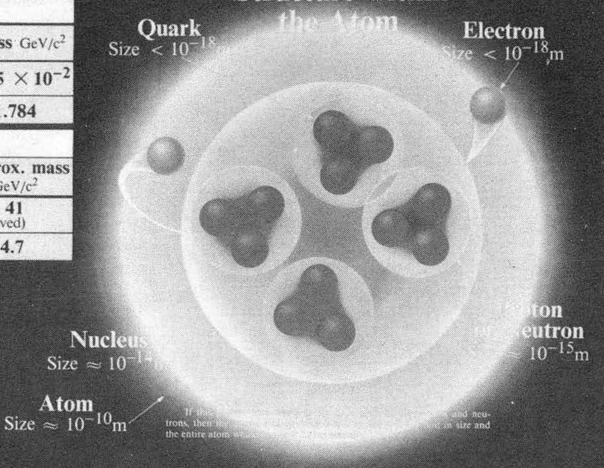
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol. Particle and antiparticle have identical mass and spin but opposite charges. The electrically neutral bosons (Z^0 and γ, and mesons made of a quark and the corresponding antiquark (e.g. $\eta_c = c\bar{c}$)) are their own antiparticles.

Booklet

The accompanying booklet for teachers contains further information on the many technical concepts and terms appearing on this chart. The booklet can be ordered from: Particle Data Group, Lawrence Berkeley Laboratory, Bldg. 50-308, Berkeley, CA 94720.

1988 edition. This preliminary version of the chart is intended to be used for field testing. Your comments are welcomed.

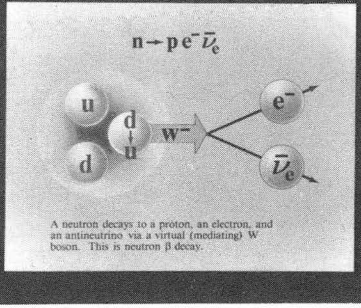
Structure within the Atom



PROPERTIES OF THE INTERACTIONS

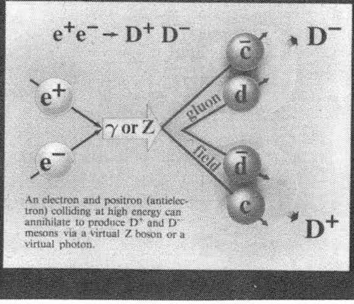
Property \ Interaction		Gravitational	Electroweak		Strong	
			Weak	Electromagnetic	Fundamental	Residual
Acts on:		Mass – Energy	Flavor	Electric charge	Color charge	See Residual Strong Interaction Note
Particles experiencing:		All	Quarks, Leptons	All electrically charged	Quarks, Gluons	Hadrons
Particles mediating:		Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromagnetic for:	Two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
	3×10^{-17} m	10^{-41}	10^{-4}	1	60	
	Two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

$n \to p e^- \bar{\nu}_e$



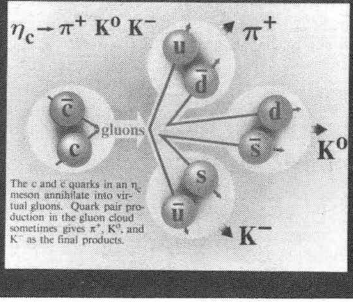
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+ e^- \to D^+ D^-$



An electron and positron (antielectron) colliding at high energy can annihilate to produce D⁺ and D⁻ mesons via a virtual Z boson or a virtual photon.

$\eta_c \to \pi^+ K^0 K^-$



The c and $\bar{c}$ quarks in an η_c meson annihilate into virtual gluons. Quark pair production in the gluon cloud sometimes gives π^+, K^0, and K^- as the final products.

BOSONS

force carriers
spin = 0, 1, 2,...

Unified Electroweak spin = 1	γ photon	W^-	W^+	Z^0
Electric charge	0	−1	+1	0
Mass GeV/c^2	0	81	81	92

Strong or color spin = 1	g gluon
Electric charge	0
Mass GeV/c^2	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically charged particles interact by exchanging photons, in strong interactions color-charged particles exchange gluons. Leptons, photons, and W and Z^0 bosons have no color charge and hence no strong interactions.

Confinement

As color-charged particles (quarks and gluons) are separated, the color force between them approaches a constant value and the energy in the color-force field increases. This energy eventually is converted into additional quark-antiquark pairs (see the figures below). The objects that finally emerge are color-neutral combinations called **hadrons** (mesons and baryons). One cannot isolate quarks and gluons; they are ***confined*** into color-neutral hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged objects.

Residual Strong Interactions

The strong binding of the color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction which binds electrically neutral atoms to form molecules. It can be viewed as the exchange of mesons between the hadrons.

Sample Bosonic Hadrons

Mesons $q\bar{q}$

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
D^+	D^+	$c\bar{d}$	+1	1.869	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

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.

Credits

This chart was created by the Fundamental Particles and Interactions Chart Committee, an outgrowth of the Conference on Teaching of Modern Physics. This project received support from the American Association of Physics Teachers (National Science Foundation grant TEI-8550610), from the Center for Science and Engineering Education and the Particle Data Group of Lawrence Berkeley Laboratory (U.S. Department of Energy), and from the Stanford Linear Accelerator Center (USDOE).

1. Introduction

1.1. PRELIMINARIES

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. Down to the smallest scales studied experimentally, these questions are answered by a theory that particle physicists call “the Standard Model.” The purpose of this chart and the accompanying book is to summarize this theory in a form suitable for presentation to beginning physics students.

The Standard Model is a well-established theory that 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 six 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 an 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 least down to a scale of about $10^{-10}m$ (the level of atoms). They know the atom has a positively charged nucleus surrounded by electrons that 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?” When physics students learn 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. The β ray, however, cannot be explained either by strong or electrical interactions. It is an energetic electron which comes from a transition in that 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 are now understood through theory called “the Standard Model” which satisfactorily describes all observed particle processes. This book does not attempt to give a history of the development of the Standard Model theory. Many experimental and theoretical contributions led to the understanding of the theory and to its acceptance as a correct description of the world we observe. Certain very important primary contributions must be mentioned here. The strong interaction $SU(3)$ theory was first suggested by Murray Gell-Mann. The $SU(2) \times U(1)$ theory of the weak and electromagnetic interactions was developed independently by Steven Weinberg and Abdus Salam. The critical importance of a fourth type of quark in the context of the $SU(2) \times U(1)$ theory was recognized by Sheldon Glashow, John Ilipoulos and Luciano Maiani. Some of the history of the experiments which led to these theoretical developments and then subsequently tested the accuracy of the predictions made by the theory is given in Chapter 5 of this book. Both on the theoretical and the experimental side there are many other contributions which we have not mentioned but which were important to the development of our understanding. The Nobel Prize in 1979 was awarded to Glashow, Salam and Weinberg for their role in the development of the electroweak theory. Gell-Mann had won the Nobel Prize in 1969 for his contributions to the understanding of strangeness, quarks, and their interactions. On the experimental side, the 1984 Nobel Prize was awarded to Carlo Rubbia and Simon van der Meer for the discovery of the W and Z bosons, a critical confirmation of a prediction of the Standard Model. In 1988, Leon Lederman, Melvin Schwartz and Jack Steinberger won the Nobel Prize for their 1962 experiment demonstrating the existence of more than one neutrino type.

The Standard Model 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 Standard Model does not include gravity because physicists do not yet know how to write a consistent quantum theory that also includes gravity. Fortunately for us, gravity is a very weak interaction and so in most particle physics processes it is an excellent approximation to ignore the effects of gravity.

The wall chart and this book describe the world in the language of the Standard Model. Throughout this book 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 that simply correspond to a choice of parameters in the Standard Model, rather than being predicted by it. For example, a particle called the top quark has yet to be observed, although we do have some indirect evidence for it; 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, that the Standard Model does not address. Particle physics research today seeks theories that 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.

The technical name of the Standard Model is $SU(3) \times SU(2) \times U(1)$., This denotes the parts of the theory in a mathematical language called group theory.* In this book, 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 book is based on an extensive mathematical structure that 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. Although the mathematics of such calculations are well beyond beginning physics students, they should understand that the names and descriptions are but a small part of any physical theory. In presenting this material, concepts and processes should be stressed 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.

The experimental basis of particle physics should be emphasized. Students are familiar with the need for a microscope to see small objects. The accelerators that are the basic tools of particle physics experiments act as 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 ever 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 detectors will be discussed in Chapter 4.

$\star$ One reads this expression as "S U 3 cross S U 2 cross U 1".

The symbols $SU(n)$ stand for the Simple Unitary group of n dimensions. For those readers who really want to know: The simplest representations of this group the set of all n-component complex vectors and the transformations among them given by $e^{-i\Sigma f^{\alpha}\lambda_{\alpha}}$ where the sum is over $\alpha = 1, 2, 3, \ldots, (n^2 - 1)$, f^{α} are $(n^2 - 1)$ arbitrary real numbers, and λ_{α} are $n \times n$ traceless, hermitian matrices. There are $n^2 - 1$ such matrices in $SU(n)$. $U(1)$ is the one dimensional Unitary group, represented most simply by the transformations of $e^{i\psi}$ acting on the set of all complex numbers.

Chapter 5 presents a brief summary of some crucial experiments.

It is important to stress the role of *interactions* as well as *constituents* in describing matter. The interactions provide the rules which explain which combinations of the fundamental particles are 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. The Standard Model allows us to 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 6 of this book we discuss the application of the Standard Model to such questions.

1.2. USING THE CHART

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. Refer 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 also should 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.

2. Overview

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

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 that we will explain here. There is no fixed rule about how to name a new particle or a new concept. It is usually 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" meaning "a force due to the gravitational interaction" or "the strong force" meaning "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 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. Strong charges are called **color charges** (or sometimes just colors) and are carried by **quarks** and by **gluons**. Particles that 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 factors contain parts of each interaction.

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[*] Again only for those who want more technical information: The three different colors of quark fields can be viewed as the three components of the fundamental representation of $SU(3)$. The eight types of gluons correspond to the coefficients of the $n^2 - 1 = 3^2 - 1 = 8$ traceless 3×3 hermitian matrices in $SU(3)$.

Spin – Bosons and Fermions.

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

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

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**. 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 that strictly limits the possible number of electrons in each level. Bosons on the other hand are not governed by this law and hence they tend to all occupy the lowest available state. In a laser, the coherence of the light is achieved by this effect; many photons are in exactly the same state.

- 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. Bosons also have antiparticles of equal mass but opposite charge. 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.

Classes of Fermions

- Leptons and Quarks

The fundamental fermions are **leptons, (ℓ),** and **quarks, (q)**. 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. 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 each neutrino type there is a separate object which is the antineutrino. Although neutrinos have no electric charge they do have a flavor charge and the antineutrino's have the opposite sign for that flavor.

Quarks have **color charge.** For every quark color and flavor there is a corresponding antiquark which has the anticolor, the antiflavor and the opposite sign for its electric 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 where u stands for an up quark and d stands for a down quark. 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.* For every baryon made of three quarks, there is an antibaryon made of the corresponding three antiquarks. Baryons can have spin 1/2, 3/2,. . . .

Classes of Bosons

There are two 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 particles are **confined**. There are eight possible types of color charge for gluons. 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. Gluons exist only inside hadrons where they provide the "glue" that holds the composite together. Most hadrons are known to be composites of both quarks and gluons. In principle, in the Standard Model there can also be some hadrons made only from gluons. As yet there is no clear experimental evidence for such objects.

- Mesons

Hadrons consisting of a quark and an antiquark (for example, π^+ which is $u\overline{d}$) 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 $\overline{u}d$. For mesons made of a quark and the *corresponding* antiquark, such as $\eta_c = \overline{c}c$, the particle and the antiparticles the same object.

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	$q\overline{q}$ = 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 those parts of the tables that relate to **electroweak** interactions and for the figures depicting electroweak processes. Encourage your students to try to understand the significance of the color coding on this chart.

3.2. THE DIAGRAM OF STRUCTURE WITHIN AN ATOM

If the figure on the wallchart 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.

This figure is used to introduce the idea of the extremely small scales that particle physics now studies. Electron and quark sizes are labeled 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 the figure can be related 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 the electric charges -1 and 0, and two quark flavors with the electric 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; this 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 electric charge, flavor, and color. All the hadrons observed so far are composites of the five lightest flavors quarks and their antiquarks. Hadrons containing the top quark or its antiquark have yet to be found.

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.

LEPTONS ℓ spin = 1/2 (Antileptons) $\bar{\ell}$

Electric charge	**Flavor**	**Mass GeV/c^2**	**Flavor**	**Mass GeV/c^2**	**Flavor**	**Mass GeV/c^2**
0	ν_e electron neutrino	$< 2 \times 10^{-8}$	ν_μ muon neutrino	$< 2.5 \times 10^{-4}$	ν_τ tau neutrino	$< 3.5 \times 10^{-2}$
−1	**e** electron	5.1×10^{-4}	μ muon	0.106	τ tau	1.784

QUARKS q spin = 1/2 (Antiquarks $\bar{q}$)

Electric charge	**Flavor**	**Approx. mass GeV/c^2**	**Flavor**	**Approx. mass GeV/c^2**	**Flavor**	**Approx. mass GeV/c^2**
2/3	**u** up	4×10^{-3}	**c** charm	1.5	**t** top (not yet observed)	> 41
−1/3	**d** down	7×10^{-3}	**s** strange	0.15	**b** bottom	4.7

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.[1] By this he meant that it was quite unexpected and seemed superfluous. 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 is another conservation law which is obeyed in the decays of leptons. Each generation of leptons has distinct "flavor"—called electron type, muon type, and tau type. Each lepton flavor type is conserved. Lepton flavor does not change when a Z boson or a photon is emitted or absorbed. When a charged W-boson is emitted by a lepton the process always involves a transition between a charged lepton and its own neutrino type. Thus when a muon decays it becomes a muon type neutrino by emitting a **virtual** W^- boson which rapidly decays to produce an electron and an anti-electron-type neutrino, thus conserving both muon flavor and electron flavor as illustrated in the table below.

	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[2] suggested that hadrons might be composed of quarks. They 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[3] and at Brookhaven National Laboratory.[4] The bottom quark, in a $b\bar{b}$ combination called upsilon (Υ), was first observed at Fermi National Laboratory in 1977.[5] A sixth quark, top (t), has been predicted by the theories, but particles containing this quark have not yet been observed (as of January 1989).

Quarks have non-zero color charge and hence, like gluons, they are confined

BOSONS force carriers spin = 0, 1, 2,...				
Unified **Electroweak** spin = 1	γ photon	**W$^-$**	**W$^+$**	**Z^0**
Electric charge	0	–1	+1	0
Mass GeV/c^2	0	81	81	92
Strong or Color spin = 1	**g** gluon			
Electric charge	0			
Mass GeV/c^2	0			

objects. Each quark flavor type 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 a total of six flavors. Quark flavor is never altered in strong or electromagnetic interactions or in the neutral weak (Z boson) processes. Since W-bosons are electrically charged, the electric charge of the final quark will be different that of the initial quark which emits a W-boson, e.g. a charged 2/3 quark makes a transition to a charge $-1/3$ quark by emitting a W^+ boson. By the definition given above this transition involves a change of quark flavor. The predominant weak processes involve transitions between quarks shown paired on the table, that is, those in the same generation. Rarer transitions occur between any $+2/3$ and any $-1/3$ charged quarks.

- Fermion Masses

The tables show masses for the charged leptons, these masses are experimentally well measured. When particle physicist use the word mass they it always mean the rest mass of the object in question. (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 labeled "approximate mass." Because a quark cannot be isolated, it is very difficult to determine its mass or even to define fully 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 confinement. 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 TABLES

The tables on the upper right of the chart shows the fundamental bosons of the Standard Model. These are labeled "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 bosons 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.

Sample Bosonic Hadrons

Mesons $q\overline{q}$

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\overline{d}$	+1	0.140	0
K^-	kaon	$s\overline{u}$	–1	0.494	0
ρ^+	rho	$u\overline{d}$	+1	0.770	1
D^+	D^+	$c\overline{d}$	+1	1.869	0
η_c	eta-c	$c\overline{c}$	0	2.980	0

Sample Fermionic Hadrons

Baryons qqq and Antibaryons $\overline{q}\,\overline{q}\,\overline{q}$

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\overline{p}$	antiproton	$\overline{u}\,\overline{u}\overline{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω	omega	sss	–1	1.672	3/2

3.5. HADRON TABLES

The two tables labeled **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 is made up from the spins of the quarks it contains and a contribution from the orbital angular momentum of the quarks' motions around one another. Different hadrons with the same quark content but with different spin are possible —for example, the π and ρ mesons shown on the table. For a complete listing of all observed particles and their properties see the "Review of Particle Properties".[6]

PROPERTIES OF THE FUNDAMENTAL INTERACTIONS

(interactions = forces)

		Electroweak Interaction		Strong Interaction	
Property	**Gravitational Interaction**	**Weak Interaction**	**Electromagnetic Interaction**	**Fundamental**	**Residual**
Acts on:	Mass–Energy	Flavor	Electric Charge	Color Charge	See note
Particles Experiencing Interaction	Particles with Mass	Leptons Quarks (hence Hadrons)	Electrically Charged Particles	Particles with "Color Charge" (Quarks, Gluons)	"Color Neutral" Hadrons (residual force)
Particles Mediating Interaction	Graviton (not yet observed)	W^+, W^-, Z^0	γ	Gluons	Mesons
Strength Relative to Electromagnetic for two u quarks at a separation of $r \approx 10^{-18} m$	10^{-41}	0.8	1	25	Not applicable to quarks
for two u quarks at a separation of $r \approx 3 \times 10^{-17} m$	10^{-41}	10^{-4}	1	60	Not applicable to quarks
for two protons in a nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

3.6. PROPERTIES OF THE 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.

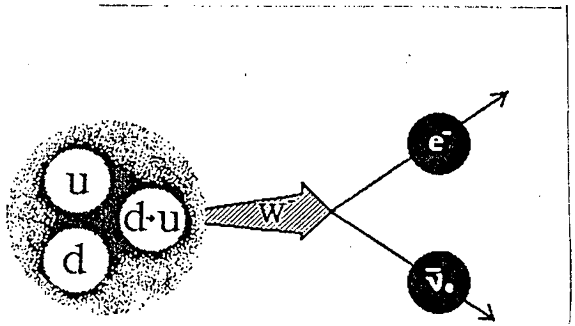
A second point to emphasize is the hypothetical nature of the situation "two quarks at distance ...". Quarks cannot be isolated and pinned down. The distance between them is constantly varying as they move around inside the hadrons. On the chart the smaller distance, $10^{-18}m$, is chosen to illustrate 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

$$\frac{V \propto -e^{-mcd/\hbar}}{d}$$

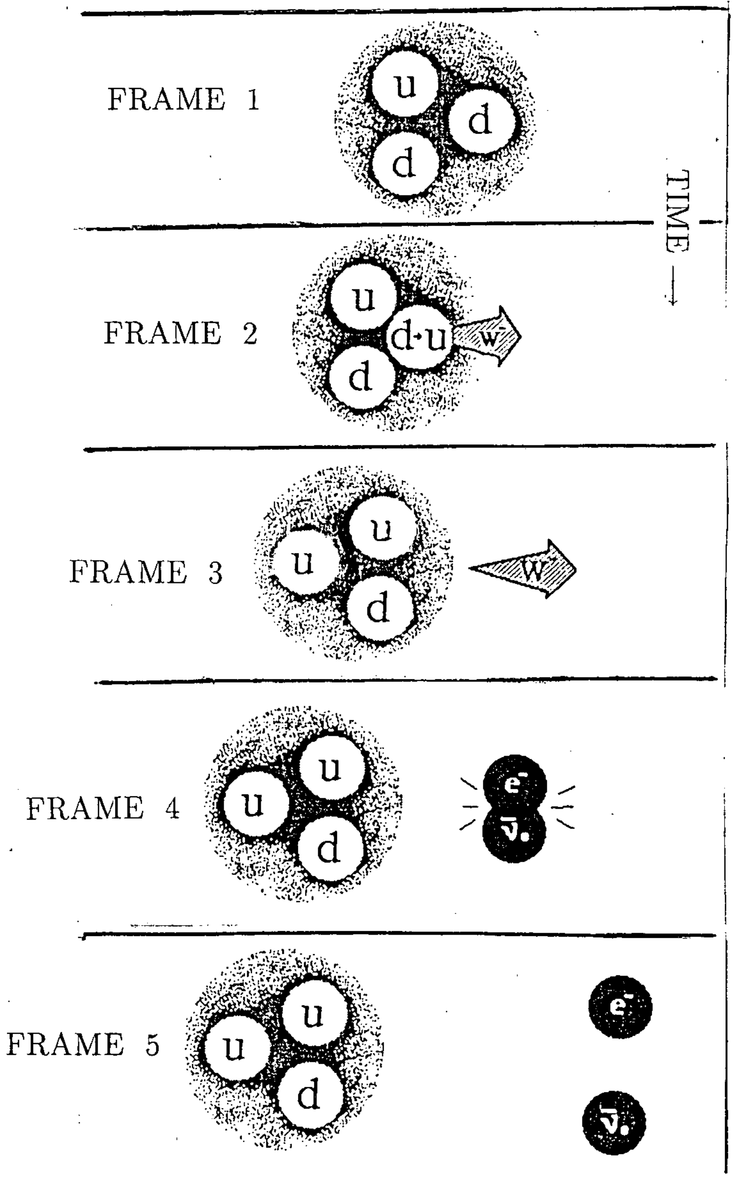
where m is the mass of the exchanged W or Z meson. Electromagnetic interactions fall off as $(-1/d)$. This is a consequence of the fact that the photon is massless. Thus, as shown on the chart, when the quarks are at a separation of $3\times10^{-17}m$ (still only about a tenth of their typical separation in a proton), the weak interaction is already much weaker relative to the electromagnetic interaction.

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 that 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.



(a) Neutron Beta-Decay
Figure 1



$n \rightarrow pe^-\overline{\nu}_e$ – Time lapse pictures showing the sequence of events in neutron β-decay.

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.

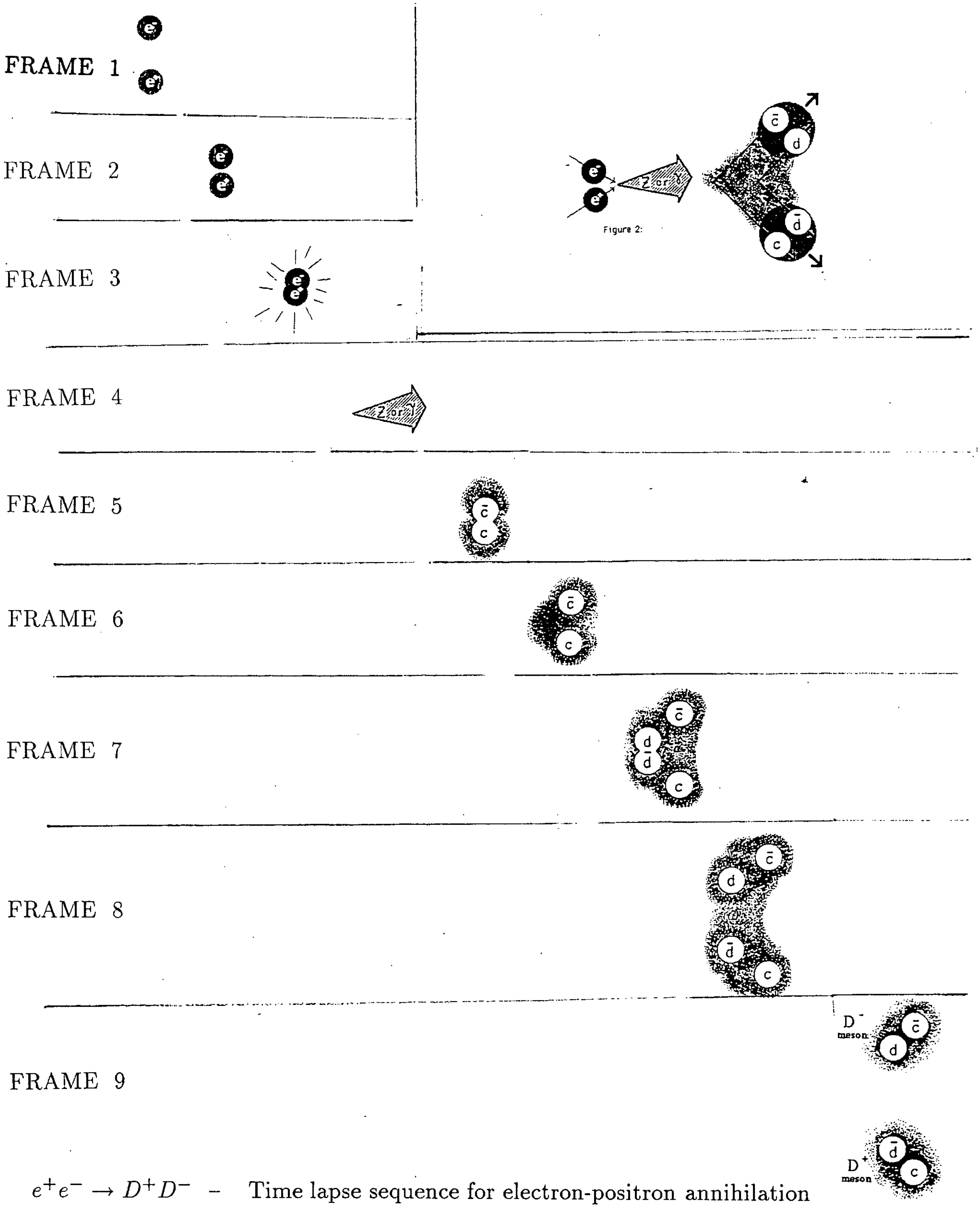
Neutron Decay

The first figure on the chard represents the most familiar weak interaction process, the decay of a neutron to a proton, an electron, and an electron antineutrino:

$$n \rightarrow p\, e^-\, \overline{\nu}_e \quad .$$

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 on the chart is an attempt to represent this entire process. It shows the history of a sequence of events. The W-boson appears as the quark changes flavor and disappears when the leptons are produced. The "time-lapse" pictures shown here represent this sequence of events. The time of these frames is very short, once begun, the entire sequence of events occurs in a time of less that 10^{-26} *s*! Thus it is impossible to actually observe the intermediate stages. The unobservable particles that appear in the intermediate stage of such a process, such as the W-boson in this example, are called "virtual" particles.

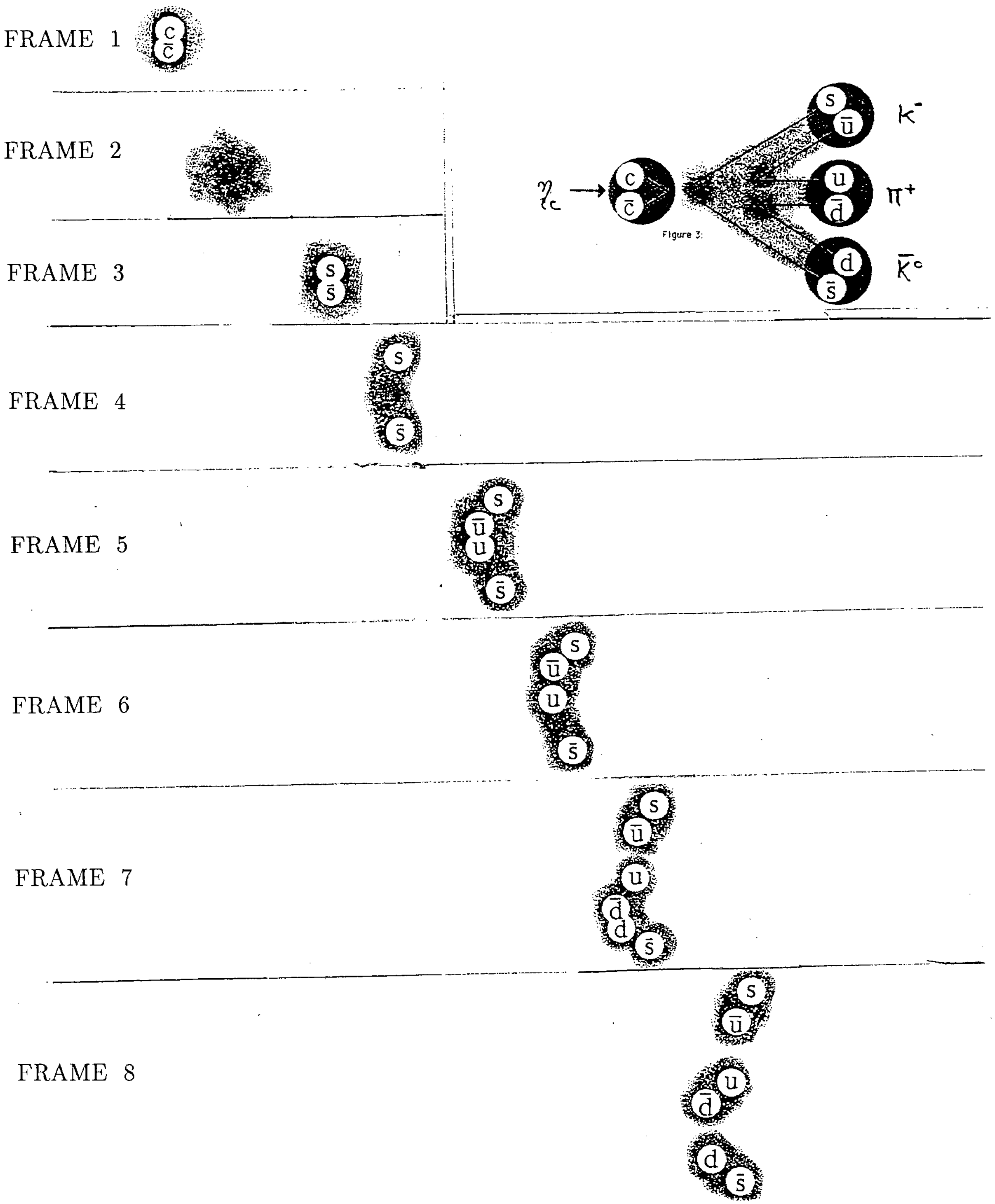


$e^+e^- \rightarrow D^+D^-$ – Time lapse sequence for electron-positron annihilation resulting in production of D mesons.

Electron – Positron Annihilation

The second figure on the chart shows a process that 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 "storage ring." 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. The "time lapse" sequence of pictures here shows the process step-by-step. Again the actual process occurs on a very short time scale. 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 most higher energy collisions many particles emerge, including sometimes baryons and antibaryons as well as mesons.



$\eta_c \rightarrow \pi^+ K^0 K^-$ – Time lapse sequence for the quarks in an η_c meson to annihilate resulting in production of a pion and two K mesons.

Decay of η_c

In the third figure on the chart we see a possible decay of an unstable hadron. The η_c contains a charm quark and its antiquark. These can annihilate to produce virtual gluons in much the same way as the electron and positron in the previous example annihilated to produce a virtual photon or 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.[6] The "time-lapse" picture here shows this process in a step-by-step fashion. Here also the process occurs so rapidly that the intermediate stages cannot be observed. The outgoing mesons are observed via their interactions with components of a detector; the explanation of the process given here is made on the basis of the Standard Model theory.

4. Accelerators and Detectors

4.1. INTRODUCTION TO EXPERIMENTAL HIGH ENERGY PHYSICS

In this chapter we describe the equipment that is used to study particles. In the next chapter we will describe some of the key experiments that led to the understanding of the microscopic world that is contained in the Standard Model. In particle physics, experiments are done to probe distances as small as 10^{-18} meters. At such extremely small distances, it is the quantum nature of particles that reigns. No ordinary (human-sized) object is sensitive to these distances. It is therefore necessary to use one particle as a probe, and shoot it into another particle acting as a target. By observing the outcome of this process, we learn about the target, the probe and their interactions. It is amazing that physicists are able to get information from such collisions, but this is, in fact, the primary way that they study particles and interactions.

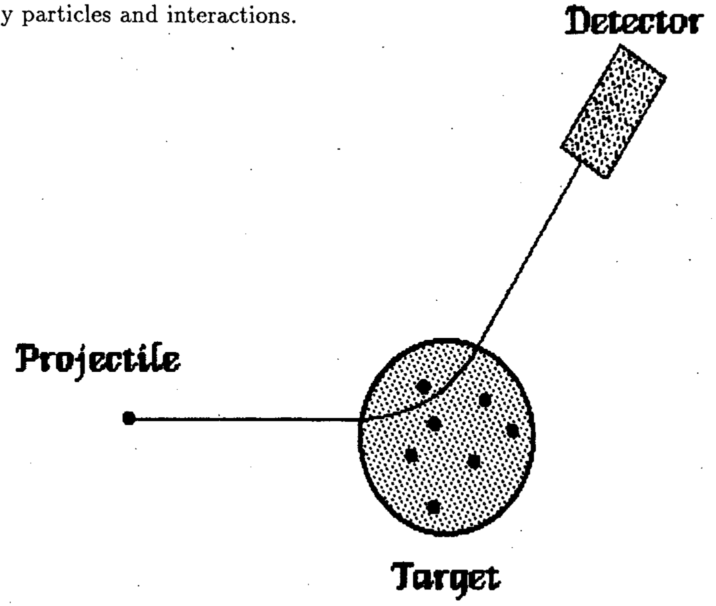


Fig. 4-1. - A projectile strikes a target, is deflected, and is observed in a detector.

Fixed Target Experiments

Figure 4-1 is a schematic diagram of what one type of experiment with particles as probes looks like. A setup of this kind is called a **"fixed-target"** experiment. By moving the detector one can study the angular dependence of the scattered particles, that is the rate per incident projectile particle as a function of the angle through which the projectile is scattered. The variation of this rate with the angle reflects the details of the internal structure of the target and the nature of the interaction between the projectile and the target. Using sufficiently high energy electrons as projectiles and protons as the target, physicists at Stanford were able to demonstrate convincingly that "hard" scattering centers existed inside the proton – the quark substructure was revealed, in much the same way that Rutherford found the nucleus within the atom.

Much information can be gained by changing the parameters of the experimental setup. Different projectiles – electrons , pions, kaons, protons, muons, neutrinos – can be (and have been) used. Each projectile possesses different intrinsic quantum numbers, many of which are conserved in the scattering and hence are directly reflected in the final state produced by the scattering. Another important parameter in the experimental setup is the projectile energy – the higher the energy of the projectile the smaller the size of objects that can be resolved in the target.

Colliding Beam Experiments

There is a second way to do high-energy experiments. Instead of a single beam of particles striking a fixed target, two high-energy beams are made to pass through each other, allowing some of the particles to collide head-on. This is called a **"colliding-beam"** experiment. Colliding-beam facilities exist for electrons on positrons (called e^+e^- colliders) and for protons on protons (pp colliders) and on antiprotons ($p\bar{p}$ colliders). An electron-proton collider is being constructed at the DESY laboratory in Hamburg, Germany. The SuperCollider (SSC) accelerator, proposed to be built in Texas, will be a proton-proton collider.

For both fixed-target and colliding-beam experiments there are many possible

final states which may result from any collision. We call each individual particle collision an **"event"**. To learn about a given process, we usually need to collect information from many events and make a statistical analysis of the various outcomes. As an example, consider the high-energy collision of an electron and a positron. These can annihilate to produce a virtual photon or a virtual Z-boson. The virtual photon will materialize as a pair of particles (that is as a particle and its antiparticle). The photon couples to all particles with electric charge. The possible outgoing particles are thus a charged lepton and antilepton or a quark and its corresponding antiquark. All quark and charged-lepton flavors are possible as long as twice the particle mass is less than the total collision energy. For the virtual Z-boson all the states described above are possible and in addition any neutrino and antineutrino pair can be formed. Such events (in which only neutrinos are produced) are very difficult to detect because the neutrinos interact so weakly that they most often will pass through the detector without leaving any evidence of their passage. The Standard Model predicts the relative probability of each of these outcomes when the experiment is repeated many times.

Since the electron and positron beam collide head-on (i.e. moving in opposite directions with the same momentum), they have net momentum of zero and total energy equal to twice the beam energy ($2E_{beam}$). The produced particles therefore will travel out from the collision point with equal but opposite momentum (back-to-back), each with an energy E_{beam}. When the produced particles are e^+e^- or $\mu^+\mu^-$ we observe them directly. If τ^+ and $\tau-$ are produced, they decay rapidly and we observe the decay products. The possible decays of a τ are into 1, 3, or (rarely) 5 charged particles plus neutral particles (neutrinos and sometimes π^os). As explained in Chapter 6, when a quark-antiquark pair are produced they feel an increasingly strong attraction as they fly further apart. They are unable to escape from the color force-field. Their energy materializes in the form of hadrons. (See for example the second figure on the chart.) With a collision energy of 30 GeV, available for example at the PEP storage ring at SLAC, the quark and antiquark typically each materialize into $6-12$ hadrons. If the initiating quarks have high

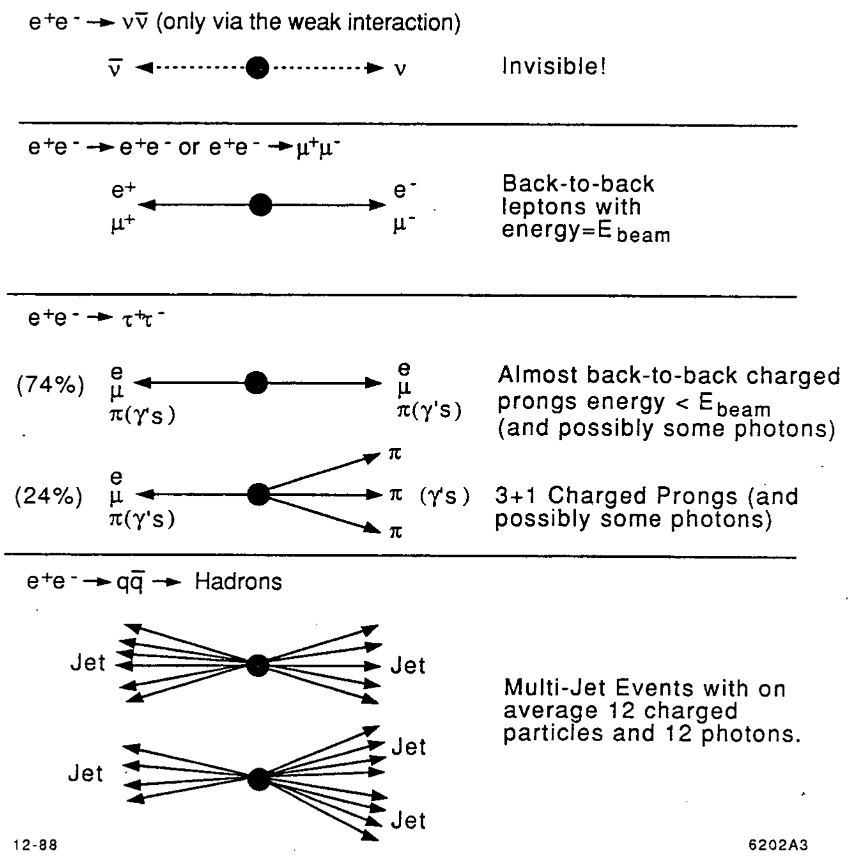


Fig. 4-2. - This figure shows pictorially typical event patterns in electron-positron collisions at a center of mass energy of about 30 GeV. The arrows represent the directions of particles produced at the collision point.

momentum, these particles will appear in "**jets**", that is in groups of particles moving in roughly the same direction, centered about the original quark and antiquark directions.

Altogether there are many possible final states. Fig. 4-2 is a depiction of the different patterns of outgoing particles which can occur in the e^+e^- collisions. In these diagrams, the arrows represent the directions of the final state particles. Among the possible outcomes seen in a detector at PEP are events with two charged tracks (back-to-back); these can result from e^+e^- or $\mu^+\mu^-$. In the case when the τ^+ and τ^- are produced and each decay includes only one charged particle, we see two charged tracks but they are not precisely back-to-back. Also possible are events with four charged tracks which can result from other decays of the τ^+ and τ^-. In some cases the charged particles are accompanied by π^os which in turn decay to produce photons. ($\pi^0 \rightarrow \gamma+\gamma$). Events that result from the $q\overline{q}$ production typically have many charged tracks and many photons.

We can now describe a typical scattering experiment. A detector is employed to record "snapshots" of millions of collisions. Those snapshots are then sorted according to the different patterns of the particles. These patterns must be understood in terms of the physics which governs the scattering. In the case of an unexpected pattern, they may point the way to "new" physics. A classic example is the discovery of the tau (τ) at the SPEAR e^+e^- storage ring at SLAC. The final state of an electron and a muon, with opposite electric charge, was observed. This outcome could only result from $\tau^+\tau^-$ production followed by the decays $\tau^+ \rightarrow e^+\nu_e\overline{\nu}_\tau$ and $\tau^- \rightarrow \nu_\tau\mu^-\overline{\nu}_\mu$. The neutrinos are of course not detected, and hence one detects only an e^+ and a μ^-. The $e^+\mu^-$ events (and similar $e^-\mu^+$ events) were unexpected. Physicists had to hypothesize a new particle, the tau, to explain them, and then confirm this hypothesis by looking for other consequences that it implied. This is how progress in particle physics is made.

We see therefore that to discover nature's secrets requires accelerators to provide high-energy collisions and detectors to map the debris resulting from those collisions. We will now separately look into prototypical accelerators and detectors.

4.2. ACCELERATORS

Introduction to Accelerators

Very high energy projectiles are needed to probe small distances. If we think of particles as matter waves, we know that we need small wavelengths to study small distances, because a wave is essentially undisturbed when it passes by an object that is smaller than its wavelength. Small wavelengths correspond to high energies. The greater the energy of the projectile, the smaller the detail that can be probed. It is thus important to be able to increase the energy of the projectile. An **accelerator** is a device that is used to increase the energy of a collision. Several types of accelerators will be briefly discussed here.

The earliest and simplest accelerators were cathode ray tubes; electrons are boiled off the hot cathode in the region of a strong electric field. The electric field then accelerates the electrons. Early in the 1920s a method to acceleraten massive ions in linear accelerators was developed. Late in the decade, the first circular accelerators were invented. These two types of accelerators are the most important for research today.

Certain points of basic physics are important in designing accelerators and in choosing which type to use. We will briefly review these points. The basic principle of all accelerators is the same. A charged particle experiences a force parallel to an electric field:

$$\mathbf{F}_E = q\mathbf{E}\ .$$

A charged particle moving through a magnetic field experiences a force perpendicular to both its velocity and the B-field:

$$\mathbf{F}_B = q\mathbf{v} \times \mathbf{B}\ .$$

(This effect is also used in detectors to measure particle momenta). Thus electric

fields are used to accelerate charged particles and magnetic fields are used to steer the direction in which they travel.

When a charged particle is accelerated it radiates photons, and this radiation causes the particle to lose energy. Accelerators need to be designed to minimize or compensate for this effect. The rate of energy loss grows rapidly as the particles become relativistic. We call a particle "relativistic" when it has a velocity close to the speed of light. Two properties of relativistic particles are important for accelerator design. The correct formula for momentum is

$$\mathbf{p} = \frac{m\mathbf{v}}{(1 - v^2/c^2)^{1/2}}$$

(At low velocity the denominator is 1 and this is the familiar form.) If you examine this formula when the speed is close to c you will see that a very small percentage change in $\mathbf{v}$ gives a large percentage change in $\mathbf{p}$. For a relativistic particle "acceleration" means that the particles gain momentum, and hence also energy, but their speed is not significantly altered. The energy that is radiated by the particles when they are accelerated also grows rapidly as $v \rightarrow c$. If they are made to travel in a circle they are, of course, always being accelerated towards the center of the circle, and hence losing energy due to this radiation. This is referred to as synchrotron radiation One has to make the radius of the circle bigger as the particles become more relativistic, or they will lose energy faster than they can gain it from the accelerator. At the energies achievable with present accelerator techniques this problem is only significant for electrons. A linear accelerator avoids this problem altogether.

Cockcroft-Walton Drift-Tube Accelerator

Two British researchers, J. D. Cockcroft and E.T.S. Walton, designed and built the first successful linear accelerator of the "drift tube" type. In the Cockcroft-Walton accelerator, a supply of protons is obtained by ionizing hydrogen. The protons are repelled by the positive electrode and attracted by the negative electrode, as shown in Fig. 4-3.

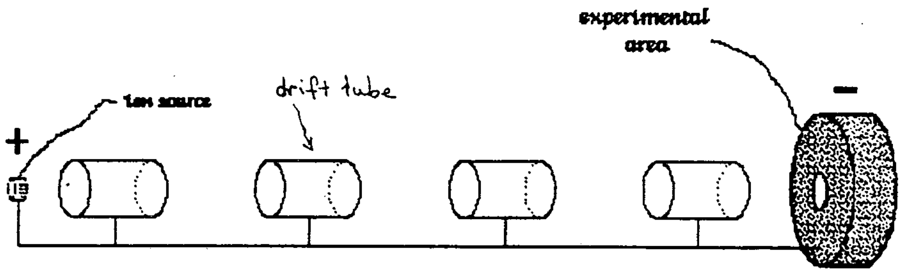


Fig. 4-3 The Cockcroft-Walton accelerator.

To avoid collisions between the protons and air in the tube, which would deplete the beam, the whole accelerator must be evacuated. The drift tubes (the cylindrical objects between the two electrodes) are at potentials between that of the positive terminal and ground (the negative terminal). Thus the tubes reduce the risk of spark formation by breaking the total potential difference into stages. They also keep the protons on a straight path. The AC power for the accelerator is rectified and smoothed by use of a capacitive buffer. If the voltage delivered to each tube is too high, the residual air remaining in the tube will ionize and then it will scatter the beam particles and destroy the beam. This limits the voltage that can be used. Even without this problem, the maximum proton energies obtainable from a Cockcroft-Walton accelerator is only an MeV or so, which is a tiny fraction of the energy achieved with modern accelerators. However, Cockcroft-Walton (and Van de Graaff) accelerators are still used today for nuclear physics experiments and as "preaccelerators" for larger machines. The preaccelerator produces a beam of protons which is then "injected" into the larger accelerator. It is easier to design a high energy accelerator if one can start with such a beam.

The Cockcroft-Walton accelerator is a precursor of many accelerators in which

particles are accelerated in a straight line. Such accelerators are called **linacs** (**linear accelerators**). Cockcroft-Walton accelerators suffered from the limitation on voltage at each stage of acceleration. In more modern linacs, the particles are accelerated in many stages, each of relatively small voltage.

One uses AC power to accelerate particles in a linac. In a linac based on the Cockcroft-Walton machine this means that the electric field in the region between the tubes is alternating in direction. The phase is designed so that the particles are accelerated in the desired direction when they are in the cavities (spaces) between the drift tubes. Then they are shielded from the electric field, because they are inside the drift tube, during the time that the electric field is in the wrong direction. The frequency must be adjusted to allow the tubes to be short enough to be reasonable to construct, which means about a meter or so in length. (Clearly as the particles speed up they travel further during the time of one cycle for a fixed frequency.)

Particles are injected into the linac in pulses or "bunches", at low energy. The voltage between the drift tubes changes with time (like a sine-function). Particles which are in the cavity region when the voltage is highest get a maximum push. The accelerator is designed so that the voltage is still increasing as the average particle leaves the drift tube and enters the cavity region. If one particle is too slow, it will be late coming from the tube and will get a slightly bigger push than average. If another particle is too fast, it will leave too soon and get a smaller push than average. As a result, the slow particle will be accelerated more and the fast particle will be accelerated less than the particles in the bunch. Thus the particles will continue to be bunched together automatically. When an accelerator is set up in this way, it has a characteristic known as **phase stability**, because the bunches tend to stay in phase with the electric field.

The practical limitations on the maximum voltage, frequency, and length for the drift tubes means that Cockcroft-Walton accelerators can achieve about 50 MeV energies, but for higher energies other designs are needed.

Electron Linacs

Because of their small mass, electrons become relativistic at low energies. Acceleration from rest through a potential of only about 500 kV increases their total energy by a factor of two. Relativistic electrons radiate substantial amounts of energy in a circular accelerator unless the radius is very large. Thus, the linear accelerator was the first device to accelerate electrons to high energy. In electron linacs the electrons are accelerated to close to the speed of light in the first few feet. After that they travel at effectively constant speed even though still gaining momentum and energy. The constant speed allows all the sections to be identical. The sequence of accelerating cavities and drift tube regions in the Cockcroft-Walton machine is simply replaced by a series of cavities separated only by discs. The discs have a small hole in the center to allow the beam to pass through. Electromagnetic fields, in the form of microwaves, are fed into this structure and travel down it at the speed of light. This means that in any cavity there is an alternating electric field pointing along the accelerator just as there was in the spaces between the drift tubes of the Cockcroft-Walton machine. Bunches of electrons travel down the accelerator, timed so that they always enter a cavity a little before the field in that cavity reaches its peak (with the force on the electron pointing in the direction of travel), so the machine has the phase stability described above.

Linacs have been built on a much larger scale since the invention of the klystron during World War II. The klystron is a device for generating intense microwave power. It was developed to power wartime radar, and was adapted to linear accelerators to supply power to them. The design for an electron accelerator described above was developed at Stanford University, led by William Hansen and Wolfgang Panofsky. The electron accelerator at Stanford Linear Accelerator Center (SLAC) now produces electrons with an energy of 50 GeV. Lower energy electron accelerators have been built with this same design and are used in radiation-therapy treatment centers.

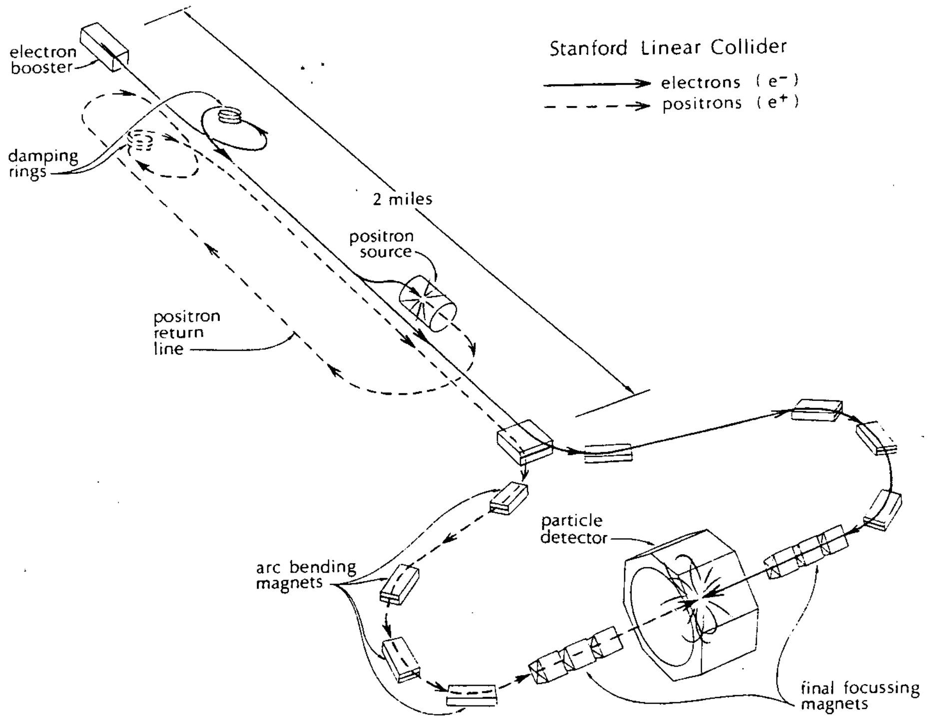


Fig. 4-4 - Schematic diagram of the SLC. (Drawing by Walter Zawojski.)

Electron-Positron Colliders

An accelerator designed for electrons works equally well to accelerate positrons. They simply have to be in the cavity when the electric field is in the opposite direction. Electrons and positrons accelerated in the linac can be fed into a "storage ring". The positrons travel the opposite way around the circle to the electrons, steered by the same magnets as the electrons. At several points around the ring the two beams are made to cross each other so that some of the particles interact. Those particles which do not interact continue around the ring and may collide at subsequent beam crossings. Most particles make millions of circuits of the ring which is why it is called a storage ring. In the ring there are some short accelerating sections to provide energy to compensate for that lost via synchrotron radiation. At SLAC there are two large storage rings (SPEAR which operates at a maximum of 3–5 GeV per beam and has a radius of 32 meters and PEP which operates at 14.5 GeV per beam and has a radius of 350 meters). A third collider facility at SLAC, called SLC (Stanford Linear Collider) collides tiny bunches of electrons and positrons but is not a storage ring because it does not recover the particles that did not interact. At SLC the beam bunches must be only a few microns across when they collide in order to achieve a high enough rate of particle collisions to study interesting physics. The particles travel around large arcs to reach the collision region as is shown in the diagram of Fig. 4-4. The design is a test for the feasibility of building two linacs which would accelerate electrons and positrons toward each other to achieve very high energy center-of-mass collisions.

Cyclotrons

At about the same time that Cockcroft and Walton were developing the first linear accelerator, E. O. Lawrence at the University of California at Berkeley was working on a different way to accelerate particles. He realized that, while a magnetic field can do no work on a charged particle, it can be used to change its direction. A charged particle moving at right angles to a magnetic field will have its path bent into an arc of a circle. For a sufficiently large region of strong magnetic field B, the particle can be kept inside the region of the field as it is accelerated.

Lawrence realized that if he created two D-shaped regions of strong magnetic field, called "dees", and arranged them back-to-back with a region of electric field between them then the path of the particles would spiral around and pass through the gap many times. He called this device a cyclotron, it is shown schematically in Fig. 4-5

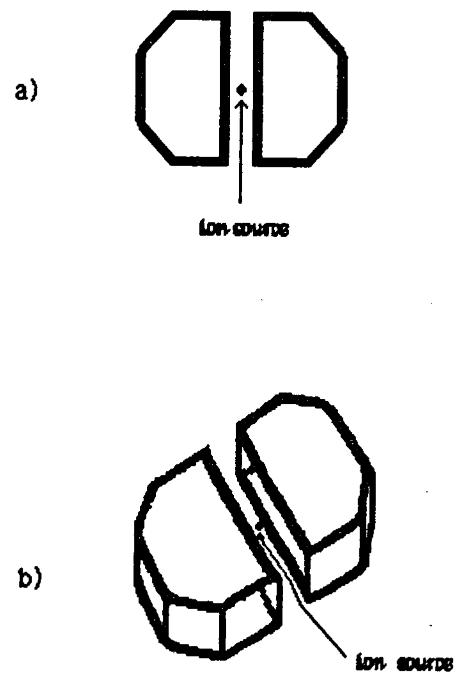


Fig. 4-5 The dees of the cyclotron developed by E. O. Lawrence. a) Top view. b) Perspective view. There is a magnetic field perpendicular to the top of the dees.

The path of a non-relativistic particle of velocity $\mathbf{v}$, mass m, and charge q has a radius

$$R = \frac{m\mathbf{v}}{\mathbf{qB}} .$$

As the particle speeds up the radius increases with the velocity. This means that, despite their different speeds, particles of various energies take the same time to complete a semi-circle. The particles are accelerated by the electric field in the region between the two dees, which switches polarity by the time the particles come through again in the opposite direction. Thus acceleration occurs each time the particle traverses the region between the dees. The frequency with which the electric field must be switched is $2\pi m/qB$. As with the other accelerators studied here, the entire acceleration region must be a vacuum. Cyclotrons have been designed both for electrons and for protons (and other positive ions). However the design is not well suited to achieve very high energies because it would require impossibly large areas of high magnetic field and high vacuum. Modern circular accelerators are all designed so that the particles travel in a circle of fixed radius. This then requires only a single evacuated tube. Electromagnets placed around this tube then provide the required magnetic field to keep the beam moving around the circle.

Synchrotron

The **synchrotron** is a circular accelerator most frequently used in high energy physics today. The beam travels in a fixed radius circle steered by the variable magnetic field of the electromagnets. The particles are accelerated by radiofrequency (RF) energy using cavities similar to those in an electron linac. The RF cavities are inserted at regular intervals around the circle into the evacuated tube surrounding the beam. The machine is called a synchrotron because the RF cavity feeding energy into the beam synchronizes the particles traveling through just as it does in the linac—the particles travel in bunches. A particle coming to the cavity too soon gets a smaller push than the average particle; one coming too late gets a greater push. A synchrotron used to accelerate electrons can operate at a fixed RF frequency because the electrons are already relativistic when they are injected into the synchrotron. The proton synchrotron must vary the RF frequency to be able to stay in phase with the protons as they speed up.

Synchrotrons lose energy from the beam by the radiation due to the acceleration that keeps the beam moving in a circle. This is referred to as synchrotron radiation. It provides a source of very high energy x-rays that can be used for medical purposes and for materials science research. It has also been suggested as a possible tool to make silicon microchips with very small integrated circuits.

The evacuated area around the beam is called the beam line. The high energies attainable by the proton synchrotron lead to designs with large radii of curvature. By the time the radius of curvature is greater than a few meters, one large magnet is not practical. The beam line is built using many small magnets. The magnets must be controlled to work in a synchronized fashion, which explains the name synchrotron.

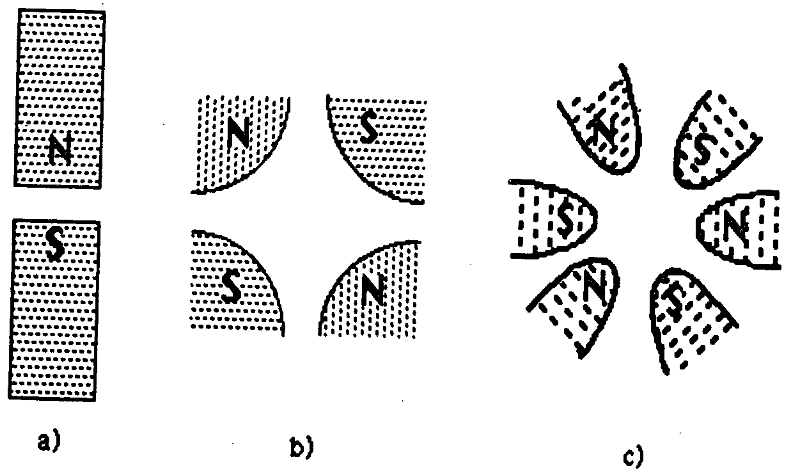


Fig. 4-6 Various magnet configurations. a) dipole. b) quadrapole. c) sextupole.

Many different types magnets are used — dipole magnets, quadrupole magnets, sextupole magnets, and bending magnets (see Figure 4-6). Each type of magnet is used for a different purpose. The bending magnet bends the beam in one direction, to make the circular orbits. Other magnets are used to keep the particles moving in a focussed beam bunch. If one looks at the effect on directions perpendicular to the beam line, a dipole magnet will bend particles at some distance from the center of the beam line toward the beam line along one axis, and bend them away from the beam line along the perpendicular axis. Quadrupole and sextupole magnets can make the beam focus better in both directions. The magnets are placed in a repeated sequence along the beam line. The particle beams are bent by magnets as light rays are bent by glass. Magnets act as lens elements. Accelerator physicists study the trajectories of particles in the beams using (essentially) the equations of geometrical optics!

Advances in magnet technology have led to ever higher energies attainable in proton synchrotrons. The proton synchrotron at Fermilab was able to double its design energy by use of superconducting magnet technology. The advantage of a superconducting coil for an electromagnet is that one can obtain higher fields at lower cost in power consumption since one is not continually losing energy due to the resistance of the coil. Also the current, and hence the field of conventional electromagnet coils are limited by the fact that resistance causes heating of the coil, and hence the magnet breaks down if too much current is passed through the coil. Superconducting coils have a different set of problems, but they have allowed higher field magnets to be operated reliably. So far magnets are only built with the older type of superconductor, which requires very low temperatures. Recently new materials have been discovered that become superconducting at higher, though still sub-zero, temperatures. No-one yet knows how to fabricate large magnets or even wires out of these materials. The proposed Superconducting Supercollider (SSC) will use superconducting magnets to guide the beam around its ring, which will be some 80 km in diameter.

Collision Kinematics

In a "fixed-target" experiment the beam is accelerated and then aimed at a target fixed in place. The total energy available in such an experiment is the energy in the incoming beam and the mass-energy of the target. Physicists use the term **laboratory frame** to describe the frame of reference in which the target is at rest.

In an experiment to study new particles the relevant quantity is the energy available to create new particles—that is the energy that can be converted into mass. However in a fixed-target experiment the total momentum of the incoming beam plus the target is large. This means that, by conservation of momentum, the outgoing particles must carry off a lot of momemtum and hence they must have large kinetic energy. The energy which goes into this kinetic energy is not available to produce new and interesting particles.

In colliding-beam experiments two beams of particles are made to cross one another, traveling in opposite directions with equal and opposite momenta. This means that the total momentum of the two colliding particles is zero and hence all the energy in both particles is available for the production of interesting objects.[*] The collisions in a colliding-beam machine are described as being in the **Center of Mass** or **CM frame**.

Comparison of the total energy in a CM collision with the energy available in a fixed-target collision is most appropriately done by viewing both collisions in the CM frame. For very high momentum, this is a calculation in special relativity. For a laboratory beam of momentum p it yields the result that

$$E \approx \sqrt{2mpc^3}$$

which can be compared with

$$E = 2pc$$

for collision of two beams of momentum p. Thus, since by assumption $p \gg mc$, it is better to have two beams of particles hitting one another than to have particles hitting a fixed target if the aim is the maximum possible total energy in the CM

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[*] This is precisely true if one of the beams is made from the anti-particles of the particles in the other beam. Even when both beams are protons and hence the colliding particles cannot annihilate it is almost true because the mass-energy of the protons is such a small fraction of the beam energy.

frame. For the most energetic accelerators, colliding beams are used. At very high energies few experiments are performed using fixed-target machines.

The fixed target machines do have one great advantage over the colliding beam machines. The target can be as long as desired and can be exposed to any number of beam particles so a large number of collisions between particles in the beam and those in the target can occur. In colliding beams, the two beams pass through one another. Since the beams are in fact mostly empty space even when they are intense, the number of collisions each time the beams pass through each other is small. Thus for experiments where a large number of events are required in order to make a precise measurement, fixed-target machines are preferred.

4.3. DETECTORS

The purpose of a detector is to record as faithfully and completely as possible the properties of the particles which are produced in high-energy collisions. At very high energies there are usually tens of particles produced in each collision (in each "event"). We require typically millions of events in order to unravel the many possible outcomes. Hence these devices must be able to record the events at a fast enough rate (typically one per second) so that experiments can be performed in a reasonable length of time, say not more than a few years (1 year $\approx 3 \times 10^7$ seconds). The amount of information recorded must also be consistant with our ability to analyze this data on a high-speed computer at a rate comparable with the recording rate. If not, the analysis time becomes decades or centuries rather than years which is, of course, an unacceptable situation.

What must the detector in fact measure? Let us return to our example of electron-positron collisions with typical event patterns shown by fig. 4-2. To fully reconstruct the final states we need to measure the momentum and trajectory of each of the final-state particles as well as its electric charge and mass. For each particle in an event, the latter two characteristics are sufficient to identify which of the known particle types it is. If we know the particle mass we can use a momentum

measurement to calculate the energy of the particle using

$$E^2 = p^2c^2 + m^2c^4 \quad ,$$

which is the Einstein mass-energy relation for a moving particle. These then are the goals of the detector design.

The particles produced in a high-energy fixed-target experiment are thrown forward (by conservation of momentum). The detectors are therefore placed to cover a limited cone in the forward region. Colliding beam experiments, by contrast, have the center-of-mass at rest in the laboratory and hence the produced particles may appear in any direction and the detector must be built to cover the full 4π solid angle. However the types of particles which are produced – namely charged particles, photons, neutral hadrons and neutrinos – are common to all experiments, and generic detector components which can "track" these different particles are found in every experiment (except for neutrinos).

A variety of techniques can be used to track any particular type of particle. For each experiment choices are made based on the characteristics of the physics process of interest, but constrained by practical considerations like cost, geometry, and the interplay of the different components (devices) making up the detector. It is not possible to discuss all possible particle detectors here. Instead we will describe some sample components and their function and then give a few examples of existing detectors to illustrate how these components are combined together to form the overall detector. We do not try to present a full historical perspective on detectors, but will mention cloud chambers and bubble chambers before focussing on the modern techniques.

Cloud Chambers and Bubble Chambers

In 1896, the **cloud chamber** was invented by C.T.R. Wilson at Cambridge. The chamber is closed and contains air saturated with alcohol at low temperature (such as supplied by dry ice). When radiation ionizes the air or alcohol molecules, the alcohol vapor condenses on the ions along the ionizing particle's track. Soon after its invention, it was realized that if a cloud chamber was placed between magnet poles, the tracks due to positive and negative charged particles would be bent in opposite directions by the magnetic force, so a particle's charge could be identified. Also, from the density of the particle's track, the experimenters could estimate the particle's mass. Permanent records of events were obtained by taking photographs of what happened for later analysis.

The cloud chamber was not really adequate for the sort of physics physicists wanted to do in the 1950's. Even with clearing fields inside them, cloud chambers were not terribly reliable. What was needed was some other detector that could handle high particle fluxes (rates) and provide evidence of what sorts of particles had been through. Donald Glaser of Michigan in 1952 developed the **bubble chamber**. Bubble chambers contain pressurized liquid hydrogen (or sometimes liquid argon or some other liquid), which is just on the verge of boiling. Liquid hydrogen boils at a very low temperature, about 40° K (or −230 degrees Celsius). When ready for use, a bellows reduces the pressure rapidly, so the liquid is ready to boil. When charged particles go through the liquid, the ions they create trigger boiling along the track of the particle. As long as the tracks are photographed before the entire liquid is aboil or the bubbles have drifted too far, they can be seen and measured. In order to get all three dimensions reconstructed, three different views of the same event are photographed. This leads to the production of immense numbers of rolls of film to record particle data.

The chamber is made ready to use again by using the bellows to increase the pressure. The bubbles become liquid again, and a small electric field sweeps ions from the previous pulse out of the way of the beam. Because of this repeated cycle, the bubble chamber was limited in the number of pulses per unit time. Because of the refrigeration equipment necessary to keep the chamber at liquid hydrogen temperature, bubble chambers were restricted in their detection volume. Furthermore the only detect charged particles. Also, if the source delivers too many particles to the bubble chamber, the pictures become so full of tracks that

no individual particle tracks can be measured. Bubble chambers were the mainstay of particle physics detection in the 1950s and 1960s but they are not much used today.

Modern Detectors

We now turn to a general discussion of modern techniques for particle detection and identification. Actual detectors used today combine many of the components described below into single, multi-faceted detectors that have many capabilities. They are quite large and complex. Among the parts one often finds drift chambers, multiwire proportional chambers, muon detectors, plastic scintillation counters, calorimeters, Čerenkov detectors, vertex detectors and very large magnets. The data is collected and analysed using computers.

The experimental apparatus in the future will be even bulkier and more dependent on the computer interface than today because the goals are far more elaborate. Physicists will have to band into even larger experimental collaborations than at present to be able to do physics at machines such as the SSC (the Superconducting Super Collider) and LEP (the new e^+e^- collider now under construction at the European Center for Nuclear Research (CERN) near Geneva in Switzerland and France). One of the collaborations building a detector for LEP involves 440 physicists from 39 universities and laboratories throughout the world (including India, China, the Soviet Union, the U.S., East and West Germany, France, Hungary, Switzerland, Netherlands, Italy, Bulgaria and Spain).

Particle Detection and Identification Through Energy Loss Rate

To detect particles we must utilize the fact that when they transverse a material medium, they transfer energy to that medium. This process occurs through ionization or excitation of the atoms in the medium. The particle detectors must utilize the remnants of the particle's energy loss in the medium to extract information. Two simple examples are the use of a gaseous detector to measure the trajectory of a charged particle or a dense material to absorb a photon. In the first

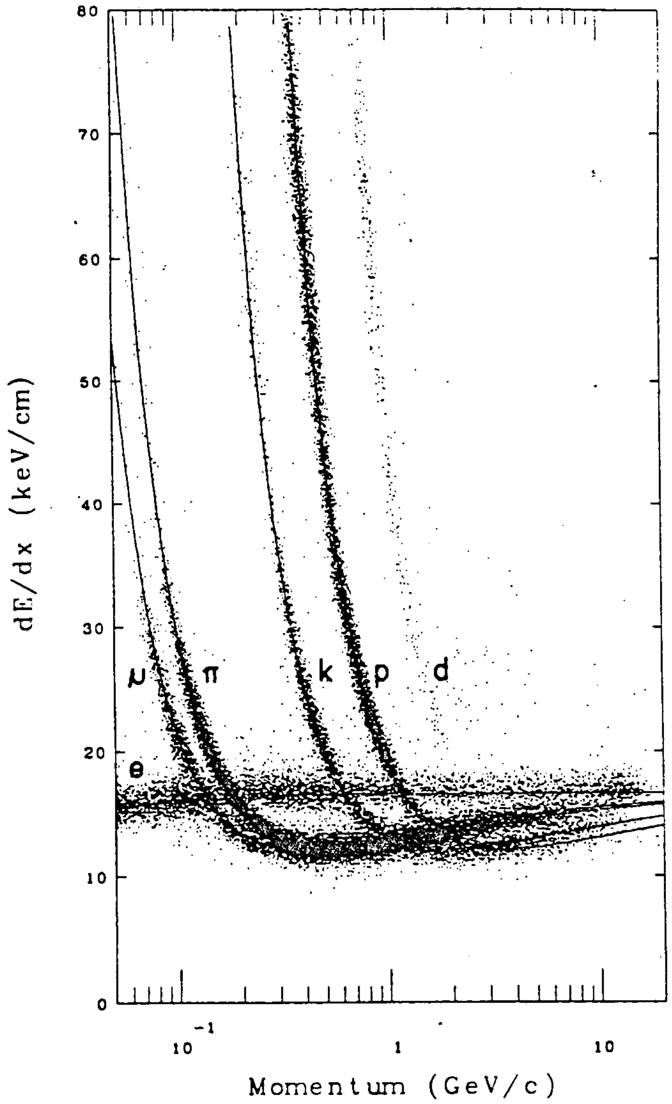

Fig. 4-7. - The energy lost per unit length in a gaseous drift chamber is plotted as a function of the charged particle's momentum (dots). The curves are the theoretical expectation for the particle types indicated on the figure namely electrons, muons, pions, kaons, protons and deuterons. This data is taken from the TPC detector at PEP.

case, the charged particle loses energy by creating a trail of ionized atoms (and liberated electrons) along its trajectory. If the position of the ionization can be sensed, then the trajectory can be inferred. In the second example, one attempts to segment and instrument the dense medium so that the site of the absorption can be determined as well as the total absorbed energy (that is the rise in temperature of the absorber).

We will begin the discussion of detector components by considering the detection of charged particles. The energy lost per unit length ($\Delta E/\Delta x$) depends on the charge (in units of e) of the ionizing particle and properties of the medium such as its atomic number, the amount of energy required to ionize its atoms, and its density. While $\Delta E/\Delta x$ does not depend on the mass of the ionizing particle, it does depend on its velocity (v). Fig. 4-7 shows the actual measurement of energy loss for charged particles as a function of momentum taken from a gaseous tracking chamber running at the PEP storage ring. The dots are the data and the curves are the theoretical expectation for different particle species. The ionization loss is seen to fall to a common minimum for all particle species and then exhibit a slow rise as the particles become relativistic. The curves corresponding to different particle species are separated when plotted against the momentum variable, since particles of different mass have different velocities at the same momentum.

When relativistic charged particles traverse a medium, they lose energy uniformly and rather slowly. After sufficient material is traversed, their velocity is reduced to the point where they will begin to lose energy more rapidly and ultimately be absorbed. Most particles produced in high-energy collisions have high momentum and will pass through many meters of gas without significant reduction in their energy. Such particles will be absorbed, however, by a few meters of heavy metal such as steel or uranium.

Electromagnetic Showers indicate Electrons or Photons

For all charged particles, except electrons, the ionization process discussed above is the most important energy-loss mechanism. A second phenomenon dominates the electron's energy loss in dense (solid) materials, because electrons are very light (the next lightest charged particle, the muon, is about 200 times heavier). In dense materials, electron paths are strongly bent by the electric fields inside the atoms that they pass through. This causes the electrons to radiate photons and thus lose energy. This is called bremsstrahlung. Each photon then typically converts to an electron and positron pair. This electron and positron in turn lose energy via bremsstrahlung and the cycle repeats itself until the energy is fully absorbed. Hence, as the electron traverses the dense medium, it loses energy rapidly, producing a "shower" which is localized along its path. The shower has a transverse size of a few centimeters and a penetration depth of about 2-20 cm for momenta of interest and for a typical absorber material like lead. This discussion also applies to the detection of high-energy photons; the same shower phenomenon takes place whenever a high-energy photon is present. To distinguish electrons from photons one needs additional components in the detector, since in a dense medium they leave the same signature.

A device to measure the electromagnetic showers described above is called a shower counter or an **electromagnetic calorimeter**. The number of showering particles is proportional to the initial photon energy, hence if a calorimeter can count the number of showering particles, the energy can be measured. A typical calorimeter is made up of a "sandwich" of dense absorber, usually lead, followed by a detector to record the showering particles, followed by another absorber plate, followed by a detector etc. The thickness of each layer of absorber should typically be about 10% of the total amount of material needed to totally absorb the incident photon. A sandwich counter of this kind therefore samples the development of the cascade rather finely.

There are several choices of detectors used for sampling the cascade. A typical example could be a **multiwire proportional chamber** which is described below. Such a device counts the ionization, but at the same time the struck wire locations measure the position of the shower, and thereby the position of the initiating photon or electron. Another option is strips of scintillating plastic in which the

ionization energy is converted into scintillation light. This light propagates along the length of the plastic counter (just as the charge propagates along the wire in the proportional chamber). Its intensity is sensed by a light-sensitive amplifier called a "phototube".

Charged Particle Tracking – Magnetic Spectrometer

We can measure the direction and momentum of charged particles, using a combination of a tracking device and a strong magnet. The fact that relativistic charged particles leave an ionization trail in a gas volume while themselves not losing a significant fraction of their total energy allows us to follow the tracks over large distances and hence measure both their initial direction and the bending of the track due to the magnetic field. Such a device is called a magnetic **spectrometer**.

Consider now placing a spectrometer, as shown in Fig. 4-8, "downstream" of the target in a high-energy, fixed-target experiment. Imagine that A and A′ are gaseous detectors capable of measuring the direction of the charged particle whose trajectory is shown in the figure. The charged particles which are produced will travel towards the spectrometer. As they leave the target, counter A measures their position and the direction (angle) of their trajectory. From the difference in the particle direction in detector A and A′, we can measure the angle of bend of the particle. This angle of bend is proportional to the magnetic field of the dipole magnet (B) and inversely proportional to the momentum of the particle. Thus if we know the magnetic field (which we can measure in a laboratory), and the angle of bend, we can calculate the particle momentum. The deflection direction also measures the sign of their electric charge. As long as the devices A and A′ have the ability to simultaneously measure the directions of all the produced particles and the spectrometer has a large enough geometrical coverage to "catch" all charged particles, this device would provide the directions and momenta of all the charged particles produced in the collision. Indeed this is how it is done in fixed-target experiments.

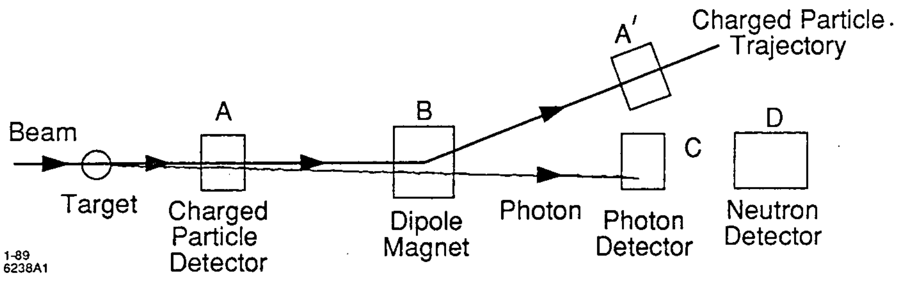

Fig. 4-8. - A schematic of a typical fixed-target detector setup. The beam enters from the left and impinges on a target. A charged particle trajectory is shown as a solid line. It is measured in the tracking chambers A and A'. A dipole magnet (B) deflects the charged particle through an angle proportional to the particle's momentum. The wavy line emanating from the target represents the trajectory of a photon produced in the target (the line is wavy only to distinguish it from the other lines; the waviness has no physical meaning). It travels through the magnet undeflected and is detected in the electromagnetic calorimeter (C). Neutral stable hadrons, like a neutron, would be absorbed in the hadron calorimeter (D), placed behind the electromagnetic calorimeter.

But what of the photons? The spectrometer will not tell us about them. (The primary source of photons is from the decay of neutral pions, $\pi^0 \rightarrow \gamma + \gamma$, which occurs very rapidly after their production.) Clearly photons proceed undeflected by the magnetic field and will arrive at the region where we have placed detector C. If detector C is a sufficiently large electromagnetic calorimeter it can measure the positions and energies of all the photons produced. A further device called a hadron calorimeter, detector D, is needed to detect any neutrons produced.

Charged Particle Tracking – Proportional Counters

Most charged particle tracking devices used today are based on the **proportional counter**. The simplest such device is a cylindrical metal tube, filled with an appropriate gas and maintained at a negative potential. A thin central anode wire at positive potential is placed in the tube, producing a radial electric field. Any electron liberated by the ionization process will drift towards the anode wire gaining energy from the electric field. If the electron gains sufficient energy to exceed the ionization energy of the gas, fresh ions are liberated. A chain of such processes results in an avalanche of electrons at the anode wire. This avalanche can be sensed as a current in the wire by a suitable electronic circuit. The device is called a proportional tube or chamber because the signal is proportional to the number of charged particles that passed through the tube.

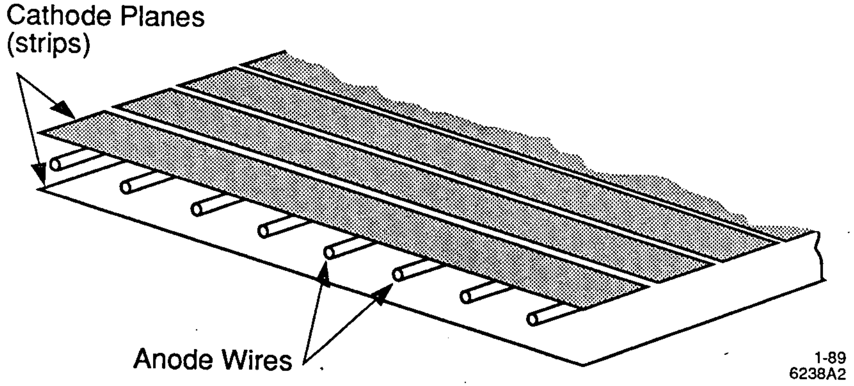

Fig. 4-9. - A portion of a multi-wire proportional chamber is shown illustrating the position of the anode wires which collect the avalanche of electrons produced in the gas when a particle traverses the device.

This same principle is used in multiwire proportional chambers as shown pictorially in fig. 4-9. A plane of many parallel anode wires is supported between two cathode planes. Each anode wire acts as an independent detector. The cathode planes may be segmented into strips running in a direction perpendicular to the anode wires. The cathode strips will detect currents induced on them from the drifting ions. These signals can also be read out to provide additional localization information. In Fig. 4-8, devices A and A$'$ could be made up of many layers of planar multiwire proportional chambers, with anode wires oriented alternately in the horizontal and vertical direction. Charged particles which traverse such a stack will leave a pattern of signals in the wires closest to the particle paths. Computer software can then be used to reconstruct the trajectories of the particles passing through the device.

Charged Particle Tracking – Drift Chambers

Multiwire proportional chambers will have a spatial resolution determined by the inter-wire spacing, namely about 1 mm. For many applications this is not good enough. In addition, they require an enormous number of instrumented anode wires to cover a large area. A refinement called a **drift chamber**, in which we measure the time taken for the ionization to travel from the point of origination to the wire, allows the inter-wire spacing to be increased to about 10 cm while still permitting spatial resolution of about 100 microns (1 micron = 10^{-6} meters). To measure this time we must measure the arrival time of the beam (the moment of the collision) very precisely. Another requirement (due to the long drift distances) is that the drift field be quite uniform. To achieve this, field-shaping wires are needed, in addition to anode and cathode sense wires, A typical design of the set of wires forming the basic unit or "cell" of a drift chamber is shown in fig. 4-10(b).

Fig. 4-10 shows the design of a cylindrical drift chamber, which is the typical shape for a collider detector. Stacks of planar drift chambers are typical in fixed-target detectors; to reconstruct the direction of tracks alternate layers are arranged to have their wire directions measure horizontal and vertical track coordinates.

Other Neutral Particles

We have now discussed the main elements of a detector illustrating how they might be combined for a fixed target experiment to measure the position and momenta of charged particles and photons. Neutrinos produced in the collisions

are not detected, though their production may sometimes be inferred because of the energy and momentum that they carry off. Neutrinos undergo only weak interactions and hence no practical method for efficient detection exists in a general detector. However, large, specialized detectors have been built which can detect the effects of the collisions of neutrinos with the immense mass of material in the detector.

Neutral, stable hadrons like neutrons require further instrumentation. Neutrons are detected in **hadronic calorimeters**. These are very much like electromagnetic calorimeters except that the material used is usually steel and the thickness of the sandwich slices is governed, not by the physics of an electromagnetic cascade, but by the multiple nuclear interactions by which the neutron loses its energy. Considerably more material is required to absorb hadrons than photons – hence hadron calorimeters are more massive. They are usually placed immediately behind the electromagnetic calorimeter, like device D in fig. 4-8. Of course all hadrons, charged hadrons too, are absorbed by such calorimeters. For charged hadrons they add a complimentary energy measurement to that obtained from the magnetic spectrometer. In many situations, particularly at higher energies, the calorimetric energy measurement is more precise than that obtained from the magnetic spectrometer. However the charged particle directions are measured considerably better by the spectrometer.

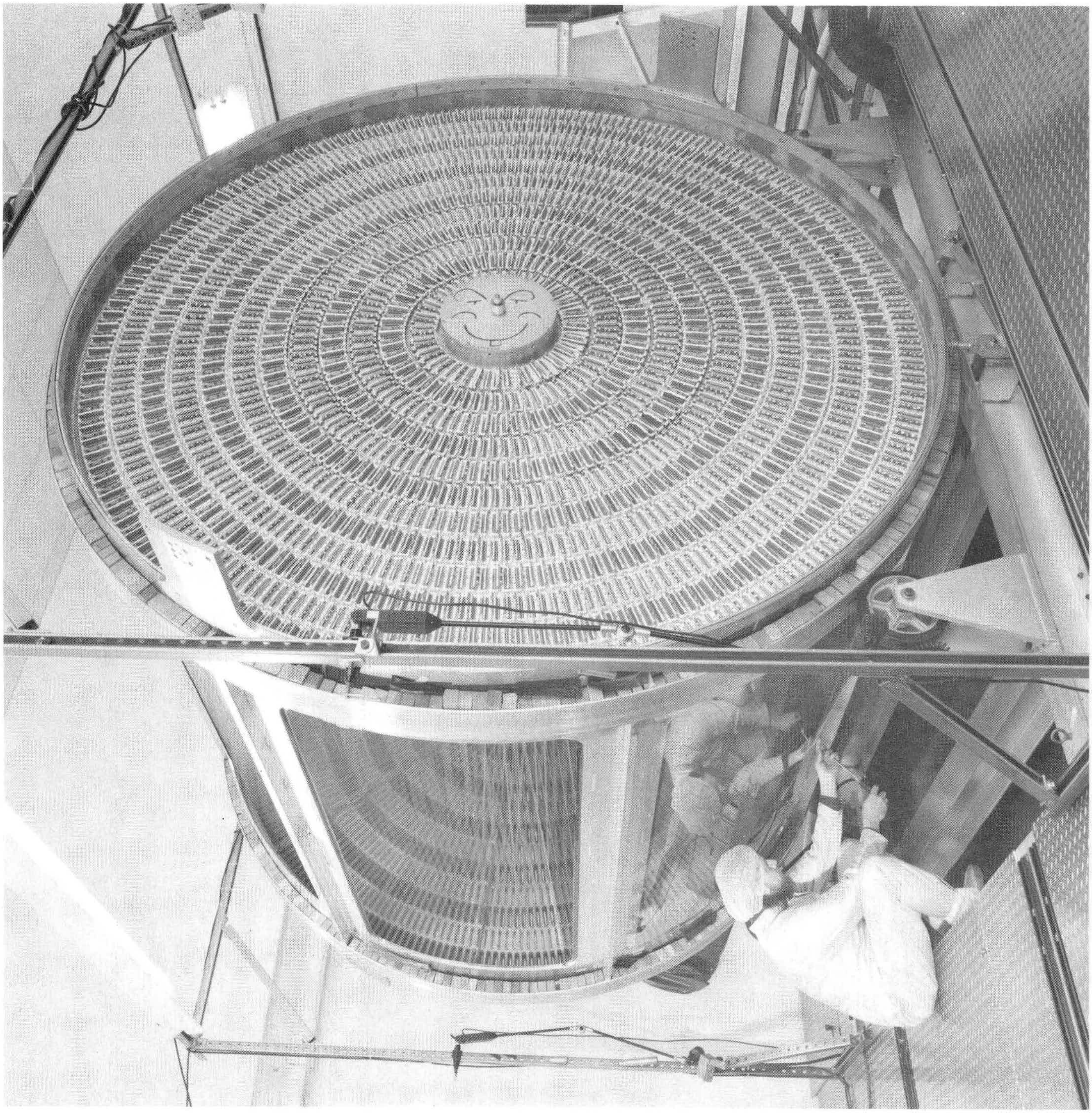

Fig. 4-10. - a) The inner part of the Mark II drift chamber during construction. The many wires can be seen, as well as the precision-drilled end-plate which serves to hold them in place. (Photo by Joe Faust).

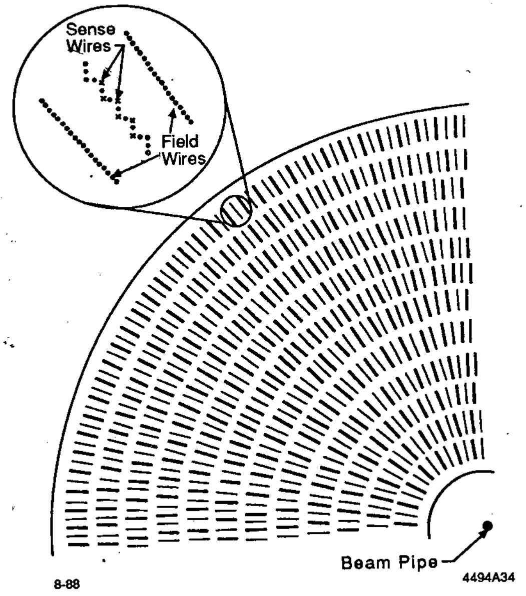

Fig. 4-10. - b) A quadrant of the end-plate of the large, cylindrical drift chamber used in the MARK II detector. A blowup region shows the position of the field wires and the sense wires for a single "cell".

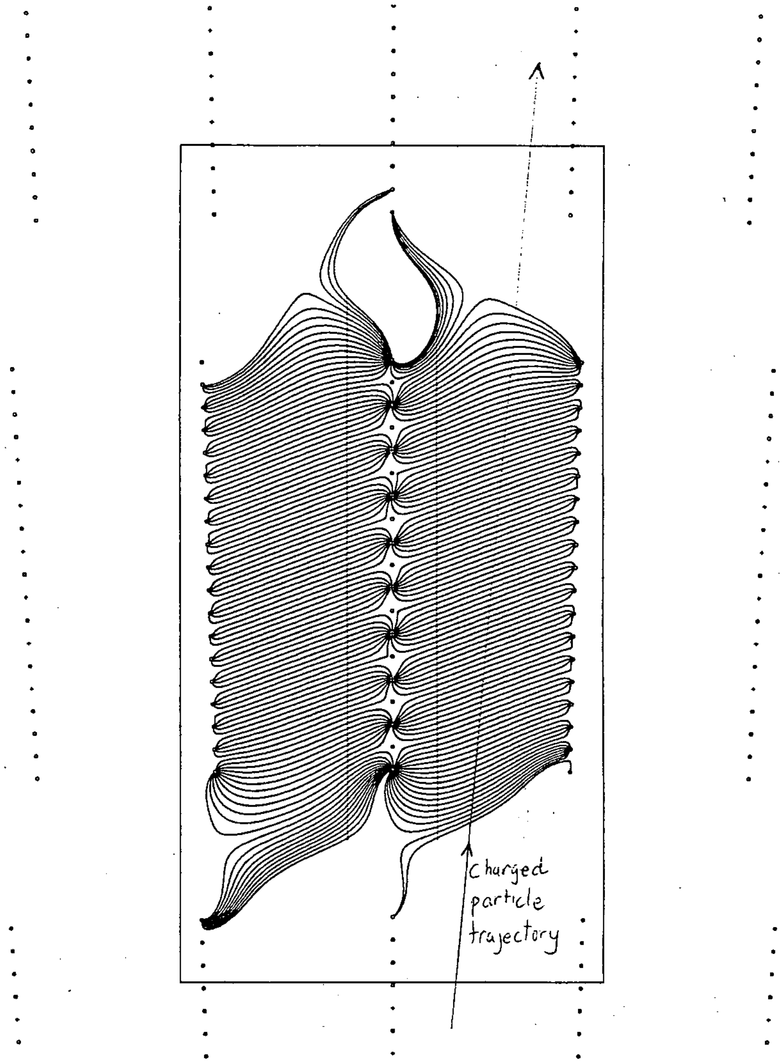

Fig. 4-10. - c) The paths taken by the electrons as they drift towards the sense wires are shown. Electrons liberated along the particle trajectory follow these drift lines to the sense wire.

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Collider Detectors

The devices which we have described as elements of a fixed-target experiment, are the same as those used in a colliding-beam experiment. However the geometry is different since the produced particles populate the full 4π solid angle (the entire sphere) subtended by the collision point. A prototypical detector, the Mark II at SLAC, is shown in fig. 4-11. The detector devices are arranged in cylindrical symmetry around the evacuated "beam pipe" which contains the particle and anti-particle beams. The beams are made to collide in the center of the detector. The ends of the cylinder are also instrumented. Charged particles produced in the collision travel out through the beampipe and are tracked in a large gas-filled **drift chamber** which provides 72 radial measurements of the ionization deposited by the particle. (The wires are parallel to the beam direction). A solonoidal magnetic field (field lines are also parallel to the beam direction) is provided by the coil as indicated in the figure. The combination of a solonoidal field and the cylindrical drift chamber allows us to measure the momentum, the sign of the electric charge and the trajectories of all the charged particles. Photons traverse the charged particle tracking system without leaving any signal and enter the electromagnetic calorimeters where their positions and energies are measured. These counters are segmented in a manner similar to the earlier explanation of "sandwich" type calorimeters. The Mark II does not have hadron calorimetry and therefore particles like neutrons are not detected in it. If a hadron calorimeter were included it would have to be placed outside the electromagnetic calorimeter, but inside the muon counters.

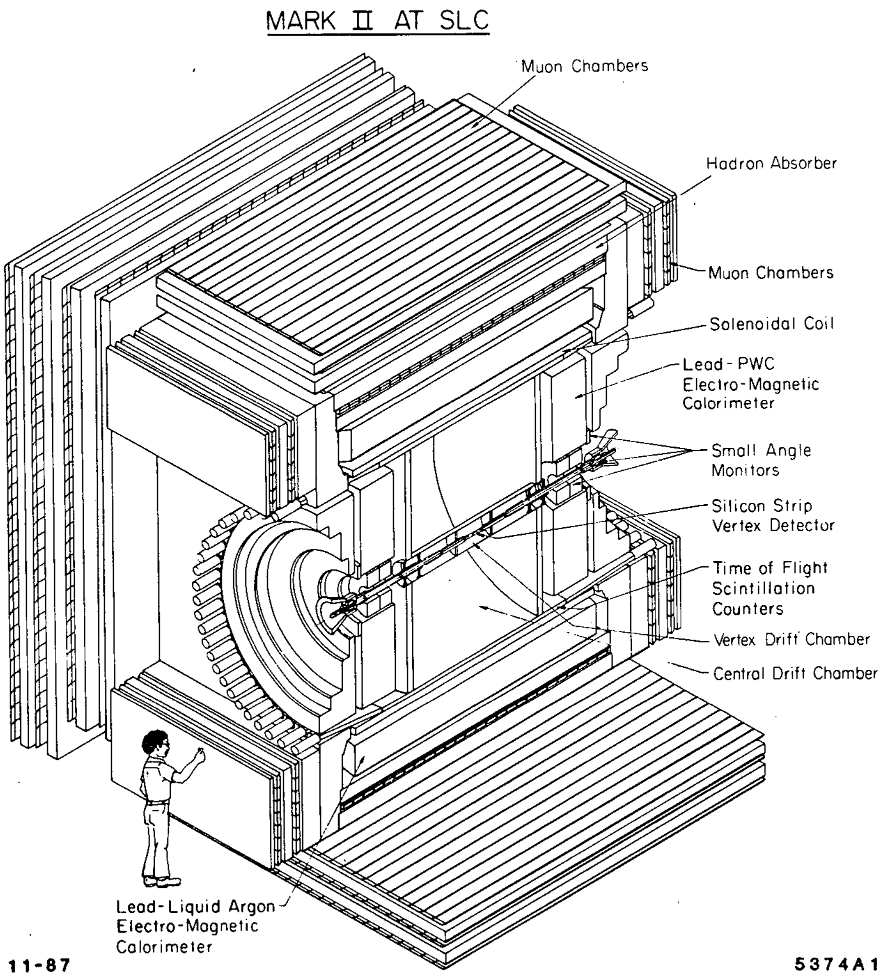

Fig. 4-11. - An drawing of a typical colliding beam detector. The major components are discussed in the text.

More on Particle Identification

We have not discussed yet how we measure the particle mass, that is the identity of the charged particles. In general it is hard to use a single device to separate all the charged particle types over the full range of momenta of interest. Fig. 4-7 shows how once a charged particle's momentum is known, its identity can be inferred by a measurement of the energy lost by the particle in the gas of the tracking chamber. However one sees that above about 1 GeV/c, the separation power is lost for most species. For higher momenta other methods must be used. Electrons are identified by the electromagnetic calorimeter where they are totally absorbed while all other energetic charged particles continue on. Hence localized showers in the calorimeter which can be linked to a charged track in the drift chamber are identified as electrons, provided that the energy measured by the calorimeter matches the momentum measured in the tracking system.

There are methods for separating high momentum pions, protons and kaons, but we omit a detailed description other than to say that they typically employ the phenomena of Čerenkov radiation. This radiation occurs when a particle travels through a medium at a speed greater than the speed of light in that medium. The radiation is emitted in a cone about the direction of travel of the particle. The angle of the cone is directly related to the speed of the particle. Hence measurement of this angle can be combined with an energy measurement for the particle to find its mass, and hence its identification.

Muon Detection

Muons do not shower in calorimeters because of the muon's greater mass. In addition they do not undergo repeated nuclear collisions in a dense absorber like steel because muons do not "feel" the strong force. So high-energy muons will traverse large quantities of steel before their energy is depleted due to ionization processes and, in fact, they leave the detector before all of their energy is gone. In fig. 4-11 then one notices that around the periphery of the Mark II there are 4 layers of thick (12 inches per layer) steel plates interspersed with proportional tubes.

The only charged particles produced at the collision point which can penetrate all four steel layers are high energy muons. The track trajectories measured by the proportional tubes between the steel plates can be linked to the track trajectories the muon made in the drift chamber. In this way muons are identified. The detection of muons is very important since they (along with electrons) play a very important role in discovering "new" physics as we saw with the example of the τ.

Vertex Detectors

Those hadrons which decay only via the weak interaction (such as the D^+ shown on the wall chart) have sufficiently long lifetimes (about 10^{-13} seconds) that they travel far enough before decaying to permit a measurement of their lifetime (about 0.2 mm). To do this requires placing high-resolution measurement devices as close to the production point as possible. Such devices are called **"vertex detectors"**. The MARK II detector (fig. 4-11) has two such devices; one is a carefully constructed, pressurized drift chamber capable of measuring track positions to 30 microns (1 micron = 10^{-6} meters) and a three-layer silicon strip device capable of measuring positions to 5 microns. Long-lived objects can play an important role in understanding or isolating unexpected physics.

Event Pictures

Fig. 4-12 shows several "event pictures" taken from Mark II data at the PEP e^+e^- storage rings. Computer reconstruction software has been applied to the measured (digitized) hits in the detector devices. In this fashion we can reproduce the trajectories and momenta of the charged tracks and find the energy and positions in the calorimeters of the photons. The patterns of the events correspond to those final states which we discussed in the "Colliding Beam Experiments" section near the beginning of this chapter (see fig. 4-2). Fig. 4-12a is the e^+e^- final state, where two oppositely charged tracks, traverse the drift chamber is a back-to-back configuration and deposit their full energy in the electromagnetic calorimeters. Contrast this with fig. 4-12b which looks identical except that the charged particles are not absorbed in the calorimeters but in fact penetrate through the steel of the muon system. This is a $\mu^+\mu^-$ final state. Following from the explanation of fig. 4-12a,b we deduce that fig. 4-12c is an event with a $e^+\mu^-$ final state, which comes from $\tau^+\tau^-$ production as discussed earlier. Finally fig. 4-12d,e are multiparticle events, both charged and neutral, coming from the process $e^+e^- \to q\bar{q}$. Notice the clear "jet" structure at these high energies. The hadrons which materialize from the quarks follow relatively well the original quark directions.

In Fig. 4-12 the charged tracks appear as curved trajectories in the central drift chamber – the larger the curvature the smaller the momentum. The small "boxes" at the periphery of the drift chamber measure the time (in nanoseconds) taken by the charged particle to travel from the production point to the time-of-flight scintillation counter. For particles with momenta below 1 GeV/c, the combination of this flight time and the momentum is sufficient to distinguish pions, kaons and protons. The hexagonal area delineates the electromagnetic calorimeter in which the energy deposited by the charged tracks and the photons (those lines in the calorimeter which do not have a charged track pointing towards them). The numbers next to the energy deposits in the calorimeter are the energy measured in GeV. In figs. 4-12 b) and c) the muon system is shown with the drift chamber track trajectory extrapolated to the hits in the muon proportional counters.

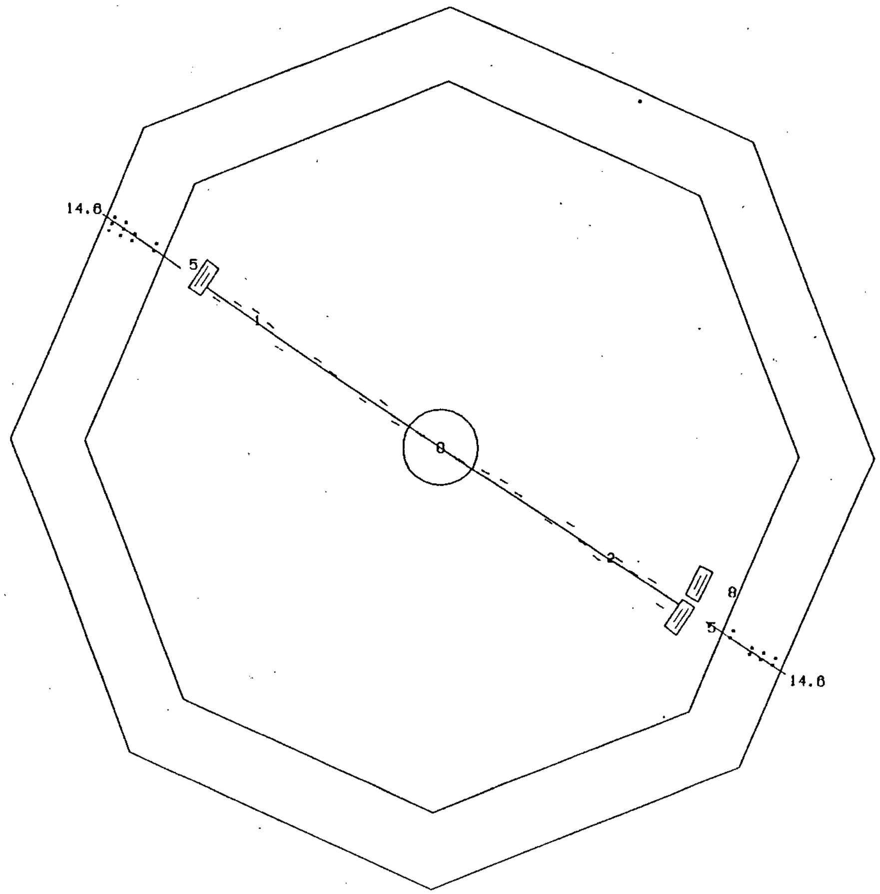

Fig. 4-12. - a) An e^+e^- final state. Two high-momentum, back-to-back tracks with momenta measured as 14.5 and 14.2 GeV/c each depositing 14.6 GeV of energy in the calorimeter. The beam energy in this run was 14.5 GeV.

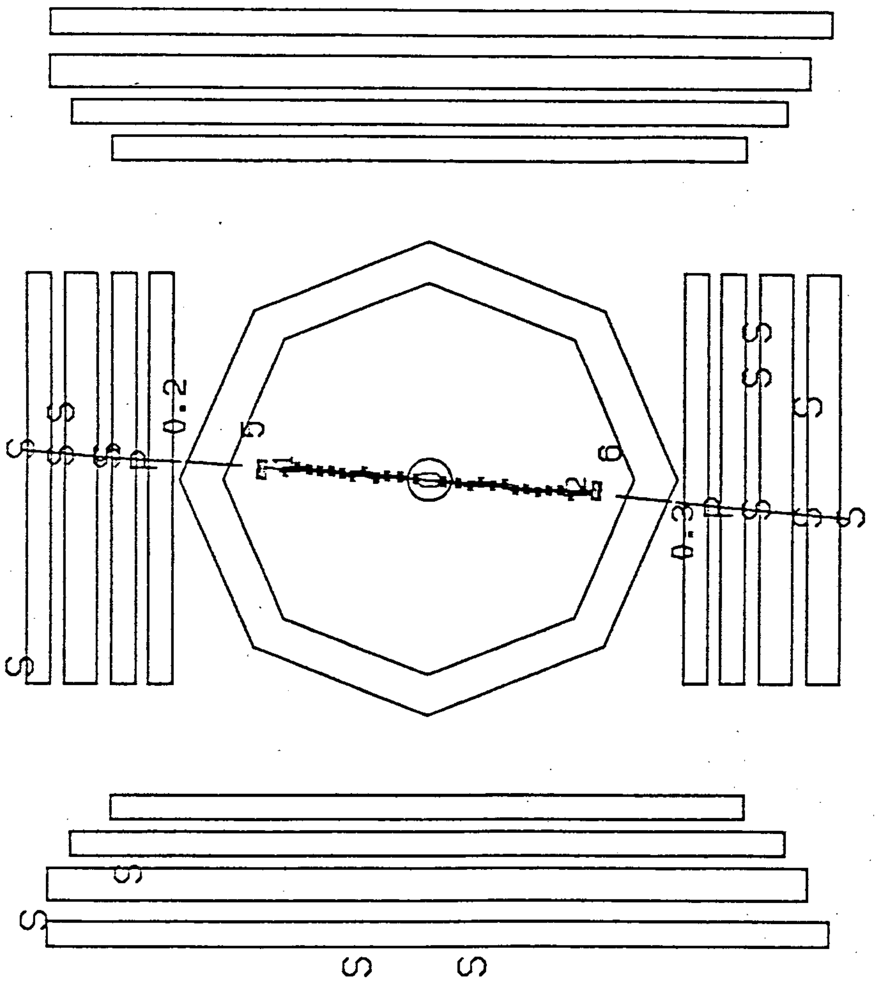

Fig. 4-12. - b) A $\mu^+\mu^-$ event. The same pattern as a) but both tracks are clearly muons. Notice the small energy loss in the calorimeter and the penetration through the full muon system.

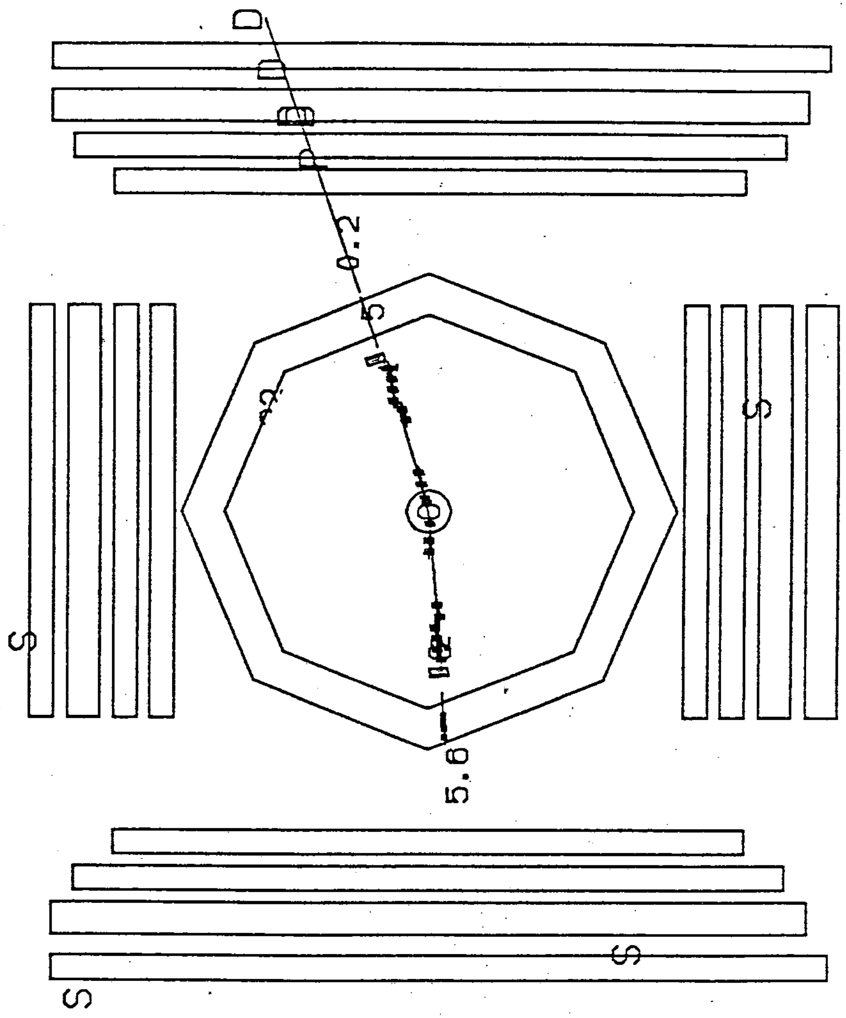

Fig. 4-12. - c) An $e^+\mu^-$ event which results from the production of $\tau^+\tau^-$ as discussed in the text.

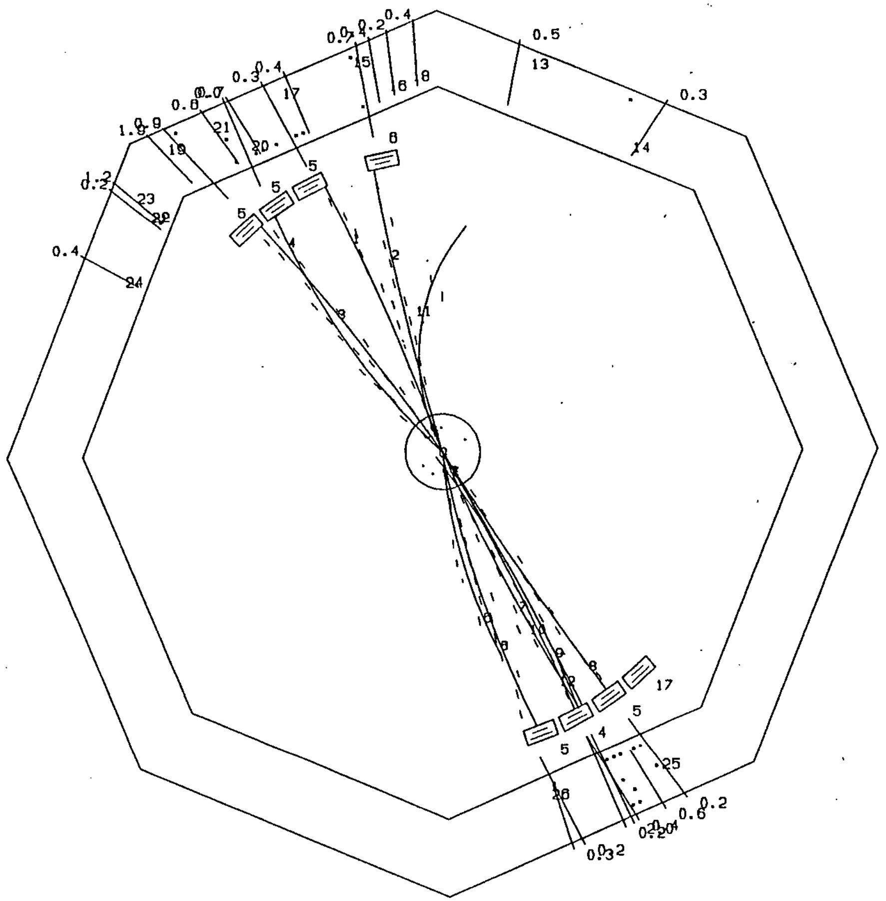

Fig. 4-12. - d) A two-jet event resulting from $q\overline{q}$ production.

5. Experimental Basis of Particle Physics

Like the rest of physics, particle physics is an experimental science. The elegant and eminently successful Standard Model stands on a firm foundation of experimental results accumulated over the past half century. This achievement is especially remarkable because the particles that are the objects of investigation are incredibly small and in most cases persist for only tiny fractions of a second.

5.1. THE NUCLEUS

How is it possible to study nuclear and subnuclear matter? The first experiment to do this was an archetype. In 1909, two young researchers, Ernest Marsden and Hans Geiger, were working the laboratory of Ernest Rutherford in Manchester, England. They used a radioactive source that emitted alpha particles, that is, ionized helium atoms. They were measuring how much the alpha particles were deflected from their original path when they passed through a thin metal foil. At Rutherford's suggestion they also checked to see if by chance some alpha particles, instead of deviating a few degrees from their original path, actually bounced backward. To the astonishment of all, they found that this happened fairly frequently. This led Rutherford to propose that at the center of the atom there must be something very small that carried a large charge - the nucleus.

Geiger and Marsden performed an experiment with a *beam*, the alpha particles, a *target*, the atoms in the foil, and a *detector*, which was a screen viewed by a microscope. See Fig. 5-1. When the alpha particles struck the zinc sulfide screen, light was emitted that was visible through the eyepiece. These same elements – beam, target, and detector – are present in nearly every particle physics experiment.

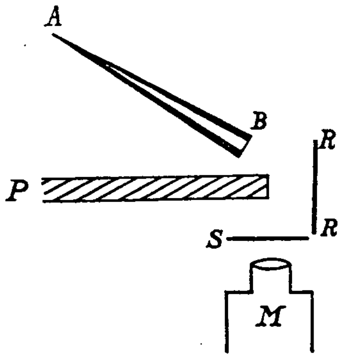

Fig. 5-1. Diagram of the apparatus of Geiger and Marsden. The alpha (α) particles emerged from the tube AB. They bounced off the screen RR and struck the zinc sulfide screen, S. This produced scintillations that could be observed through a microscope, M. The shield, P, prevents alphas from striking the screen directly.

5.2. COSMIC RAYS

The alpha particles that Rutherford used for his beams have a severe limitation: they have energies of only a few MeV (million electron volts). Other researchers began to study collisions of cosmic rays with targets. The cosmic rays are generated in outer space and rain upon our atmosphere. They collide with atoms in the atmosphere and create more particles that have very high energies, much higher than those of emitted alpha particles. On the other hand, the cosmic rays cannot be controlled, nor their time and place of arrival anticipated.

Using a cloud chamber in 1932, C. D. Anderson of the California Institute of Technology discovered the *positron*, a particle just like an electron, but with the opposite charge. He observed a track in his cloud chamber that curved in the magnetic field. See Fig. 5-2.

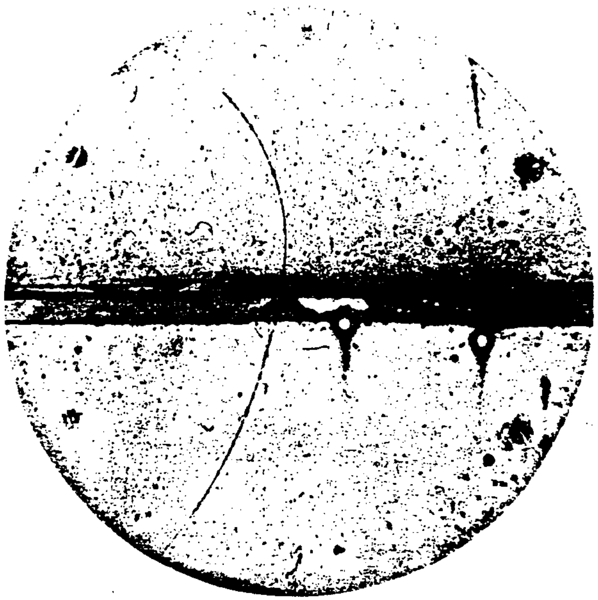

Fig. 5-2. The cloud chamber picture taken by C. D. Anderson showing a positron entering from below and passing through a lead plate. The positron lost energy in the plate and therefore followed a more curved path in the magnetic field afterwards. From the direction of the curvature the particle was known to have a positive charge. A proton with the same momentum could not have traversed such a great distance, so the track must have been made by a previously unknown particle. [C. D. Anderson, *Phys. Rev.* **43**, 491 (1933)]

In the middle of the cloud chamber he had placed a metal plate. This enabled him to determine whether the particle had entered from above or below the plate because the particle lost momentum in passing through the plate and curled up more in the magnetic field. From the direction of the particle's motion and its curvature Anderson knew it was positive. From its ionization track he knew it could not be a proton. He had found the first elementary particle that does not exist in ordinary matter. The positron is not found ordinarily because when it collides with an electron the two annihilate to form two photons. This process has an important medical application, positron emission tomography (PET), which enables researchers to locate precisely artificially produced positron emitters that can be introduced into the body in specially prepared radioactive compounds.

Five years after Anderson's discovery a new particle, the muon, was found in cosmic rays. The muon is distinguished by its ability to penetrate large thicknesses of material. Electrons do not penetrate nearly so far because they lose large quantities of energy by emitting photons. Protons do not penetrate very far because they undergo nuclear collisions.

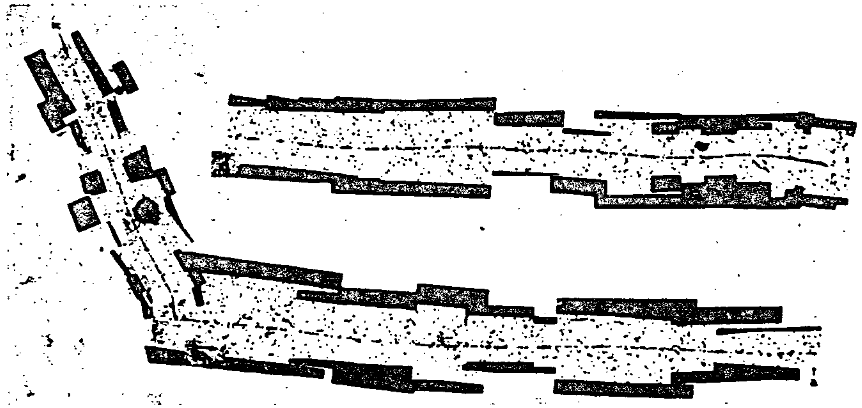

Fig. 5-3. A picture of a photographic emulsion showing a π^+ meson coming to rest (from upper left corner). The $\pi^+ \rightarrow \mu^+ + \nu$ reaction occurs and the μ^+ goes off to the right (continued above) and also comes to rest. The μ^+ also decays to an e^+ and neutrinos. This emulsion was, however, not sensitive enough to record the e^+ (and neutrinos are not observable in such experiments). [C. M. G. Lattes *et al.*, *Nature* **159**, 694 (1947)]

When the muon was discovered it was mistaken for a particle that had been predicted by Hideki Yukawa of Kyoto University. Yukawa had shown that the binding of neutrons and protons in the nucleus could be explained by a particle

with a mass a few hundred times as great as that of the electron. Just after World War II, further cosmic ray research revealed that the muon was not Yukawa's particle because it did not interact strongly with the nucleus. The true Yukawa particle, the pion, was discovered in cosmic ray events and it was found that it decayed into a muon and a neutrino, see Fig. 5-3.

5.3. STRANGE PARTICLES

In the first few years after the Second World War, many perplexing discoveries were made studying cosmic rays. All involved particles with very short lifetimes.

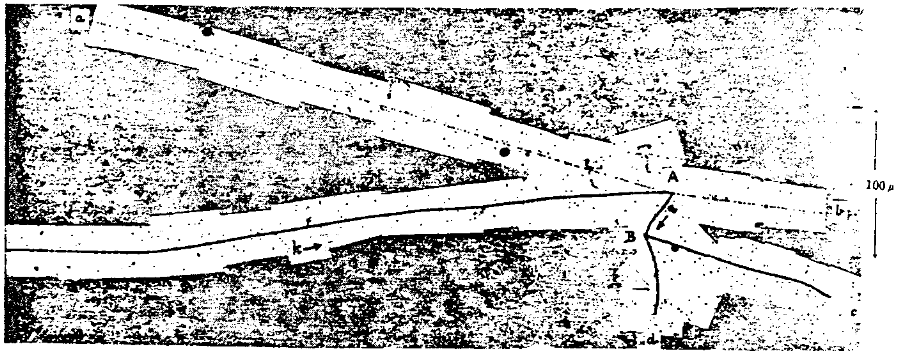

Fig. 5-4. The decay of a K^+ to $\pi^+\pi^+\pi^-$. The picture is of a photographic emulsion exposed to cosmic rays that was sensitive to charged particles. The K^+ entered along the path labeled k. At the point A, the K^+ decayed into three charged particles. The π^- interacted with a nucleus at the point B. [R. Brown et al., *Nature* **163**, 82 (1949)]

Just as we cannot predict when a radioactive nucleus will decay, we cannot say when an unstable particle will decay, only what its life expectancy is. The charged pion has a lifetime of about 2.6×10^{-8} s. Cosmic ray studies revealed new particles with lifetimes from 10^{-8} to 10^{-10} s. These included the Λ, which decays either into

$\pi^- p$ or $\pi^0 n$, and the K^+ which decays in many ways, including $K^+ \rightarrow \pi^+\pi^+\pi^-$ and $K^+ \rightarrow \mu^+\nu$. See Fig. 5-4.

These new particles brought confusion because their lifetimes seemed too long! The particles were created in collisions of neutrons and protons, or between other particles that feel the effect of the strong interactions, which bind together the nucleus. It was possible to estimate that if this same strong force was also responsible for their decay, their lifetimes should have been shorter by about a factor of 10^{-13}. The solution to the paradox was given by A. Pais and M. Gell-Mann. The new particles were created in pairs. Each of the new particles could be assigned a value of "strangeness," a quantity like electric charge except that this charge is conserved only in the strong and electromagnetic interactions. Thus the collision of two nonstrange particles, π^- and p can create a K^+ with strangeness one and a Λ with strangeness minus one. The Λ decays to $\pi^- p$ in a process that changes strangeness. (The decay $\Lambda \rightarrow K^- p$, which would not change strangeness, cannot take place because the mass of the Λ is less than the sum of the masses of the K^- and the p.) This flavor-changing process occurs through the weak interactions. Because the weak interactions are in fact weak, the decays proceed more slowly than they would if they were strong decays.

5.4. PARITY VIOLATION

Perhaps the most remarkable event in particle physics history was the overthrow of the law conservation of parity. Simply stated, the conservation of parity says that if an experiment is performed in front of a perfect mirror an observer cannot determine which was the real experiment and which is the image. Both would appear to follow all physical laws. Sometimes this is phrased as "Nature does not distinguish between right-handed and left-handed," since a right-handed experimenter would appear left-handed in the mirror. Why did people believe that conservation of parity was correct? All of the known laws of physics - Newton's Laws, the Maxwell equations, the Schrödinger equation, etc. - made no distinction between right and left. (The occasional "right-hand" rules that afflict the study of

magnetism are always matters of convention. The magnetic field is defined with a right-hand convention, but then the force law also has a right-hand convention. We get the same results for physical quantities like forces if we use left-hand rules everywhere.) No experiments had ever shown a violation of parity conservation.

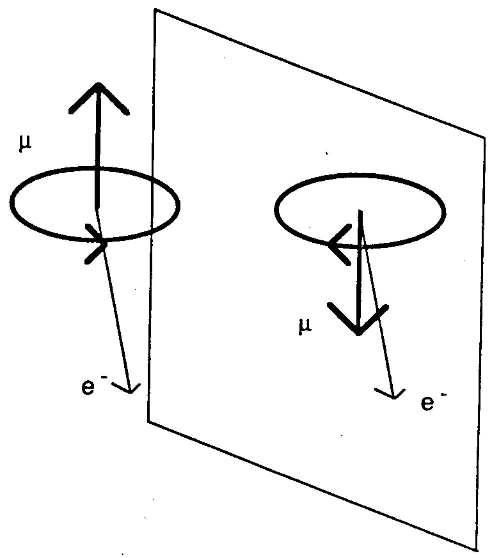

Fig. 5-5. A nucleus with spin in front of a mirror. The mirror image has its spin and magnetic momentum pointing opposite that of the real nucleus. If there is a correlation between the direction of the magnetic moment and the direction of the outgoing electrons from β decay, the correlation in the mirror will be the opposite. Thus it will be possible to distinguish between the real experiment and its mirror image. C. S. Wu and her co-workers found such a correlation and thus demonstrated that parity is not conserved.

T. D. Lee and C. N. Yang realized that no experiments had been done that could test whether parity was conserved in weak interactions. They proposed a number of experiments that could and the first one was carried out by Madame C. S. Wu (of Columbia University) and her collaborators. Most nuclei have magnetic moments, which point along the spin (angular momentum) of the nucleus, and in this sense act like spinning tops. The direction the magnetic moment points is defined by the rule that if the fingers of your right hand curl in the direction of motion, then your thumb points along the magnetic moment. Now this means that the mirror image of a nucleus with its magnetic moment upward has its magnetic moment pointing downward. (In the mirror the thumb will be pointing upward, but it will be the left thumb!) What Madame Wu measured was the direction of the electrons emitted by radioactive Co^{60}. The cobalt nuclei were polarized with a strong magnetic field. The question was whether the outgoing electron direction was correlated with the direction of the magnetic moment. See Fig. 5-5.

Suppose for simplicity that in the laboratory the electron always emerged opposite the direction of the magnetic moment. In the mirror it would always emerge exactly along the magnetic moment and it would be possible to distinguish the real experiment from the mirror image. In fact the emitted electrons favored the direction opposite the magnetic moment. Parity was not conserved in weak interactions.

Further investigations of β decays showed that the inequivalence between right-handed and left-handed could be summarized as follows: it is mostly left-handed particles that undergo weak interactions. When is a particle left-handed? For particles like an electron, muon, and neutrino, which have "spin one-half," we can measure the component of the spin along the direction of the particle's motion, just as we can consider "spin-up" and "spin-down" for electrons in an atom. The principles of quantum mechanics tell us that such a measurement will find either the spin parallel to the direction of motion or anti-parallel to it. If it is anti-parallel we call it left-handed.

5.5. MORE AND MORE HADRONS

Though studies of β decay were prominent in understanding weak interactions, the preponderance of particle physics starting in the early 1950s was carried out with high-energy particle accelerators. With accelerators it was possible to direct a beam on a target and to place a detector in an appropriate location. As soon as the accelerators achieved an energy of a few GeV (billion electron volts), they supplanted cosmic-ray research for the most part. The accelerators produced high-energy protons or electrons and with these beams it was possible to generate secondary beams of pions or kaons. Among the early results with high-energy particle accelerators were confirmation of the prediction of Pais and Gell-Mann that strange particles are produced in pairs, the discovery of the antiproton at the Bevatron in Berkeley by O. Chamberlain, E. Segrè and co-workers, and detailed studies of K mesons. Fig. 5-6 shows a picture of an event in a photographic emulsion which gave the proof of antiproton annihilation.

Soon after its invention by D. Glaser, the bubble chamber became the workhorse of high-energy physics. Fig. 5-7 shows an example from L. W. Alvarez's bubble chamber, filled with liquid hydrogen, of how such a picture can permit a detailed analysis of a complicated event. The analysis of large numbers of bubble chamber pictures led to the discovery of a number of new particles with lifetimes less than 10^{-23} s. Of course such particles, even moving at nearly the speed of light, would not go a perceptible distance before decaying. However, by measuring the tracks of the particles into which they decayed it was possible to infer their existence. More and more such hadrons were found and they expanded the enormous list of known particles. Order was brought to this vast collection by the introduction of the quark model by M. Gell-Mann and G. Zweig in 1964. All the known strongly interacting particles could be accounted for by the u, d, and s quarks, but there was no evidence that quarks as such actually existed. They seemed at the time more a convenient mathematical construct.

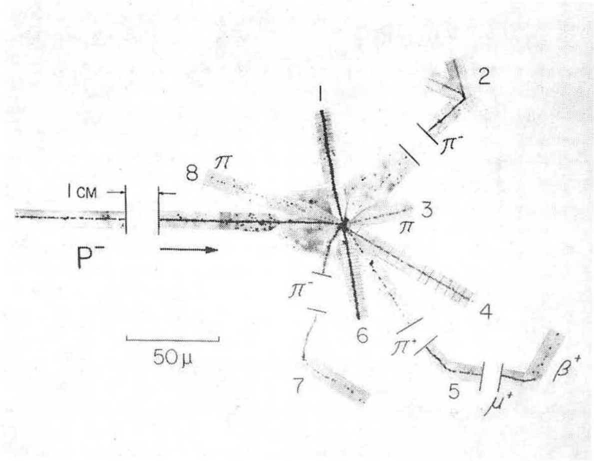

Fig. 5-6. A photgraphic emulsion picture of an antiproton - nucleon annihilation (a nucleon is either a proton or a neutron). The antiproton enters the emulsion from the left and slows down until it comes to rest. It is then captured by a nucleus and annihilates a nucleon. This event was the first to prove the annihilation process because the energy observed (1300 ± 50 MeV) in the outgoing tracks was greater than the rest mass/energy ($E = m_p c^2 = 938$ MeV) of the antiproton. The reaction thus involved the destruction (annhilation) of both the antiproton and an additional nucleon from the nucleus. [O. Chamberlain et al., *Phys. Rev.* **102**, 921 (1956)].

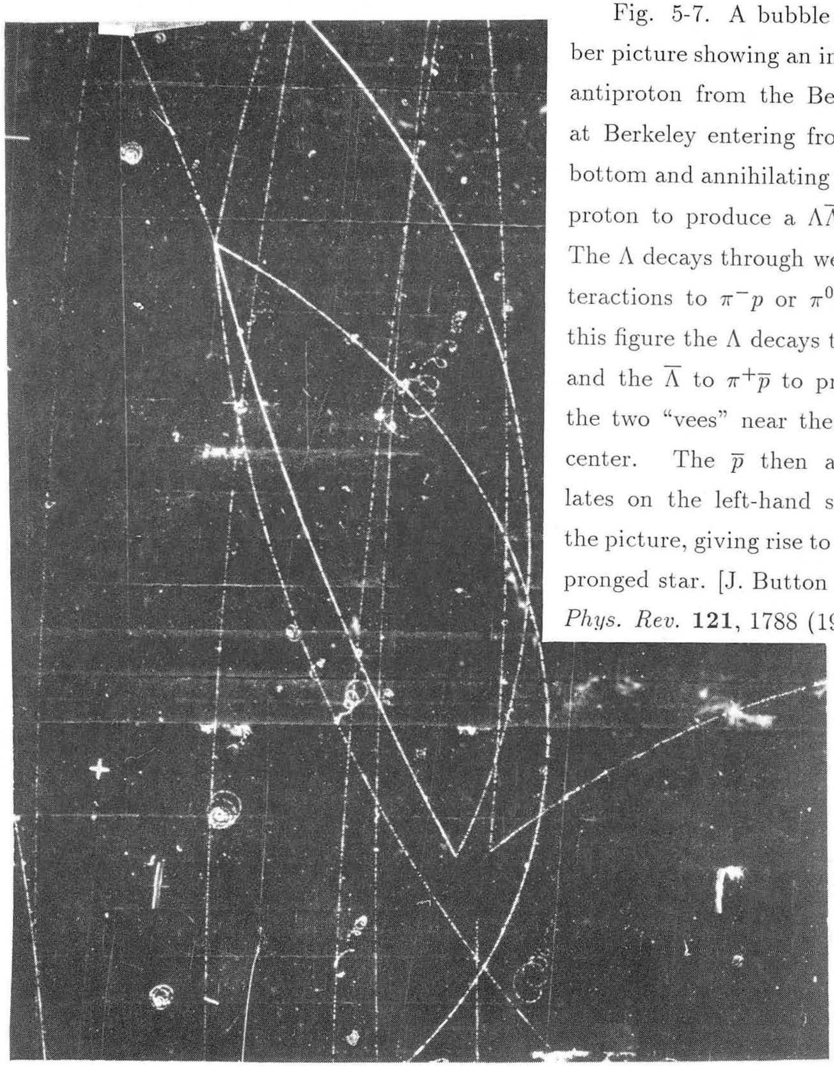

Fig. 5-7. A bubble chamber picture showing an incident antiproton from the Bevatron at Berkeley entering from the bottom and annihilating with a proton to produce a $\Lambda\overline{\Lambda}$ pair. The Λ decays through weak interactions to $\pi^- p$ or $\pi^0 n$. In this figure the Λ decays to $\pi^- p$ and the $\overline{\Lambda}$ to $\pi^+ \overline{p}$ to produce the two "vees" near the lower center. The $\overline{p}$ then annihilates on the left-hand side of the picture, giving rise to the 4-pronged star. [J. Button et al., *Phys. Rev.* **121**, 1788 (1961)].

5.6. STRUCTURE OF THE NUCLEON

During the 1950s and 1960s proton accelerators played a dominant role, but toward the end of the 1960s a new and very powerful accelerator began to operator at Stanford. The Stanford Linear Accelerator Center's electron beam was capable of reaching about 15 GeV. When the electrons scatter off protons and neutrons, the electrons remain intact and their energy and direction can be measured in large spectrometers. The surprising results that were obtained were reminiscent of the results of Geiger and Marsden. It had been expected that the probability for scattering through a large angle would be rather small. In fact it turned out not to be so infrequent. The conclusion was similar to the one drawn by Rutherford half a century earlier. Inside the proton and neutron there must be small charged objects. Feynman and Bjorken developed a model that explained these results on the basis of constituents within the proton. It looked likely that these constituents were quarks.

5.7. NEUTRINO EXPERIMENTS

Important evidence for the quark model came from comparing the results obtained from electron scattering with results from neutrino scattering. Neutrinos had originally been proposed by Pauli to explain an apparent lack of energy and angular momentum conservation in β decay. Pauli's neutrinos were massless and chargeless. They have no electromagnetic or strong interactions so they interact only weakly with matter. As a result, they usually pass through enormous quantities of material before undergoing a collision with a nucleus. Only by using an enormous number of neutrinos and a very large detector is it possible to observe them.

The first direct detection of neutrinos was achieved by Reines and Cowan using a nuclear reactor at Los Alamos National Laboratory. When the reactor is running, there is a large flux of neutrinos from the β decays of fission products. In 1962, a team led by Lederman, Schwartz, and Steinberger used an accelerator at

the Brookhaven National Laboratory to make a beam of neutrinos intense enough to be detected. The beam was made by using a pion beam. The charged pion decays into a muon and a neutrino, and the muons are removed from the beam. The neutrinos that remain can then be detected in the rare instances when they interact with material in the detector. In the interaction the neutrino is turned into a muon. If the neutrinos in the beam come from β decay, they turn instead into electrons. That is, there are two kinds of neutrinos, an electron neutrino and a muon neutrino (and a third kind discovered later).

Very high energy neutrino beams became available at the large accelerators at Fermilab near Chicago and at CERN in Geneva, Switzerland. Experiments similar to the ones done with electrons at SLAC measured the scattering of neutrinos from protons and neutrons. The results were similar and verified the apparent presence of quarks inside the proton and neutron. Because the electrons interact electromagnetically, the scattering rate for the electrons depends on the charges of the quarks. By comparing the rates for electron scattering and neutrino scattering it was possible to confirm the fractional charge assignments for the quarks.

5.8. NEUTRAL CURRENTS

Neutrino experiments in 1973 revealed something much more surprising. Events were seen in which the neutrino that scattered off the target emerged not as a muon or electron, but still as a neutrino. Such events were called neutral current events because no charge was carried to or from the neutrino. There had been searches before for neutral currents, but in processes that also involved a change of strangeness, for example the decay $K^0 \rightarrow \mu^+\mu^-$. It was known that such processes were extremely rare. However, the new results showed that neutral current process were not rare when there was no change in strangeness.

This discovery reflected on the basic nature of weak interactions. The earliest studied weak interaction was β decay. The simplest β decay is the decay of a neutron into a proton, an electron, and an antineutrino. Yukawa, in his work of 1935, had already proposed that the electron and antineutrino were the decay products of a particle now called the W boson. More precisely, the neutron was viewed as decaying into a proton and a "virtual" W boson.

Up until 1973 it appeared experimentally that the W bosons, if they existed, were charged. Thus in β decay a virtual W^- decays into an electron and an antineutrino. In muon-type neutrino scattering, the neutrino emits a virtual W^+ and becomes a μ^-. The virtual W^+ is absorbed by the target, increasing its charge. The results from the CERN experiment done with the Gargamelle bubble chamber showed that there must be another weak boson (now called the Z) that was neutral. This was especially exciting because theories had been developed – largely by S. L. Glashow, S. Weinberg, and A. Salam – that called for just such neutral bosons. Moreover, using the results from neutral current experiments it was possible then to predict the masses of the W and Z bosons. These predictions were in the range of 80 GeV, a mass too high to be reached with any accelerator that existed at the time.

5.9. J/ψ PARTICLE

The next year produced another stunning discovery. Two groups, doing very different kinds of experiments, discovered a particle with a surprisingly long lifetime, with a mass of about three times that of a proton. One group was working at SLAC using a newly constructed ring that collided electrons with positrons. When the two collided they occasionally annihilated into electromagnetic energy that converted into various particles that were observed in the detector. Typically the rate for such events varies only slowly with the energy of the colliding particles. However, the team at SLAC found that a total center-of-mass energy near 3.1 GeV the rate suddenly increased by a factor of 100 and then gradually fell back to its previous value. This is shown in Fig. 5-8. The peak was evidence for a particle, which the group named the ψ.

Another research team working at the accelerator at the Brookhaven National Laboratory measured electron–positron pairs produced in the collisions of protons

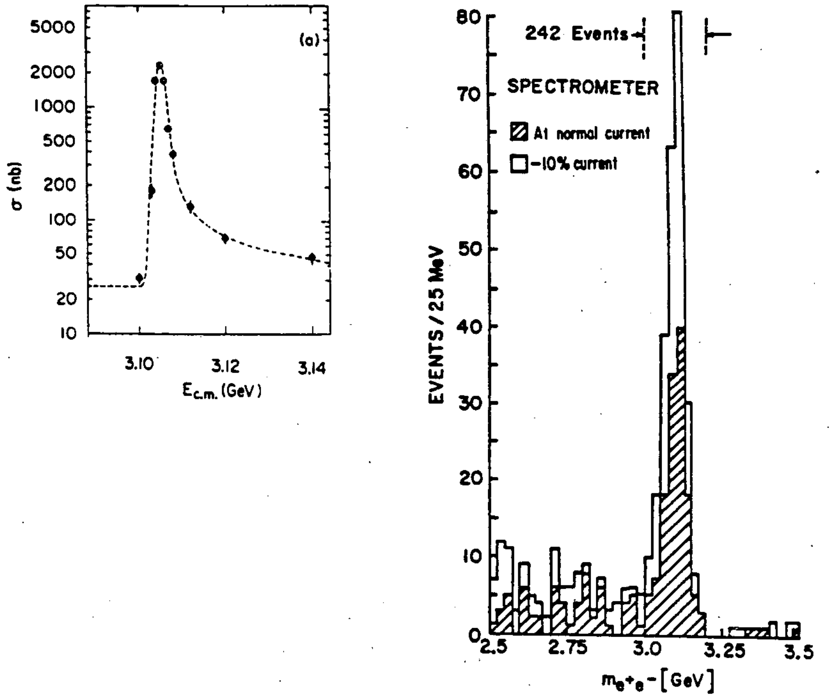

Fig. 5-8. a. The cross section (which is proportional to the reaction rate) for e^+e^- annihilation observed by B. Richter and co-workers at energies near the mass of the J/ψ. Note the logarithmic scale. [J.-E. Augustin et al., *Phys. Rev. Lett.* **33**, 1406 (1974)]. b. The mass spectrum of e^+e^- pairs observed by S. C. C. Ting and co-workers in collisions of protons on a beryllium target. The peak occurs at the same value as the peak observed at SLAC. [J. J. Aubert et al., *Phys. Rev. Lett.* **33**, 1404 (1974)]

with nuclei. The produced electron and positron momenta were measured carefully using magnetic fields. From the momenta and the directions of the electron and positron it is possible to calculate the mass of the object that decayed into the pair. They too found a peak when the mass of the electron–positron pair was near 3.1 GeV. This showed the existence of a particle, which they named the J (by convention we now call the particle the J/ψ). The most astonishing aspect was the narrowness of the peak, which was ultimately found to be 70 keV, compared to perhaps 500 MeV that might have been expected for a hadron of such a mass. The relation $\Delta E \Delta t \geq \hbar/2$ (a form of the Heisenberg Uncertainty Principle) can be used here to interpret the width, 70 keV, in terms of the lifetime of the state. The narrow width meant the state was living thousands of times longer than would usually be expected for a particle decaying by the strong interaction.

An interpretation was immediately proposed. The particle was formed from a new, fourth quark (the charmed quark) and its antiparticle, bound together much like an electron and a proton in a hydrogen atom. Another such meson, the ϕ, was already understood as being formed from the strange quark and its antiquark. The ϕ decays into $K\overline{K}$, and each K contains a strange quark or antiquark. In fact, the mass of the ϕ is just barely greater than twice the mass of the K, so this decay is allowed. For the newly discovered J/ψ, the mesons that contain the charmed quark are called D and the mass of the J/ψ is less than the mass of two Ds. Thus the J/ψ cannot turn into $D\overline{D}$. Instead, the charmed quark, c, and the anticharmed quark, $\overline{c}$, must run into each other and annihilate. It is this process that takes so long (10^{-20} s) and accounts for the narrowness of the peak.

This explanation was especially convincing because it was actually a prediction made before the discovery of the J/ψ. The Standard Model required that there be equal numbers of quarks with charge $-1/3$ and charge $2/3$. The first pair was u and d. The charmed quark, c, was needed as the partner of the s. In order to verify that this interpretation was correct it was necessary to show that the charmed quark, when it decayed through weak interactions, produced a strange quark. This was achieved when the charmed meson, called D, was observed in

processes like $D^0 \to K^-\pi^+$. This was first accomplished by G. Goldhaber and his collaborators using the SLAC-LBL Mark I Detector. The detector was able to track the passage of charged particles. A magnetic field caused the particles to curve and measuring the curvature determined the momenta of the particles. By combining the momenta of the particles the mass of an object that would have decayed into this configuration could be calculated. An accumulation of events with the particles $K^-\pi^+$ pointed to a mass of about 1.86 GeV.

Just as the strange particles, the charmed particles are produced in pairs. Their lifetimes are about 10^{-12} s so they travel only a short distance before decaying. See Fig. 5-9.

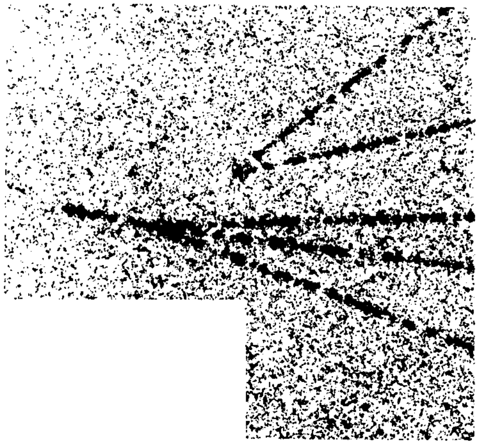

Fig. 5-9. A bubble chamber picture of the production and decay of a charmed particle and an anticharmed particle. One particle is charged and makes a track that splits into three tracks at the decay point. The other particle is neutral and decays into two charged particles. The particles were produced at SLAC by directing a beam of 20 GeV photons at the bubble chamber. The charmed particles were both created at the left end of the track of the charged charmed particle. [K. Abe et al., *Phys. Rev. Lett.* **48**, 1526 (1982)]

5.10. τ LEPTON

While the story of the J/ψ and the charmed particles was being unraveled at SLAC, another, less anticipated phenomenon was observed. A new lepton, analogous to, but much heavier than, the electron and muon was observed. The τ as it is called decays by turning into a neutrino and a virtual W boson, which in turn decays, sometimes into hadrons (strongly interacting particles like the pions), sometimes into an electron and a neutrino, and sometimes into a muon and a neutrino.

The discovery of the τ was made by M. Perl and his collaborators using the SLAC-LBL Mark I Detector in studies of e^+e^- annihilation. The annihilation results in the creation of electromagnetic energy, which then materializes, sometimes as hadrons, sometimes as leptons. When a $\tau^+\tau^-$ pair is created occasionally one τ produces an electron and the other a μ. The rest of the produced particles are neutrinos and are not observed. It was the occurrence of these very unusual events with just $e^+\mu^-$ (or $e^-\mu^+$) observed that first demonstrated that something new had been produced.

The discovery of the charmed quark appeared to complete two sets of leptons and quarks, two families: (ν_e, e, u, d) and (ν_μ, μ, c, s). However, the discovery of the τ suggested that there ought to be two more quarks, which were dubbed b and t.

5.11. FIFTH QUARK

In 1977, a collaboration at Fermilab led by Leon Lederman found evidence of the fifth quark. In an experiment similar to one of the two that discovered the J/ψ, $\mu^+\mu^-$ pairs were found that resulted from a narrow meson, this time with a mass of about 9.4 GeV. As was the case for the ψ, additional mesons were found nearby, showing that the system was rather like an atom with a series of closely spaced energy levels. A search was begun for mesons containing the new quark. Ultimately the search succeeded with the discovery of B mesons, which contain b

quarks. The partner of the b, the t quark is the subject of intensive searches at this time.

5.12. W AND Z BOSONS

The mounting evidence for the Standard Model of electroweak interactions, including neutral current experiments and the discoveries of the c and b quarks, called for an all-out attempt to find the W and Z bosons. No existing machine was capable of producing them, but it was possible to modify an accelerator at CERN to do so. To produce a W or Z it is necessary to collide a quark and an antiquark. There are antiquarks within a fast-moving proton, but they carry little of the energy of the proton. A better approach is to get the antiquark from an antiproton, since the primary constituents of the antiproton are antiquarks. Thus it was arranged to create and store a beam of antiprotons and to collide it with a beam of protons. This was done by circulating the two beams in opposite directions in the same ring, a feat accomplished under the direction of S. van der Meer and C. Rubbia at the CERN laboratory in Switzerland. With each beam having an energy of 270 GeV there was enough energy in the quarks and antiquarks to produce the expected Ws and Zs.

Evidence for their creation was found by looking at outgoing electrons and muons. The Ws decayed some of the time into an electron and a neutrino, producing events with a single electron with large momentum transverse to the direction of the beams. The neutrino, which had the balancing transverse momentum, was of course not observed. Similar events were observed with muons in place of electrons. There were as well events in which a Z decayed into an electron and a positron, both of which were observed, and similar events with μ^+ and μ^-. See Fig. 5-10. The observed events indicated that the W and Z had masses in agreement with the predictions of the Standard Model.

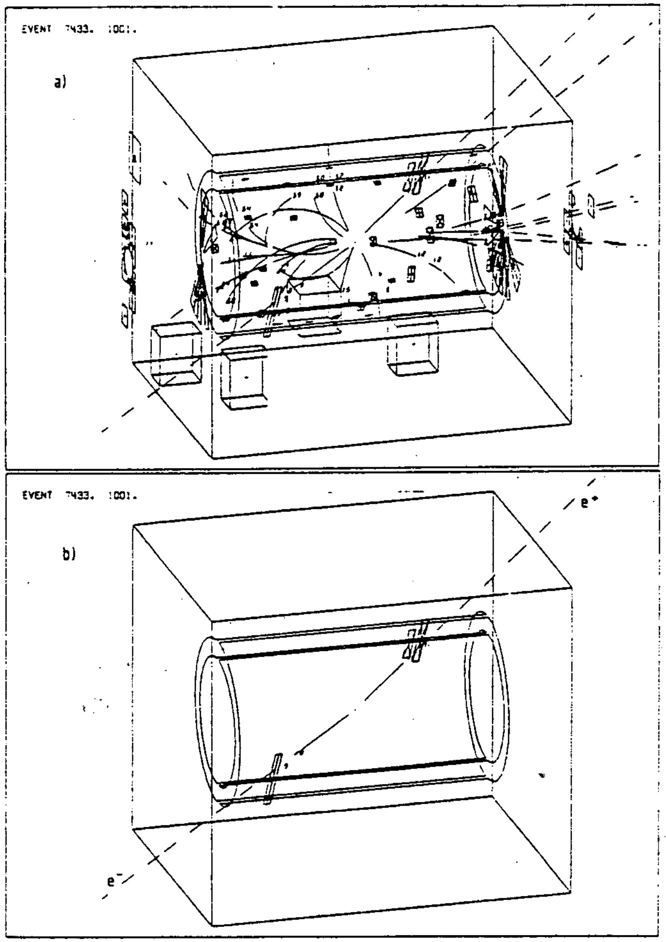

Fig. 5-10. A display of an event containing a Z that decays into e^+e^-. The top figure shows tracks of many of the particles produced in the collision of the proton and antiproton. The lower figure shows only those tracks with large momentum transverse to the direction of the colliding beams. By observing a number of such events, experimenters at CERN were able to demonstrate the existence of the Z. [UA-1 Collaboration, *Phys. Lett.* **126B**, 398 (1983)]

5.13. FUTURE

The successful conclusion of the search for the W and Z does not end the experimental challenge to the Standard Model. There remains a t-quark to be found, and much more. While the Standard Model is a success, it leaves many questions unanswered, questions that demand experimental answers. In the simplest version of the Standard Model there is a particle called the Higgs boson that is intimately tied to the existence of mass. Some other versions of the Standard Model have several Higgs bosons. Others have no ordinary Higgs bosons, but instead have a plethora of other new particles. We cannot know which, if any, of these models is correct without further experimental results. Such results may come from experiments about to be carried in which millions of Z bosons are created by e^+e^- annihilation. They may come from collisions of protons and antiprotons at very high energies at Fermilab and CERN. The highest energy collisions will come from the Superconducting Super Collider (SSC) to be built in Texas. We can only speculate on the new kinds of leptons, quarks, Higgs bosons, Zs that may appear when we reach this new domain.

5.14. REFERENCES

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6. Further Explanations

This chapter provides a more detailed discussion of some of the concepts previously introduced. The scope of this book does not allow a full discussion of any of these subjects–we leave the interested reader with the advice to search further and provide a bibliography as a starting point.

6.1. THE STRUCTURE OF ATOMS

The Pauli Exclusion principle is fundamental to the structure of matter. No two fermions can occupy the same state of a system. In a quantum mechanical system the word "state" is used to describe any allowed configuration of the system. Let us begin by reviewing these concepts as they apply to the familiar case of the electron states in an atom. We can calculate, for example, the possible states for electrons bound to the nucleus of charge Z. In quantum mechanics, the solution of such a problem takes the form of a quantity called the "wave function". For each possible state in our example we can calculate the wave function as well as the energy of the electron in that state.

The possible states of an electron in an atom can be completely labeled by the set of quantum numbers (n, ℓ, ℓ_z, s_z). The meaning of these quantum numbers is as follows:

n is the principal quantum number. It is related to the radial structure of the wave function. n is a positive integer.

ℓ is the orbital angular momentum quantum number. The square of the orbital angular momentum of the electron about the nucleus is $\ell(\ell+1)\hbar^2$. For a given n, ℓ can have integer values of $0 \leq \ell \leq n-1$.

ℓ_z gives the component of ℓ along the z-axis.* In a quantum theory this also is quantized; ℓ_z can take integer values $-\ell \leq \ell_z \leq \ell$ (including zero). Thus there are $2\ell+1$ values for ℓ_z for each ℓ. The z-component of orbital angular momentum is $\ell_z \hbar$.

s_z gives the component of the electron spin (internal angular momentum) along the z-axis. The spin can be either aligned with the z-axis ($s_z = +1/2$, *i.e.*spin up) or anti-aligned ($s_z = -1/2$, *i.e.*spin down).

The energy of the electron states increases with n and, to a lesser extent, with ℓ. We call the set of nearly-equal-energy states of a given n an "energy level". For each choice of n and ℓ we can see from the above definitions that there are $2(2\ell+1)$ allowed states, because there are $2\ell+1$ choices of ℓ_z and, for each of these, two choices of spin orientation (s_z).

Now let us imagine adding electrons one by one to a nucleus of charge Z. The first electron will work its way down, by radiating energy in the form of photons, until it reaches the lowest energy state ($n = 1$). The second electron will do likewise but, because of the exclusion principle, these two electrons will have different spin orientations. However, now this level is fully occupied (since only $\ell = 0$ is allowed at $n = 1$). By the exclusion principle, one cannot add any more electrons to it. Next we start filling the states at $n = 2$, which can take up to 8 electrons, and then we must begin filling the $n = 3$ states. This is the reason for the pattern of the periodic table of the elements. Note that the energy of the state increases with both n and ℓ.

For $n > 2$, the states of higher ℓ for a given n require more energy than the low ℓ states for $n+1$. This is the source of the complications of the transition element region of the periodic table.

Suggested Student Exercise

Explain why there are 8 elements in the second row of the periodic table.

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* The choice of axis is of course arbitrary. We can choose any axis and classify the complete set of states by projection along that axis. This is called a choice of basis. The states of one basis can be re-written in terms of the states of another basis. By convention we choose to classify states with respect to the z-axis. (You can choose any direction to be that axis.)

Solution

The second row of the table are atoms where the outermost electrons are in $n = 2$ states. Let us count such states:

$n = 2, \ell = 0$ has 2 spin states

$n = 2, \ell = 1$ there are 3 z-projections $\ell_z = +1, 0, -1$, each with 2 spin states.

Thus (2 states) + (3×2 states) = 8 states.

For an electron in any given state, the relative magnitude of the square of the wave function represents the relative probability of finding the electron at any position. Your students are probably familiar with some kind of picture of electron orbitals. Such pictures attempt to represent this probability distribution, or at least the regions where it is largest. Given the wave function of a state, one can evaluate various quantities such as the average position or the average momentum of an electron in that state. The uncertainty principle,

$$\Delta p \Delta x \geq \hbar/2 \quad ,$$

is the statement that in any wave function there is a spread in the position and momentum values about their average values. If a wave function (or rather its square) is very peaked in position values, then it must be more spread out in momentum values and *vice versa.*

The potential energy is lower when the electron is closer to the nucleus but even so, the lowest energy electron state has a non-zero average size. This is because there is a kinetic energy associated with localizing a particle in a region. This energy is inversely related to the size of the region. One way to understand this is to view the localized state as a superposition of waves of different wavelengths, chosen to add constructively in the small region and to interfere destructively

elsewhere. Clearly one must build such a state mostly out of wavelengths which are as small as, or smaller than, the size of the region in which the particle is to be localized. For all particles, just as for photons, the momentum of a wave is inversely proportional to the wavelength ($p = \hbar/\lambda$). Thus the kinetic energy gets a contribution which grows as the region in which the particle is localized shrinks. The spatial spread of the lowest energy state is that which gives a minimum for the sum of kinetic and potential energies.

Since the probability distribution does not have sharp edges, specifying the size is not as simple as talking of the radius of a ball. We must define the size of the atom using the language of quantum mechanical probability distributions. We choose to define the size of the atom as the average radius of the electron distribution.

Most of the mass of the atom of course comes from the mass of the nucleus, but there is also a tiny contribution from adding the electrons. This contribution is actually less than the sum of the masses of the electrons. Even though the electrons have some kinetic energy in the localized states, the energy of an electron in any of the bound states is *less* than $m_e c^2$ (that is less than the mass–energy of a free electron at rest) because of the negative potential energy due to the electrical interaction. We would have to add energy to remove an electron from the atom, so by conservation of energy the electrons are bound to the positively charged nucleus; they cannot leave it unless they obtain additional energy from some outside source. That is what we mean by a bound state.

Notice in this discussion that when we talk of a composite object, or even an elementary object that is charged, the separation of energy into mass-energy and potential energy is quite arbitrary. The total energy in a given situation is always well defined. We choose to say that the separated positive and negative charges have zero potential energy. Thus we *define* the mass-energy of a charged particle such as the proton or the electron to include the energy stored in the Coulomb (electric) field that surrounds it. Now consider what happens if we bring a proton and an electron together to form a hydrogen atom. Some of their Coulomb fields cancel one another, so the total energy of the system is reduced. Thus the mass of the atom, which is just this total energy divided by c^2, is less that the sum of the masses of the separated proton and electron. In other words we are forced to define the potential energy as negative in the atom once we have defined it as zero for the separated objects. We are not then free to define the zero of potential energy differently in the two cases. There is real content to the statement that the potential energy is negative in the atom. It is the reason that atoms are stable objects.

6.2. THE STRUCTURE OF THE NUCLEUS

The same kind of quantum mechanical description and the exclusion principle apply again when we go to the much smaller scale of the nucleus and ask about the positions of the protons and neutrons inside the nucleus. Now there is no massive central object so we treat the problem in terms of positions relative to the center of mass of the nucleus. Here the attractive interaction is due to the residual strong interactions between nucleons–that is, the protons and neutrons–because of their color-charged constituents. This interaction provides a much more complicated potential than the Coulomb potential of the previous problem. In fact we do not yet know how to derive the nucleon-nucleon potential, although we do know some of its properties.

The mass of the nucleus is somewhat less than the sum of the masses of its constituents, the nucleons. Again, we define the potential energy to be zero for widely separated nucleons. Then the potential energy is negative when they are closer together, tending towards zero for large separation r as

$$V(r) \propto \frac{-e^{-mcr/\hbar}}{r} \quad .$$

Here m is the mass of a pion. This mass enters in defining the residual strong interaction potential because exchange of pions provides the longest range part of

the residual strong interaction. (Note the same form appears here as in the weak interaction case, the only difference is the mass of the exchanged particle.) For the protons there is also a correction to this potential due to their Coulomb interaction; this interaction is repulsive because they all have the same charge. Thus the protons in a nucleus tend to be a little more spread out than the neutrons. This is a small effect because the Coulomb term is much weaker at the range of the typical nucleus than is the residual strong potential (as the chart shows, it is weaker by about a factor of twenty). The kinetic energy of the protons and neutrons in the nucleus also gives a small contribution to the mass of the nucleus, however, as in the atom, this positive contribution is small compared to the negative potential energy in a stable nucleus.

The wave function for each nucleon state provides a probability distribution for the location of a nucleon in that state. Again we can define the size of the nucleus as some average property of the distribution. The size of the system is again dynamically determined by the competition between the lowering of the potential energy and raising of the kinetic energy as the system gets smaller. The stable size is that which minimizes the total energy.

We can (in principle) solve for the energy levels of a system of nucleons. Ignoring the small correction due to the Coulomb repulsion between the protons, we have two identical sets of states – one set for neutrons, and one set for protons. In a nucleus containing Z protons and $(A-Z)$ neutrons, they fill these levels starting from the lowest, in the same way that the electrons fill levels in an atom. For small nuclei the lowest energy for a given number, A, of nucleons occurs when there are approximately equal numbers of neutrons and protons. However, since the Coulomb term falls off more slowly with distance than the residual strong interaction term, for larger nuclei it becomes a significant correction. Hence the levels for protons are at somewhat higher energy than those for neutrons at the same n and ℓ. Thus larger stable nuclei have a small excess of neutrons over protons.

The working of the exclusion principle at the level of nucleons explains the patterns of stable isotopes and the radioactive decays of one element to another. Consider, for example, a nucleus in which all the states at a given energy for protons are filled, but not all the states at that same energy for neutrons. In this nucleus, a neutron cannot decay via β-decay. A free neutron is heavier than a free proton but in this nucleus one more proton and one less neutron would make a heavier object. This is because, by the Pauli Exclusion principle, the proton would have to be put into a higher energy state than that occupied by the neutron. Thus the neutrons inside such a nucleus are stable, and so is the nucleus itself, at least against β^--decay.

Furthermore, the nucleus formed by adding one more proton to this nucleus will be heavier than that formed by adding one more neutron, even though a neutron is heavier than a proton. This is because the additional neutron can be put into a lower-energy state in the nucleus than is available for the additional proton.

Now let us consider a nucleus in which the outermost proton is in a state of higher energy than the lowest-energy state available for a neutron. This proton can become a neutron by emitting a positron (anti-electron) and a ν_e; this is called inverse β-decay or β^+-decay. This decay is allowed because the nucleus with the proton is heavier than the same nucleus with the proton switched to a neutron. An isolated proton is lighter than a isolated neutron and hence, by energy conservation, cannot decay via inverse β-decay

Other radioactive decay processes are spontaneous fission and α-emission. The latter is actually fission too, where one of the resulting nuclei is a helium nucleus which is called an α-particle in this situation. Spontaneous fission occurs because the energy per nucleon in large nuclei is larger than the energy per nucleon in small nuclei in which all the protons and neutrons can be in low n levels. By rearranging the many nucleons of, for example a uranium nucleus, energy can be released in the form of kinetic energy of the fragments and photons (γ-emission). The competition between the Coulomb repulsion of the photons and the attractive forces due to the residual strong interactions determine the rate at which nuclei undergo fission.

6.3. THE STRUCTURE OF NUCLEONS AND OTHER BARYONS

Now we go to a yet smaller scale and consider the distribution of quarks within a nucleon. Again there is some wave function that describes this distribution. The size of the proton is some average of this distribution. However now we notice something that seems very strange. The mass of the proton or neutron is greater than the sum of the masses of its constituent quarks, yet we have said elsewhere that these constituents cannot escape from the nucleon. How can this be? For the two previous cases we defined the potential energy to be zero for two infinitely separated objects and negative elsewhere. This definition makes sense because we can indeed isolate the constituent objects and define their masses in that way. For the fundamental strong interaction we must make a very different choice. This difference is forced on us because for the fundamental strong interaction we have a very different type of potential. Like the previous two cases it does go to minus infinity as $r \to 0$ but, unlike them, as $r \to \infty$ the color-potential energy behaves as

$$V(r) \propto r \quad .$$

In other words, the potential energy grows without limit as we attempt to separate the quarks, because of the energy in the color-force field between them. There is no way we can define the potential so that it vanishes at infinite separation. The typical separation of quarks within a nucleon is such that the potential energy contribution to the mass of the nucleon is small. Unlike the two previous cases the major contribution comes from the kinetic energy of the constituents. This is because the nucleon is much smaller than the nucleus, and its constituents are light. The mass of the proton is approximately $3\hbar/r$ where r is the radius of the proton and hence the typical wave length of a quark confined inside a proton. The factor of 3 is because there are three quarks, each with average kinetic energy $\hbar/r$.

Having said all this one might well wonder what we mean by the masses of the quarks. We can compare two otherwise similar hadrons that contain different quarks; these hadrons have the same potential and kinetic energy contribution to their masses. Hence we can use the differences between such hadron masses to find the differences between quark masses. This still leaves the puzzle of defining the lightest quark mass. It turns out that individual quark masses can be defined by how they respond (in the sense of $F = ma$) to a very high frequency disturbance. The high frequency of the probe means that we can ignore the response of the color-force fields to the instantaneous acceleration of the quark because this response happens on a slower time scale. Hence the mass of the quark itself is what controls the instantaneous (immediate) response of the quark. The quark masses given on the chart are defined in this way. The way in which the values of these masses are actually measured is quite technical, but it corresponds to the definition given here. (You may find elsewhere that a quite different definition is used, one which includes the strong interaction potential energy and the kinetic energy due to confinement as part of the quark masses. This gives much larger masses for the u and d quarks. In the jargon of physicists the masses we defined are called "current" quark masses, and the masses that include the interaction energy are called "constituent" quark masses.)

The proton is made of three quarks uud. Although a u-quark is lighter than the d-quark, the proton is the lightest three quark object. The Δ^{++} particle which contains three u-quarks, has spin 3/2 and is, in fact, considerably heavier than the proton. Since the three quarks in a baryon have different colors the exclusion principle alone is not enough to explain this fact, but it is a consequence of the same fundamental symmetry requirement that is the reason for the exclusion principal.*

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* The exclusion principle is a consequence of a property required by quantum mechanics for the wave function of a system containing more than one of the same type of fermion. This property is that the wave function must be antisymmetric under the exchange of any two of the same type of fermions. This means that the wave function changes sign when we swap all the coordinates of the two fermions. (Boson wave functions must be symmetric.)

Now consider a wave function for two fermions as a product of the wave functions of each one separately

$$\Phi(X_1, X_2) = \psi_1(x_1)\psi_2(x_2)$$

6.4. CONFINEMENT

By now it is clear that physicists regard quarks as very real objects that can be found inside protons and other hadrons. However it has been stated several times that quarks can never be observed in isolation. The philosophers among your students are likely to be bothered by this. How can we call something a particle that is never seen except as a part of something else? This question can be answered on two levels. The first answer is that you do not always have to take something apart to observe its constituents. The Standard Model makes many predictions that depend in detail on the properties of the individual quarks, such as their electric charges, and these predictions are borne out in nature. Just as Rutherford discovered the nucleus within the atom by scattering α-particles off atoms, so high energy experiments today probe the structure within the nucleons.

The second answer is perhaps a little deeper–the unobservability of separated quarks is a matter of entropy–the state is not impossible but merely extremely improbable. Let us consider a more familiar situation for comparison–say a room full of air. In principle there exists a possible state of that room where all the air molecules just happen to be within one centimeter of the ceiling, but you will never observe a room in such a state. The state is so highly ordered that the chance of its occurrence is, for all practical purposes, zero. The same is true of separated quarks. In high energy electron–positron collisions, we often produce a quark and an antiquark moving rapidly apart. Between them there is a region of color force

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The rule for fermions is that

$$\Phi(x_2, x_1) = -\Phi(x_1, x_2) \quad .$$

Clearly this cannot be true in the example above if ψ_1 is the same function as ψ_2. Thus the two fermions cannot be in the same state (i.e. have the same individual wave functions) because antisymmetry of Φ requires ψ_1 to be different from ψ_2. In a three-fermion state this same rule of antisymmetry applies when any pair of fermions is swapped. The color-neutral three-quark state is antisymmetric in the three color labels. When the three quarks have the same flavor it is clearly symmetric in the flavor labels and the lowest state is spatially symmetric ($\ell = 0$). To maintain overall antisymmetry this requires it to also have all three spins aligned the same way so that it is also symmetric in the spin part of its wave function–hence the 3/2 spin.

field. There is enough energy density in this field to produce further pairs of quarks and antiquarks. There are many more possible states of the system with such additional pairs than there are states for the system with all that energy stored in the color-force-field. The further apart the quark and antiquark are separated the more improbable it becomes that no additional pairs are formed. Thus what we always observe is the system rearranged into color-neutral combinations of quarks and antiquarks, (that is, hadrons,) just as we always observe the air filling the room. Highly improbable states of a system are simply not observed.

6.5. THE QUARK CONTENT OF HADRONS

In the standard model, every hadron is a composite object made from quarks and gluons. When we say a proton is made from three quarks, we are merely describing the simplest combination that can give a proton. Because the quarks can emit and absorb gluons, the proton at any instant will contain some gluons and perhaps even some additional quarks and the corresponding antiquarks. The internal composition of a proton is forever changing; only the flavors of the three basic constituents (quarks) are unchanged. In other words, a real proton is a more complicated object than just three quarks. The simplest content of a hadron, however, is all that is required to explain its basic properties such as charge and strangeness. The quantum numbers of the hadron are given by combining the quantum numbers of its basic constituents. For electric charge and strangeness, combining just means adding. For color charge, the rule of combination is that a color-neutral baryon can be made by taking one of each of the three possible colors of quark. The additional gluons or quark-antiquark pairs are always formed in such a way that the overall quantum numbers are unchanged.

The rules for mesons are similar to those for baryons. One can find the electric charge and the strangeness of a meson by adding the charge and strangeness of its constituent quark and antiquark. Any color-neutral combination of a quark plus an antiquark is a possible meson. However, for neutral mesons such as the π^0, the situation is a little complicated. For example, there is no meson which is just $u\overline{u}$.

While for each possible spin combination there is one meson state for each quark-antiquark pair state, the light neutral mesons are mixtures of more than one pair of quark and antiquark. For example the neutral pion, π^0, is a mixture of $u\overline{u}$ and $d\overline{d}$ while the η (eta) and $\eta\prime$ (eta prime) are mixtures of $u\overline{u}, d\overline{d}$ and $s\overline{s}$. These mixtures are to be understood in the quantum mechanical sense, there is equal probability that the π° is a $\overline{u}u$ or a $\overline{d}d$. Conversely if you form a spin zero $\overline{u}u$ state, there is some probability that you will find a π°, but also some probability it will be an η or an η'. There are three spin zero states for the three quark-antiquark pairs but the correspondence is not one to one. The precise probabilities for each meson are found by observation and are not easily explained, or even fully understood. Because they have such different masses, the heavier quarks do not get significantly mixed in this way, thus the η_c is almost pure $c\overline{c}$, and, likewise, the η_b is almost pure $b\overline{b}$.

6.6. COLOR AND COLOR NEUTRALITY

The $SU(3)$ factor in $SU(3) \times SU(2) \times U(1)$ refers to the fundamental strong interactions. The 3 in this formula is the reason that there are 3 quark colors and $8 = (3^2 - 1)$ colors of gluon. The mathematics of the group $SU(3)$ also explains which objects can be color neutral. One often hears an analogy between the fact that there are three primary colors which can be combined to make white (no color), and the fact that three quarks of different color charges combine to a color neutral object. This analogy may in fact have been part of the reason the Gell-Mann chose the term "color" for the strong interaction charges, but it must be remembered that it is a very limited analogy that does not extend to explain other color neutral objects.

There is no fixed convention for naming the quark colors. Physicists often write the greek letters α, β, γ, so that q^α means a quark of one color, q^β another and so on. More often, in fact, the color-charge labels are suppressed–that is they are not written at all–so that we say $\overline{q}q$ is a color singlet object. Let us for the moment call the three quark colors red, yellow and blue. Then the color-singlet quark anti-quark combination is actually an equal quantum mixture of (red and anti-red), (yellow and anti-yellow) and (blue and anti-blue). That means that there is equal probability at any time that the color neutral object is any one of these three combinations.

When a quark emits or absorbs a gluon its color can be changed. Since quarks emit and absorb gluons very frequently within a hadron, there is no way to observe the color of an individual quark–that is why we generally do not even bother to denote the color changes. Imagine we start with a quark-antiquark pair that are red and anti-red. The red quark becomes a yellow quark by emitting a gluon that carries both a red and an anti-yellow charge. Now the anti-red quark absorbs this gluon. This cancels its anti-red charge and leaves it with an anti-yellow charge. Repetition of similar process explains how we can have an object that has equal probability of being (red and anti-red), (yellow and anti-yellow) and (blue and anti-blue).

To explain the eight gluon charges we can say that a gluon carries a combination of a color and an anti-color, as in the example above we had a gluon with red and anti-yellow charges. Since there are three colors and three anti-colors there are nine combinations. However, as we have just stated, the combination that is a equal mixture of (red and anti-red), (yellow and anti-yellow) and (blue and anti-blue) is in fact color neutral. There is no gluon that is color neutral, so that combination is not a possible gluon charge; this explains why there are only eight rather than nine types of gluon.

The baryons are color-neutral objects whose basic quark structure is three quarks, one of each color. (If the color group were $SU(n)$ instead of $SU(3)$ then there would be n types of color charge for quarks and one would need n quarks to form a color-neutral baryon). Color-neutral objects can also be formed from any number of gluons except one. One can add any number of gluons and any number of quark-antiquark pairs to any color-neutral object and still arrange the overall system to be color-neutral.

6.7. WORDS AND PICTURES FROM EQUATIONS

In order to explain the key concepts of particle creation and annihilation and of virtual particles, we need to review a little of the formalism called field theory. Field Theory is the mathematical language in which the standard model is written. It is important to recognize that when a physicist says "interactions are due to the exchange of virtual particles", or "the photon is the quantum of the electric field", these words are a verbal interpretation of this mathematical formalism. They describe the way the physicist thinks about the calculations. The real test of the theory is not whether the words sound plausible; the test is whether the behavior predicted by the calculations is matched by the outcome of the experiments. In this test the standard model is extremely successful, at least in the regimes where the calculations can be reliably made. (Another area of current research is to learn new ways to calculate the predictions of the theory in the regimes where the usual method is not reliable, and hence to develop further tests of the theory against experiment.) The mathematics of the Standard Model is too complicated for the beginning physics student, so this book can only give the verbal description. When students find this description peculiar or hard to understand it may help to remind them that it is based on something more than an intuitive, descriptive approach.

The Standard Model belongs to a class of mathematical theories that incorporate special relativity and quantum mechanics. No one has yet learned how to write a theory that also incorporates general relativity–that is gravitation–and yields sensible predictions for physics. That is why the standard model does not contain gravity. The aim of much current theoretical particle physics research is to find a formalism that will allow us to write a theory that includes both the Standard Model and general relativity.

The aim of the game in particle physics is to find one particular theory for which the predictions match the observed particles and their behavior as found in all experiments. The mathematical formalism contains rules for calculating (at least under certain conditions) the expected rates of various physical processes such as particle decays or scattering events. The conservation laws of physics are built into this formalism, as are the properties that distinguish fermions and bosons. For example, the symmetry properties required by field theory for the wave function provide the explanation of the Pauli Exclusion principle.

We will now try to explain some of the words and pictures that emerge as physicists interpret field theories. Feynman introduced a way of calculating the probabilities of various processes by summing contributions from all possible histories (that is, sequences of events) that can result in the outcome observed. Let us explain this further. In a field theory, particles are viewed as excitations of the various fields of the theory, and there is a separate field for each particle type. For each history we can draw a diagram which traces out what happens to the fields as a function of position and time. The diagram show where the excitations were in each field at each time. We begin by depicting the history of very simple process.

Because our page only has two dimensions we use one of those to display position and the other for time. Of course, real processes involve three dimensions of space. The pictures here only display one. Fig. 6-1 represents a process in which a particle of type A, sitting at rest at position x_0, decays at time t_0 and transfers its energy to two particles of type B which move off back to back. This process conserves momentum as well as energy. This process would only be allowed in a theory in which A and B are bosons that do not carry any charges.

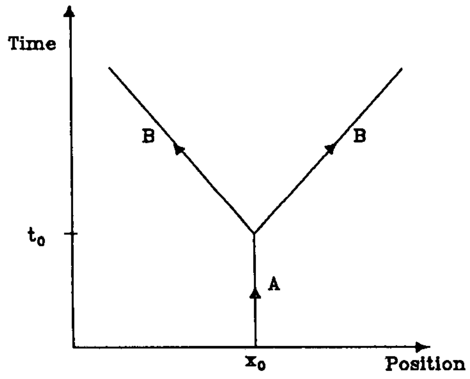

Fig. 6-1

Suggested Student Exercise

Given the mass of $A = m_A$, the mass of $B = m_B$, and the relativistic mass-energy relation

$$E^2 = m^2c^4 + \mathbf{p}^2c^2$$

use energy and momentum conservation to find the momentum of each B particle.

Solution

Before t_0:

$$E_{total} = m_Ac^2; \quad \mathbf{p}_{total} = 0$$

After t_0

$$E_{total} = (m_B^2c^4 + \mathbf{p}_1^2c^2)^{1/2} + (m_B^2c^4 + \mathbf{p}_2^2c^2)^{1/2}$$

and

$$\mathbf{p}_{total} = \mathbf{p}_1 + \mathbf{p}_2$$

Use energy and momentum conservation. Doing a little algebra one finds:

$$\mathbf{p}_1 =^{-} \mathbf{p}_2; \quad |\mathbf{p}_1| = (m_A^2/4 - m_B^2)^{1/2}c$$

$$|\mathbf{p}_1| = -\mathbf{p}_2 = \left(m_A^2/4 - m_B^2\right)^{1/2}c$$

Histories involving fermions are governed by a different set of rules. When Paul Dirac first found an equation that could describe a spin 1/2 particle such as the electron, he found to his surprise that the theory automatically contained not one but two types of particle with equal and opposite electric charges. He tried at first to interpret the positively charged particle as a proton. It was soon realized (first by Oppenheimer) that the equation represented two particles of the same mass, which ruled out that interpretation. The equations predicted a new particle! The remarkable prediction of the equation was later confirmed. The antiparticle of the electron, the positron, was discovered in 1932. However the prediction was even more striking in its implication. Not just for the electron, but for every kind of fermion, the equation demanded an equal mass but oppositely charged partner, an antiparticle. There were only two possibilities; either the equation was the wrong one or every fermion must have an antiparticle partner. Subsequent experiment have confirmed that Dirac's equation is the correct description of the motion of fermions, and that for every fermion type there is another particle of equal mass with the opposite value for all charges. We call this its antiparticle. Furthermore it has been found that all charged bosons also have antiparticles of equal mass but opposite charge. Such bosons are represented in field theory by a complex conjugate pair of fields. The one exception is a boson with zero value for all types of charge. This can be represented by a single real field. Any real field is its own complex conjugate; similarly one can say that such a boson is its own antiparticle. For a boson with no charges, there is no distinction between particle and antiparticle, they are the same object.*

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* Note that an editing error on the wall chart makes it read incorrectly on this point. If you change the outer parentheses in the paragraph titled "Matter and Antimatter" to commas it reads correctly; i.e. only the specified neutral bosons are their own antiparticles. A neutral meson which has non-zero flavor charge, e.g. $K^\circ = d\bar{s}$, does have a separate antiparticle.

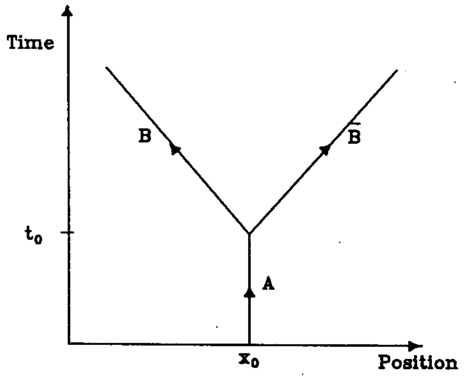

Fig. 6-2

Now let us redraw our picture of the production of a pair of particles in case in which the B particles are charged or are fermions. The picture has not changed much–all that has changed is that we have labeled one line B and the other $\overline{B}$. The A-particle could now be thought of as a photon. In the picture the A-particle creates a B particle and its $\overline{B}$.

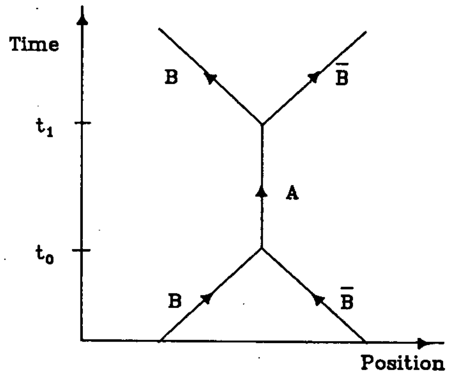

Fig. 6-3

Now consider a slightly more complicated history. Here is a process where initially there are two particles–a B moving right and a $\overline{B}$ moving left with equal energy. They meet and "annihilate"; that is, they disappear and transfer all their energy to an A-particle at time t_0. Sometime later, at t_1, the A-particle transfers the energy back by creating anew B and $\overline{B}$ particles, but now, in this example, the $\overline{B}$ is moving right and the B moving left. Thus, we can say that the B and $\overline{B}$ have scattered because of their interaction with the A-particle. (Scattering is the particle physics jargon for any process in which the initial particles interact; the resulting particles may be the same or different, and the momenta are changed). All this looks perfectly sensible until you think more carefully about the interpretation of the A as a photon. A photon has zero mass. It should satisfy

$$E^2 - p^2c^2 = m^2c^4 (= 0 \text{ for a photon})$$

(This is Einstein's mass-energy relationship for moving particles.) The A-particle in this diagram, Fig. 6-3, has zero momentum but non-zero energy–how can it be a photon? We will agree that it cannot be a real photon and invent a set of words to go with the picture. It is a "virtual" photon. It does not have the right energy and momentum to be a real photon, but it is somehow related to the photon; it is a lump of energy stored in the field that represents the photon in this theory. Thus we have now classified A excitations into two types. If $E^2 - p^2c^2 = 0$, then the particle is a real photon. Such a particle is a stable object which can last a long time and hence travel long distances in space. An excitation with the wrong relationship between its energy, momentum and mass only lasts a very short time. What this really means is that the net contribution from long histories for such a particle is very tiny, essentially zero, which is the same as saying that it is very improbable that such a history would occur. In this context the uncertainty principle can be written in terms of energy and time instead of position and momentum

$$\Delta E \Delta t \geq \hbar/2$$

When the particle lasts for such a short time Δt that one cannot measure its energy sufficiently accurately to determine that there is a difference between E^2 and $p^2c^2 + m^2c^4$, then there can be a reasonable contribution from that history to the overall process. These objects do not last long enough to be observed, because they do not have the right relationship between energy, momentum, and mass to be real particles. They are called "virtual" particles. The sense in which such things exist is simply that histories involving these objects are part of the calculations of the overall rate of processes; these calculations give results that are confirmed precisely by experiment.

Now, let us now draw a couple more diagrams:

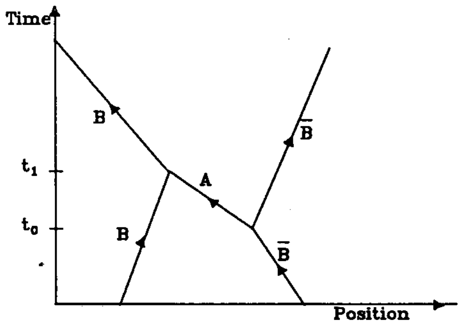

Fig 6-4

Here is another possible scattering process. The $\overline{B}$ particle moving left creates an virtual A particle and itself bounces back to the right. The A particle later bumps into the right moving B particle and is absorbed by it, changing its direction of motion. In Fig. 6-4 the net result is the same as in Fig. 6-3– the B and the $\overline{B}$ have scattered. Here they have done so by *exchanging* a virtual photon, whereas in Fig. 6-3 they *annihilate* to form a virtual photon, which later it creates new B and $\overline{B}$ particles.

Both diagrams are possible. Furthermore there are many cases of each, corresponding to different choices of t_0 and t_1. All are histories that contribute to the total rate of $B\overline{B}$ scattering.

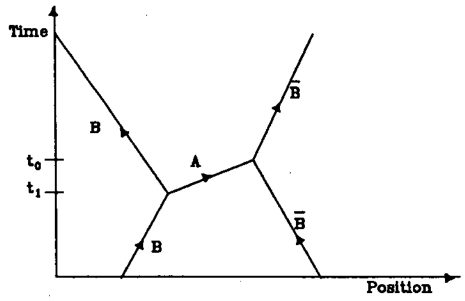

Fig 6-5

In fact, here is a third type of diagram, Fig. 6-5, where the B emits the virtual A-particle and the $\overline{B}$ absorbs it. This contributes to the same process as the others.

Particle physicists use a version of these diagrams called Feynman Diagrams as an aid to calculating the probability of a process such as this scattering. Feynman diagrams are simply a short hand for the calculation of quantum mechanical processes. Notice the Fig. 6-4 and Fig. 6-5 can be distorted into one another by changing the order in time of the processes. (In 6.4

$t_1 < t_0$ whereas in 6.5 $t_1 > t_0$). Feynman diagrams specify only the momentum and energy and of the particles, and not their position at each time. They represent all the histories that contribute to the process. The meaning of the uncertainty principle in this context is simply that, when we calculate the rate for a process with well-measured momenta, the histories which contribute come from many different positions in space. Fig. 6-6 shows the Feynman diagrams for the $B\overline{B}$ scattering process discussed above.

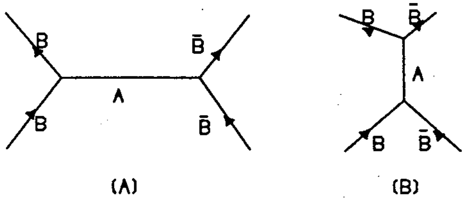

Fig 6-6 Feynman Diagrams

The first diagram of Fig. 6-6 includes all possible choices of t_0 and t_1, both those represented by Fig. 6-4 and those represented by Fig. 6-5. The second diagram represents all choices of t_0 and t_1 in Fig. 6-3. There are rules that define a calculation of a quantum contribution for each Feynman diagram. The probability of a given process such as

$$B\overline{B} \rightarrow \overline{B}B$$

is given by the square of the sum of the contributions corresponding to all possible diagrams for the process.*

In this section, we have seen that particle and antiparticle can disappear–we say they *annihilate* each other–but their energy and momentum must be transferred to some other field. For example, energy and momentum can be transferred out of electromagnetic fields and *create* a charged particle and its antiparticle. The diagrams of Fig. 6-4 and 6-5

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* All the peculiarities of quantum behavior come from the fact that this is the square of the sum and not the sum of the squares. The latter would correspond simply to a separate probability for each history. However, because we add the contributions and then square, there is *interference* between the various histories.

also show why physicists talk about interactions as particle exchanges. One can view these pictures as the exchange of a virtual photon between the B and the $\overline{B}$ particles. We have also introduced a generalization of Einstein's famous $E = mc^2$. The well known formula is only true for a particle at rest. For a moving particle, the Einstein equation is $E^2 = m^2c^4 + p^2c^2$.

Suggested Student Exercise

Show that when p is small compared to mc we can rewrite this formula

$$E = (m^2c^4 + p^2c^2)^{1/2} \cong mc^2 + p^2/2mc$$

$$+ \text{ terms of order } (p/mc)^4$$

which gives the usual (low energy) version of E = rest energy + kinetic energy.

Solution

First rewrite the expression as

$$E = mc^2(1 + (p/mc)^2)^{1/2}$$

then make a Taylor series expansion of the square root.

$$(1 + x)^{1/2} = 1 + x/2 - x^2/8...$$

The diagrams also introduce the notion of a virtual particle. It is a disturbance in a field that does not have the right energy-momentum relationship and hence only gives contributions from very short-lived histories. In the Feynman diagrams virtual particles appear as an intermediate stage of processes.

This explains how a neutron can decay via a weak interaction even though the W-boson, which is a particle associated with the charged weak field is much heavier than the mass difference between the proton and the neutron. The neutron decays to a proton and a "virtual" W-boson and then the W-boson produces an electron and an anti-electron neutrino. Since the W is very heavy compared to the available energy it lasts an extremely short time. Furthermore, since nothing travels faster than the speed of light it only travels a very short distance. This is why processes mediated by massive particles have a corresponding interaction potential which falls off with distance r like

$$V(r) \propto \frac{-e^{-mcr/\hbar}}{r} \quad .$$

Note that for a massless particle this corresponds to the familiar $1/r$ behavior of the electric and gravitational potentials. We know that the graviton must be a massless (or very light) particle even though it has never been observed, because we know that the gravitational potential behaves as $1/r$ to a very high accuracy.

6.8. RESIDUAL STRONG INTERACTIONS

Even though hadrons are color-neutral objects, there are residual interactions between them. This is not so strange – atoms are electrically neutral objects but they interact with one another and bind to form molecules or crystals. This binding occurs because of residual electrical interactions, which in turn result from the way the charged constituents are distributed within the neutral atom. We can view the molecular binding as being due to the exchange or the sharing of electrons between two atoms. Similarly we can view the residual strong interaction as due to quark swapping between the hadrons.

Fig. 6-7(a) shows the Feynman Diagram for this process. Fig. 6-7(b) shows two possible time histories represented by this diagram. Each of these can be seen as production of an extra quark and antiquark within one hadron. The antiquark and another quark leave the hadron; this quark antiquark combination forms a meson. When the meson arrives at the other hadron the antiquark is annihilated by one of the quarks in that hadron. Thus we see that the process of quark interchange between separated hadrons is exactly the same thing as meson exchange. The old view that meson exchange explains the binding forces in the nucleus still applies. However, when the hadrons come so close together that there is a significant overlap between their wave functions, we can describe the interaction between them more directly, in terms of interactions between their constituents.

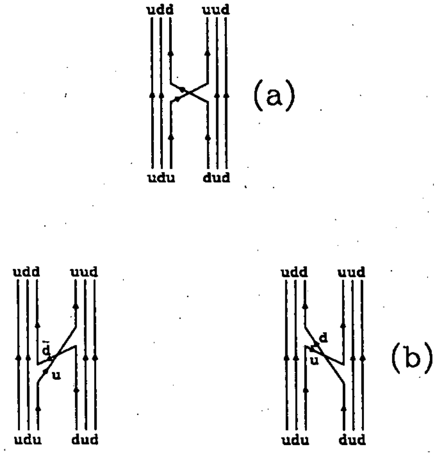

Fig 6-7

6.9. DECAYS OF UNSTABLE PARTICLES

In the standard model, only the massless particles plus the electron and the proton are stable particles. In some extensions of the standard model, even the proton is not stable, though it has a half life of greater than 10^{25} years. As explained earlier, nuclei can be stable, even though they contain neutrons. For all other particles the standard model predicts decay patterns that are also calculated using Feynman diagrams. The rate of any decay process is controlled by several factors; the two most important of these are the type of interaction involved and the amount of excess mass in the initial state compared to that in the final state. Clearly a decay cannot happen unless the initial state has more mass than the final state. When the excess is small the process proceeds more slowly. The precise dependence is complicated, it depends on the number of particles in the final state and their individual masses as well as on the total mass difference. It also depends on all the other quantities which must be conserved in the decay, such as angular momentum, electric charge, and so on. We call a decay forbidden if it violates any conservation law. A forbidden decay is one which cannot occur.

Let us start by analyzing decay processes at the quark level. Quark flavor is conserved in strong interactions. This means that any decay mediated by the strong interaction does not change quark flavor. The example of a strong decay process shown on the wall chart is the decay of the η_c which occurs when the c and $\bar{c}$ quarks within the η_c annihilate each other. There are many possible final states. The one shown has a *branching fraction* of about 4%. That means that it is observed in about 4% of all η_c decays. Any other final state in which the number of quarks is equal to the number of antiquarks for each flavor gives an allowed decay, provided energy, angular momentum conservation, and all other conservation rules can be satisfied. At present we do not know how to predict accurately the branching fractions of all the various decays, although in principle the standard model should provide such predictions. Some other examples of a strong decay are processes involving heavy baryons such as the $\Delta^{++}(1232)$, e.g.,

$$\Delta^{++}(uuu) \rightarrow p(uud) + \pi^{+}(u\bar{d})$$

and similarly heavy meson decays such as a ρ decaying to two pions. No quark flavors change in any strong decay process, so if there is a quark of a given flavor in the initial hadron, but no matching antiquark, then that flavor of quark must be found in one or other of the final hadrons. In each of these processes an additional virtual quark-antiquark pair is produced in the gluon field within the original hadron, and then the quarks and antiquarks find a way to rearrange themselves so that there is enough energy available to make the virtual pair real by splitting the initial baryon into a lighter baryon plus a meson. The half- life of the η_c is

approximately 10^{-22} , of the $\Delta(1232)$ has a half-life of approximately 10^{-23} . These numbers show that decays mediated by strong interactions proceed very rapidly indeed.

Nuclear fission, in which a nucleus splits into two smaller nuclei (including α emission processes) is due to rearrangement of the nucleons in the residual strong interaction potential and occurs whenever allowed by conservation of energy. Such processes generally occur much more slowly than fundamental strong decays, partly because the residual strong forces are weaker than the fundamental ones and partly because of the smaller mass differences involved.

Electromagnetic and weak decays proceed much more slowly than strong decays (although still extremely fast on human scales). Because of this it is very difficult to observe them except in cases where there is no competing strong process allowed. Because the pion is the lightest meson there is no possible strong decay for it. The neutral pion decays to two photons by an electromagnetic transition in which the quark and antiquark within the pion annihilate to produce the photons. (The decay into a single photon is not an allowed decay because that cannot conserve energy and momentum, or angular momentum.) The rate of this decay depends on the quark charges, and furthermore it is proportional to the square of the number of quark colors. In a model with no color this process would be expected to proceed nine times less rapidly than in a model with three colors of quark. Thus the rate of $\pi_0 \rightarrow \gamma\gamma$ is one of the key pieces of evidence for the standard model. since it is nine times bigger.

A more familiar example of electromagnetic decays occurs in atomic processes. An excited atom is one with its outer electron in a state which has higher energy than the lowest allowed state for that electron. The excited atom decays to its ground state when the electron makes a transition to the lower state and emits a photon. Because each electron state has a definite energy, the photon energy (and hence frequency) will be the same any time a transition between these two particular states occurs. Conversely, the atom can absorb a photon only when it has the correct energy to excite an electron from one allowed state to a higher one. This is what is responsible for the characteristic emission and absorption spectra of atoms.

Weak decays of hadrons, in which quark flavor is changed, always involve W-bosons as virtual intermediate particles. The example of neutron β-decay shown on the chart is the classic weak process. Heavy quarks all decay to lighter quarks by emitting a virtual W. The W may then itself decay or it may be absorbed by some other quark within the initial hadron causing that quark also to change its flavor. When the W decays it can produce either a lepton and an antilepton or a quark and an antiquark. The diagrams of Fig. 6-7 show some weak decay processes.

6.10. THE HIGGS BOSON

There is one part of the standard model which we have not yet mentioned. The model requires some spin zero particles which have no color charge but do have weak and electromagnetic properties. These particles are necessary to provide a mechanism for giving nonzero masses to the fundamental fermions and to the W and Z bosons. They are known as Higgs bosons (named after one of the theorists who proposed them). In the standard model the Higgs bosons are fundamental particles, in some extensions which go beyond the standard model they are composite objects composed of some new types of fundamental fermions. So far there is no direct experimental evidence for Higgs bosons. One of the goals of the SSC–the new accelerator proposed for construction in Texas–is to find these Higgs bosons and, we hope, to learn much more about what is beyond the Standard Model by studying their properties.

6.11. PARTICLE THEORY IN ASTROPHYSICS AND COSMOLOGY

Particle physics studies the structure of the universe on the tiniest scales. Astrophysics studies the largest objects we can observe such as galaxies or even clusters of galaxies and cosmology goes a step further and tries to explain the evolution of the entire universe based on the laws of physics and the presently observed properties of the visible universe. Both cosmology and astrophysics depend on a full understanding of the underlying particle processes. The conditions inside stars or at early times in the evolution of the universe are so hot and dense that there are many energetic particles present. Thus, in a fascinating way, the physics of the smallest observable scales becomes important to understand the behavior of the largest observable objects. We do not attempt here to discuss this subject. A number of good popular books have been written including the following:

Cosmic Code: quantum physics as a language of nature, by Heinz R. Pagels (Bantam, 1984).

Longing for the Harmonies: themes and variations from modern physics, by Betsy Devine and Frank Wilczek (Norton, 1988).

A Short History of Time:from the Big Bang to black holes, by Stephen W. Hawking (Bantam, 1988).

The First Three Minutes: a modern view of the origin of the Universe, by Steven Weinberg (Basic Books, New York, 1977).

The Big Bang: the creation and evolution of the universe, revised edition, by Joseph Silk (Freeman, San Francisco, Calif., 1988).

The Left Hand of Creation: the origin and evolution of the expanding universe, by John D. Barrow and Joseph Silk (Basic Books, New York, 1983).

While most of this book is devoted to explaining the things that physicists now understand through the standard model, it is important to recognize that this theory leaves many questions as yet unanswered. Particle physics research today can be divided into two main areas. The first is concerned with improving methods of calculation of the predictions of the Standard Model. Better predictions would allow the model to be subjected to further comparisons with data to probe its accuracy and find where there are details which do not fit correctly. It is always by investigating such details that one finds the clues to the next level of theory. The second area of research is to seek a theory which incorporates the standard model, but that goes beyond it in some way that answers some of the remaining questions. What are these questions? Perhaps the most important to understand masses and gravity. Einstein sought a unified theory of all interactions–that remains the holy grail of particle physics. We want the world described completely by a single unified theory, preferably one that contains very few, if any, free parameters that are adjusted arbitrarily to fit the data. The standard model contains many such parameters, for example the masses of all the quarks and the charged leptons are independent parameters not predicted by the Standard Model. Although we can accommodate quark masses in the Standard Model, we do not in any sense understand the pattern of masses or even why there are repeated generations of quarks. The Standard Model cannot tell us whether or not there are still further generations with yet heavier quarks and charged leptons. Only by further experiments can we find the clues that will allow us to go beyond the Standard Model and find answers to these and many other questions.

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An erudite presentation of the history of modern physics demanding considerable background of the reader. The last third of the book deals with four decades of elementary particle physics.

7.5. Periodicals

Two of the best sources are the monthly *Scientific American* and the weekly *New Scientist*; unfortunately the latter, published in England, is not widely available in the USA.

Material relating to the teaching of physics, including particle physics, can be found in two journals published by the American Association of Physics Teachers, *The Physics Teacher* and *American Journal of Physics.*

Material at a more popular level will be found in publications such as *Discover*, *National Geographic*, *Science Digest*, *Science News* and *Smithsonian.*

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