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The Ultimate Structure of Matter

The High Energy Physics Program from the 1950s through the 1980s

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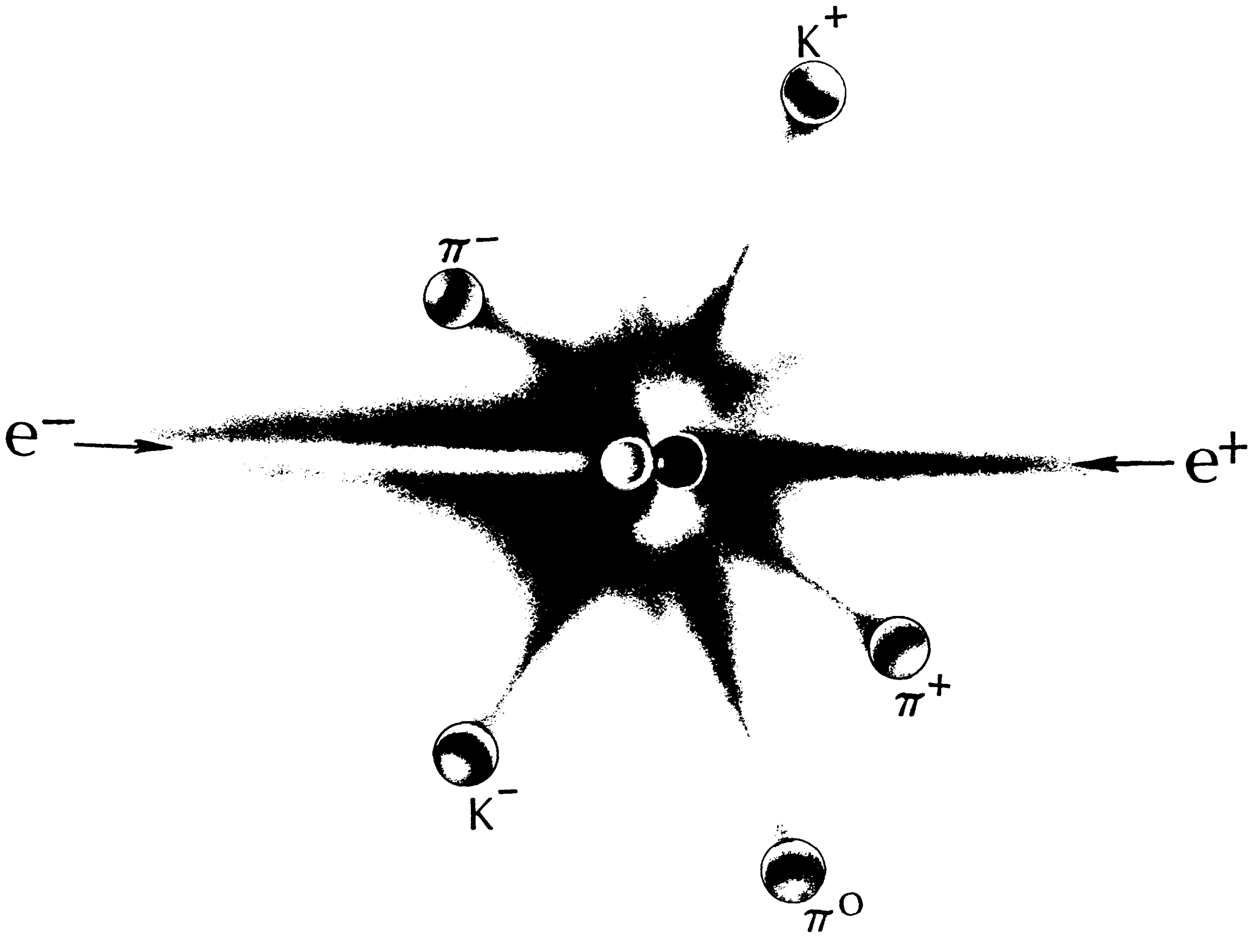

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U.S. Department of Energy
Office of Energy Research
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MASTER

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PREFACE

High-energy physics today is a productive and exciting field. Over the past three decades, its practitioners have put together what they call the Standard Model—a picture of matter that encompasses almost everything known about the particles and forces in nature. They are now planning the Superconducting Super Collider, or SSC, a huge device designed to explore the behavior of matter at energies well beyond the capabilities of existing machines and to help supply missing pieces of the Standard Model. Housed in an oval tunnel 53 miles around, the SSC will be the largest single piece of scientific equipment ever built. Scheduled for completion in the late 1990's, it will be an effort as significant as the Manhattan Project to build the atomic bomb during World War II or the Apollo space program of the 1960's.

The Standard Model and the SSC, however, are only the capstones of an enormously productive period in high-energy physics. Since the 1950's U.S. scientists have learned much about the basic building blocks of matter and the principles by which they behave. But to uncover this knowledge, they had to build and operate particle accelerators—the workhorses of high-energy physics and forerunners of the SSC. Physicists' ability to understand ever deeper regions of matter has gone hand-in-hand with the construction of ever-larger and more powerful accelerators.

The first particle accelerators were usually built with private investment, but after World War II scientists had to find bigger sources of funds. While a few early accelerators were funded by the U.S. Office of Naval Research, more and more frequently the Atomic Energy Commission (or AEC) provided the investment. Established in 1946, the AEC was succeeded in 1974 by the Energy Research and Development Administration (or ERDA). These government agencies funded the construction of the accelerators—as well as the equipment, salaries, and expenses of the physicists who worked on them.

Today the U.S. Department of Energy (or DOE), which succeeded ERDA in 1977, is the principal supporter of U.S. high-energy physics. It funds not only the construction of the accelerators, but also the operating costs of the national laboratories at which they are located as well as many of the university scientists who, as users of these facilities, perform most of the research. At present there are three such laboratories—Brookhaven National Laboratory on Long Island, New York; the Stanford Linear Accelerator Center in Menlo Park, California; and the Fermi National Accelerator Laboratory in Batavia, Illinois.

The research funded by the DOE and its precursors at these and other facilities has not only brought high-energy physics to the verge of a unified picture of matter, it has also produced numerous technological spinoffs, including advanced computers, superconducting magnets, medical equipment, and much more. Because of this work, the U.S. has assumed world leadership in high-energy physics research, and its physicists have won over two dozen Nobel prizes since the end of World War II. This document summarizes some of these achievements.

1. INTRODUCTION

High-energy physics is the study of matter at extremely small distances. It tries to answer questions like "What is the world made of?" and "How is it put together?" Whereas ancient philosophers saw nature as made from basic elements like earth, air, fire, and water, high-energy physicists seek the smallest set of elementary particles with a few simple forces acting among them. The great variety of natural phenomena occurs, at least in this picture, because there are so many different ways to arrange such fundamental building blocks. By discovering what the elementary particles are—and how they interact with each other—physicists hope to account for this diversity.

At the beginning of the twentieth century, most physicists considered atoms to be the fundamental building blocks of nature. So miniscule are these bits of matter that a trillion trillion of them can fit easily inside a common thimble. But the atom itself was soon found to be composed of far tinier things: swarms of negatively charged electrons (denoted by the symbol e^-) gyrating about a central core called the *atomic nucleus*. If an atom were somehow blown up to the size of a football stadium, its nucleus would be no bigger than a common housefly buzzing around near the 50-yard line. Yet over 99 percent of an atom's mass is concentrated in its nucleus!

In the 1930's atomic nuclei were themselves found to be made of *protons* (denoted by p) and *neutrons* (denoted by n) stuck together in various combinations. A proton is almost 2,000 times heavier than an electron and has the opposite electric charge; the electrically neutral neutron is slightly heavier than the proton. As both are components of nuclei, they are often referred to as *nucleons*.

With the discovery of these two nucleons, matter seemed simple again. All the various types of atoms could be readily explained as different combinations of electrons, protons, and neutrons. But this simple picture of matter did not last long. Many other particles similar to the nucleons turned up during the late 1940's and early 1950's, clouding the picture tremendously.

During the past three decades, however, high-energy physicists have discovered that protons, neutrons, and a large group of heavy particles like them are not truly "elementary" as previously thought. These subatomic particles are instead composed of pairs and trios of unusual particles called *quarks*. Electrons and quarks are today thought to be the fundamental building blocks; both have no apparent size, as far as we can tell. For all we know, they may be truly elementary—in every sense of the word.

To study matter at small distances, scientists use energetic (high-speed) particles. From the way these particles rebound from an object, its structure can be determined. The higher the energy of the probes, the tinier the structural features that can be examined. Using visible light, made of elementary particles called *photons*, one can easily discern objects like human cells millionths of an inch across. Electron microscopes probe matter with beams of electrons accelerated through thousands of volts to uncover features hundreds of times smaller. The most powerful and sensitive electron microscopes today can even resolve individual atoms.

To probe *inside* the atom and discern its internal components and their structure, however, particles with far higher energies are required. They must be boosted to extremely high speed and shot *through* atoms. Any deflection of these probes indicates the presence of something inside.

In 1911, the British physicist Ernest Rutherford used streams of high-energy *alpha* particles (actually the nuclei of helium atoms, made of two protons and two neutrons) to peer inside gold atoms and discover the atomic nucleus. Produced by nuclear disintegrations, these alpha particles came shooting out violently. By aiming them at a gold foil and observing how they bounced off it, Rutherford and his assistants were able to conclude that a gold nucleus was very tiny indeed—about a trillionth of a centimeter (10^{-12} cm) across.

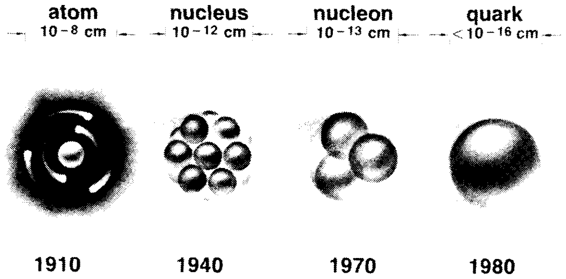

Figure 1. Atoms are known to be composed of electrons and nuclei, which are themselves made of protons and neutrons. These nucleons, in turn, are built of quarks.

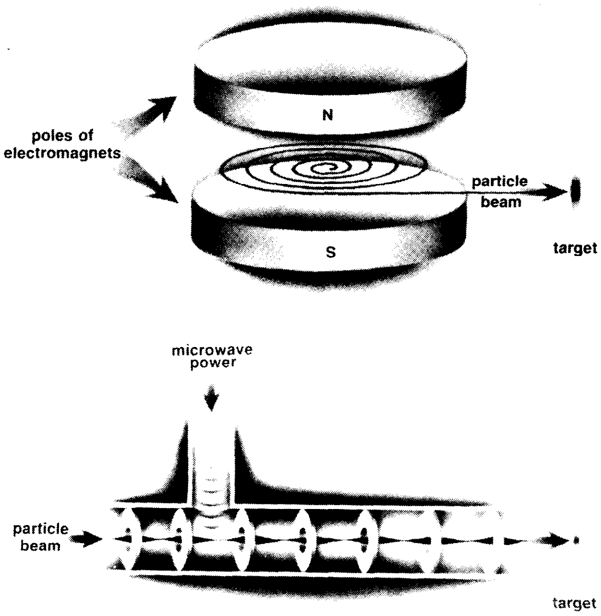

Figure 2. Simplified sketches of a cyclotron and a linear accelerator.

When Rutherford and collaborators later resolved nuclei into protons and neutrons, physicists naturally wanted to take a closer look at them, too. But to do so required even higher energies. Projectiles with enough energy could be found in the hail of naturally occurring cosmic rays raining down from the heavens. But they provided a chaotic, unreliable source at best—hardly conducive to systematic studies. Exotic new particles often turned up in this celestial debris, but it was difficult to learn much about their innate properties and proclivities.

Thus was born the need for modern particle accelerators. These devices subject particles with electric charges, like the proton and electron, to intense electric and magnetic fields that push on them relentlessly. The particles gain energy in transit and emerge in compact beams or bunches. Circular machines called *cyclotrons,* able to accelerate protons to tens of millions of volts, were developed during the 1930's by a group of physicists at the University of California, Berkeley, led by Ernest Lawrence. In the late 1940's *linear accelerators* were built at Stanford University that could propel electrons to similar energies. Shortly after World War II, protons and then electrons were accelerated to hundreds of millions of volts—enough energy, in fact, to begin producing new particles in the laboratory.

Physicists measure the energy imparted to a subatomic particle in units of *electron volts*. One electron volt, written 1 eV, is just the energy an electron picks up as it falls through a potential drop of one volt. This is about the energy an electron gains in traversing an ordinary flashlight battery. The streams of electrons in a common television set pass through a potential drop of thousands of volts before striking the phosphor screen to produce images. Thus they gain energies of thousands of electron volts—or keV, in physicists' shorthand. Similar amounts of energy are imparted to the electrons in an electron microscope.

Accelerators of the 1930's and 1940's generated particles with energies in millions of electron volts, written MeV. Today's accelerators do much better. Electrons and protons emerge with energies measured in billions or even trillions of electron volts (written GeV and TeV, respectively). The Stanford Linear Accelerator, for example, speeds electrons to energies of 50 GeV, or 50,000 MeV. The Tevatron at the Fermi National Accelerator Laboratory accelerates protons to almost 1 TeV, or 1,000 GeV.

According to Albert Einstein's famous equation, $E = mc^2$, one can convert energy into an equivalent amount of mass, and vice-versa. Thus we can express the mass of a subatomic particle in terms of equivalent energy units—the total amount of energy locked up in its mass. The electron has a mass-energy of 511 keV or 0.511 MeV, for example, while the proton and neutron weigh in at 938 and 940 MeV, or almost 1 GeV. This may sound like a lot of energy, and it is, on a subatomic scale. But it only corresponds to a mass of about a trillionth of a trillionth of a gram!

When accelerators called *synchrocyclotrons* capable of generating energies in the hundreds of MeV were built in the late 1940's and early 1950's, physicists could finally create subatomic particles known as pions (pronounced "pie-ons" and denoted by the Greek letter π) from little more than pure energy. Depending on their electric charge, which can be positive (π^+), negative, (π^-) or neutral (π^0), pions have masses of 135 or 140 MeV—or about one-seventh the mass of the proton. Predicted in 1935 by the Japanese physicist Hideki Yukawa, these particles were discovered in cosmic rays just after World War II. Beams of pions were soon being produced at particle accelerators around the globe.

Yukawa originally proposed pions as a way to explain the *strong* force thought to be binding nucleons within atomic nuclei. Something had to be holding them together. If not, the natural repulsion of the positive charges on the protons inside a nucleus would force them violently apart, causing it to explode. The stable matter we observe all around us would be absolutely impossible under such conditions. But pions are known to flit between the nucleons, "carrying" the effects of strong force from one to the other, binding them together tightly.

Unlike electrons, protons, and neutrons, which are the constituents of normal matter, pions have a fleeting existence. Outside of a nucleus, they survive only several billionths of a second before disintegrating into other subatomic particles. The former are relatively stable examples of *matter particles,* while the latter are among the *force particles* that carry forces from one matter particle to another.

Another force-carrying particle is the common photon, which (in its many guises) carries the effects of the electromagnetic force (electricity and magnetism) between charged particles. Photons stream away from an electric light bulb because the atoms and electrons in its filament are extremely agitated; these photons then disturb atoms in our retinas, and our brains form images based on the information transmitted. Whenever we "jiggle" electrons, which is what happens in a radio transmitter, they emit photons that carry electromagnetic force to other electrons in a receiving antenna and cause them to jiggle in turn.

This division of the particle kingdom into matter particles and force particles is very deep and powerful. The task of high-energy physicists thus becomes one of identifying and studying the fundamental building blocks of matter and the particles that carry the forces between them.

By the late 1940's, physicists had an excellent theory called *quantum electrodynamics,* or QED, that described the behavior of the photon—the carrier of the electromagnetic force. A marriage of quantum mechanics and Einstein's theory of special relativity, QED makes predictions accurate to parts per *billion.* (Quantum mechanics is the mathematical framework physicists use to describe molecules, atoms, and smaller particles.) Many theorists hoped that a theory similar to QED would also be found to describe the behavior of the pions carrying the strong force.

Nature, unfortunately, failed to cooperate. Other particles feeling the strong force besides nucleons and pions kept turning up in cosmic rays. The *kaon* (pronounced "kay-on" and denoted by K) weighed in at 495 MeV, while the lambda (Λ), at 1,115 MeV, is even heavier than the neutron. More massive yet were the *sigma* (denoted by Σ)and *xi* ("ks-eye" denoted by Ξ) particles, which were discovered in the 1950's.

What were all these odd new particles? Who needed them, anyway? Physicists began to despair of ever incorporating this unruly menagerie within a simple, powerful theory like quantum electrodynamics.

To help study all these new particles and their interactions, physicists of the 1950's began building powerful new particle accelerators able to speed protons and electrons to billions of electron volts. In 1952, the 3 GeV Cosmotron began operations at Brookhaven National Laboratory on Long Island. Three years later, Berkeley scientists completed their own machine, the Bevatron, able to accelerate protons to 6 GeV. At Stanford a series of linear accelerators was built during the decade, culminating in the Mark III, which could generate electron energies up to 1 GeV.

While cyclotrons and the other small accelerators were often built with private funds, these big new machines required funding in millions of dollars. More often than not, it was the Atomic Energy Commission (AEC) that met the need. A pattern arose in which this government agency paid for the construction of a particle accelerator and all its supporting equipment—as well as the salaries and expenses of the staff. Physicists from universities who did their research at these machines were often supported by the AEC, too.

Other government agencies like the U.S. Office of Naval Research and the National Science Foundation built and operated accelerators and supported theoretical and experimental research. But the bulk of the funding for high-energy physics came from the AEC. This pattern has persisted to the present day, with the U.S. Department of Energy (DOE) now playing the role of principal (90 percent) investor.

Today, most high-energy physics experiments in the United States are carried out at four Laboratories—three built and operated by the DOE and one, the Cornell Energy Storage Ring at Cornell University in New York, built and operated by the National Science Foundation.

At the energies generated by these machines, physicists could produce not only particles of matter, but also particles of *antimatter* known as *antiparticles,* which have exactly the same mass as their counterparts but the opposite electric charge. The first antiparticle to be identified was the *positron* (e^+), or positive electron, discovered in 1932 in cosmic rays. In 1955, Berkeley scientists working on the Bevatron produced the first man-made *antiproton* ($\bar{p}$)—the antiparticle of the proton. Antiparticles effectively doubled the already burgeoning list of subatomic particles.

Physicists of the 1950's recognized yet another force operating on subatomic particles—an exceedingly feeble force called the *weak* force, responsible for phenomena like radioactive decay of atomic nuclei. The strong force holds nuclei together, while the weak force triggers their disintegration. It began to be identified as a completely different force during the 1930's, when the Italian physicist Enrico Fermi formulated an ad hoc theory that explained radioactive decay as due to the transformation of a neutron into a proton, electron, and a very light, possibly massless, neutral particle called the *antineutrino,* the antiparticle of still another massless particle, the *neutrino* (ν).

In the late 1940's and early 1950's, other physicists realized that Fermi's theory could help explain the decays of pions, kaons, lambdas, and a host of other unstable subatomic particles. The weak force triggering these decays is far more feeble—many thousands of times—than the electromagnetic or strong forces. It acts only over extremely short distances smaller than the size of a nucleon. Thus a neutrino or antineutrino, which feels only the effects of the weak force and not the other two, can speed through millions of miles of matter without ever once being absorbed or deflected.

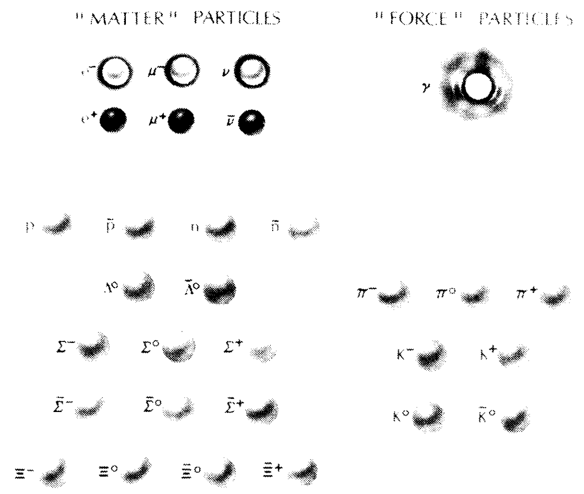

Figure 3. The subatomic particles and antiparticles (with bar) identified by the mid-1950's.

This, in brief, was the state of high-energy physics by the mid-1950's. The list of supposedly elementary particles had swollen to over 20 individual species—an untidy state of affairs. They interacted with one another through the agency of three very different forces. (The fourth force, gravity, plays no measurable role in elementary particle interactions.) Physicists had a completely satisfactory theory only for the electromagnetic force, while the strong force seemed hopelessly complicated. Out of this widespread confusion, however, emerged a number of truly remarkable discoveries that simplified matters tremendously during the next few decades. These great scientific advances, which are discussed in the next seven chapters, form the core of this booklet.

The knowledge obtained in high-energy physics has already begun to have a major impact upon other scientific fields like astrophysics, cosmology, and nuclear physics. Our understanding of the first moments of the universe, when matter was extremely energetic and packed together very densely, relies on the insights gained at particle accelerators over the past 30 years. And the technologies developed for high-energy physics are finding practical use in areas as diverse as medicine and materials science. Such wider applications of high-energy physics are the subject of the final two chapters.

2. THE PARTICLE ZOO

Physicists of the 1950's tried to understand the burgeoning list of subatomic particles by classifying them according to their discernible properties and interactions. In the absence of convincing theories of the strong and weak forces, such a taxonomical approach made good sense. It was like zoology before Darwin: animals had to be grouped into phyla, genera, and species before an evolutionary paradigm could unify the entire kingdom.

A distinguishing feature of subatomic particles is whether or not they feel the strong force. Electrons, for example, do not. If you shoot an electron across the bow of an atomic nucleus, it will be diverted from its straight-line path by the electromagnetic forces exerted by the protons and neutrons inside; it might even catch a whiff of the weak force, too. But the strong force that locks the nucleons together has no direct effect upon the electron. The same is true of the neutrino, which doesn't even feel the electromagnetic force. Only the weak force can perturb its path.

Particles like the electron and neutrino that do not feel the strong force are known as *leptons*, from the Greek word meaning small or light. Compared to the proton, these are two exceedingly light particles. But leptons need not necessarily be so light; indeed, we shall soon encounter a lepton that is heavier than the proton. The single defining characteristic of a lepton is the simple fact that it is oblivious to the strong force.

During the 1950's particles that felt the strong force began to be known collectively as *hadrons*, from the Greek word for thick or heavy. Protons, neutrons, and pions are all hadrons because they interact with one another by the strong force. So are their more exotic cousins—the kaons, lambdas, sigmas, and xis mentioned in the previous chapter.

There was another subatomic particle known by the 1950's, the *muon* (pronounced "mew-on" and denoted μ). It had turned up in cosmic rays in the 1930's and been mistaken for Yukawa's hypothetical carrier of the strong force. That would have made it a hadron. But experiments during and after World War II proved that this new particle interacted with matter far too feebly to be a hadron. In fact, the muon has all the same properties as the electron except for the fact that, at a mass of 106 MeV, it is about 200 times heavier.

Muons are therefore classified as leptons. They survive for a few microseconds, a long time in the subatomic world, before decaying into an electron or positron (depending on their charge) plus a neutrino and an antineutrino. Along with neutrinos, muons are the principal decay products of the somewhat heavier pions. Because they are long-lived, penetrating particles, muons are a major component of the cosmic-ray debris that eventually reach the Earth's surface.

Until 1956 nobody had ever seen a neutrino directly. Its existence had been inferred from theoretical arguments, and sensitive measurements of pion and neutron decays showed that *something* very light and neutral was indeed spiriting energy away. (A neutron, once isolated, decays to a proton after about 12 minutes.) But because neutrinos interact with matter so feebly, these ghostly particles had never left visible traces in detectors.

During the 1950's, however, nuclear reactors funded by the AEC emerged as a copious source of neutrinos, which also are produced in radioactive decays of atomic nuclei like uranium. In 1956 two physicists from the Los Alamos National Laboratory (located in New Mexico) buried thousands of gallons of cadmium chloride solution next to the giant Savannah River reactor in South Carolina. With trillions of neutrinos speeding through the huge volume every second, a few occasionally collided in the solution and made flashes of light that were identified as due to neutrinos.

Producing controlled beams of neutrinos for research, however, took a few more years. In 1952, the same year that the Cosmotron began operations at the Brookhaven National Laboratory, three physicists there had developed a new accelerator technique known as *strong focusing*. This ap-

Figure 4. Aerial photo of Brookhaven's Alternating Gradient Synchrotron. This proton accelerator lies in a tunnel under the circular mound at top left.

proach, which allowed drastic reductions in the size of an accelerator's vacuum pipes and magnets, is now employed in virtually every major particle accelerator. In previous machines like the Cosmotron, particle beams spread out when accelerated, requiring a wide "bore" on the vacuum pipes carrying them and hence, large magnets surrounding these pipes. With strong focusing, however, the beam pipes could be just a few inches in diameter and the magnets much smaller too, resulting in great savings in construction costs.

Among the first machines to use strong focusing was the Alternating Gradient Synchrotron, or AGS, a 30 GeV proton accelerator built with AEC funding at Brookhaven. About a kilometer in circumference, this synchrotron could not fit in a single large building like the Cosmotron and Bevatron. Instead it was housed in a circular tunnel under a mound of earth. Completed in 1961, the AGS is still in operation today. One of the most productive scientific instruments ever built, its particle beams have been used to make three Nobel prize-winning discoveries, and still are in use today.

With the AGS, physicists could begin producing beams of neutrinos. To do this they smashed high-energy protons from the AGS into a metal target, generating copious quantities of pions that subsequently decayed in flight, yielding muons and neutrinos. Filtering out the charged particles by passing all this debris through a thick stack of iron plates, they were finally able to produce a pure beam of neutrinos.

A team of Brookhaven and Columbia University physicists led by Leon Lederman, Melvin Schwartz, and Jack Steinberger studied these neutrinos in 1962 to determine whether there was only one or actually two different kinds. Were the neutrinos emerging from disintegrations of atomic nuclei exactly the same beasts as those that escaped from decaying pions? These physicists proved that the answer to this question was *no*. Of the trillions of neutrinos passing through their detector, less than 50 interacted, but all of these interactions gave off a muon and none produced an electron.

This key experiment, for which Lederman, Schwartz, and Steinberger shared the 1988 Nobel prize, proved that there are at least two completely different kinds of neutrinos. The one that emerges in tandem with an electron or positron in radioactive nuclear decays is known as the *electron neutrino*. The one that surfaces together with a muon when a pion decays is called the *muon neutrino*. After 1962, therefore, we knew about four fundamental leptons: the electron, the muon, and their respective neutrinos (plus their antiparticles, of course).

While the number of leptons remained small and manageable, the list of hadrons continued expanding during the 1950's and on into the 1960's. A further division of the hadron kingdom became necessary. *Baryons,* from the Greek word for heavy, are matter particles like the proton, neutron, lambda, and sigmas. All baryons have at least as much mass as a proton. The *mesons,* from the Greek for middle, are carriers of the strong force like pions and kaons. These lightest mesons weighed in between the electron and proton, but much heavier mesons eventually turned up, too.

Other types of particles, discovered in the early 1950's, were initially thought to be baryon-meson combinations. Enrico Fermi found the first such *resonance* at a mass of 1,236 MeV at the University of Chicago. It survived about a trillionth of a trillionth of a second, far too brief to leave tracks in particle detectors. For awhile these resonances were not classified on the same level with other hadrons. But as their ranks began to swell without bound in the 1960's, they began to appear in tables of baryons and mesons.

A defining characteristic that separates baryons from mesons is *intrinsic spin,* the amount of rotation a particle has about an internal axis. Like charge, intrinsic spin is an inherent property of a particle; as long as it exists, its spin does not change. According to quantum mechanics, the spin of a particle must be an integer (0, 1, 2, . . .) or half-integer (1/2, 3/2, 5/2, . . .) times a fixed value (equal to Planck's constant *h* divided by 6.29). Physicists say that a particle is "spin-0" or "spin-1/2" or "spin-1" (the commonest values) if it has 0 or 1/2 or 1 units of spin, respectively.

Baryons have half-integer spin and mesons have integer spin. The lightest baryons, like the proton and neutron, have spin-1/2, while the lightest mesons, like the pion and kaon, have spin-0. Resonances generally possess higher spins and are classified as baryons or mesons according to whether they have half-integer or whole number values. The resonance that Fermi discovered at 1,236 MeV, for example, is a baryon with spin-3/2.

All other subatomic particles have a definite spin and are classified accordingly. Leptons have spin-1/2 like the light baryons; they too are matter particles. With spin-1, the photon was in a class by itself—at least during the 1950's. It has whole-number spin like the mesons; all are force-carrying particles that glue matter together. But unlike mesons, the photon has zero mass, which means it can carry the electromagnetic force over very large distances. Mesons can transport their forces only over very short distances.

Another property of subatomic particles was recognized in 1953, called *strangeness* by Murray Gell-Mann, a theoretical physicist at the California Institute of Technology. Unlike spin or electric charge, it has no parallel in everyday life. Baryons and mesons have varying degrees of strangeness, ranging from -3 to +3 units, depending roughly on how heavy they are and how much they resemble the nucleon and pion, which both have strangeness 0. For example, kaons, the next lightest mesons after the pion, have strangeness −1 or +1. The lambda particle has strangeness −1 while its antiparticle has +1.

More than mere numbers, these properties of subatomic particles— charge, spin, and strangeness—determine how they behave in the many possible encounters with one another. As the particle list began to swell in the early 1960's, some physicists continued to maintain order in the kingdom by classifying the new particles according to these properties. Dissatisfied with this taxonomic approach, however, others had already begun the search for a deeper explanation.

3. THE STRONG AND THE WEAK

To make sense of this growing list of subatomic particles, physicists turned to what are called symmetries and conservation rules. In physics, as in everyday life, some things never change. The total amount of energy, for instance, remains the same after a physical process as it was before. Physicists say that energy is "conserved;" energy may change forms in the process, but the total amount of it remains the same. Such a principle, first established in classical physics, holds true in the realm of quantum mechanics, too. An apparent violation of energy conservation in weak radioactive decays, for example, led to the proposal of the neutrino as one way to spirit off the missing energy.

Other physical quantities are conserved, too—such as momentum, angular momentum, and electric charge. Unless sufficient force is applied to retard its motion, a car continues speeding forward because of momentum conservation. A top keeps spinning about its axis (until the force of friction slows it down) due to the conservation of angular momentum. And nobody has yet seen electric charge evaporate. If you put an amount of charge into one end of a copper wire, the same amount eventually comes out the other end.

These may seem like trivial statements, but to physicists such conservation is profound evidence of underlying *symmetries* in the laws of nature. Energy is conserved because these laws do not change with time; momentum is conserved because they do not change with position. So the mathematical expressions of these laws cannot contain terms that depend on time or position. Physicists say the laws are "symmetric" in time and space. They mean that a change in these variables does not alter the outcome of processes governed by these laws.

Conservation rules hold true in the subatomic realm, too. Because angular momentum is conserved, for example, a spin-1 particle cannot decay into a spin-0 and a spin-1/2 particle. Conservation of angular momentum means the laws of nature do not depend on one's orientation; they cannot contain any terms that depend on angle. Similarly, we never witness any interactions where net electric charge is created or destroyed—the total charge remaining afterwards is always the same as it was beforehand.

As one way to understand the forces between subatomic particles, physicists of the 1950's began to identify other physical quantities that were conserved in their interactions. Some of these quantities do not have analogues in classical physics, either. Once established, conservation rules implied additional symmetries of the laws governing the forces. The concept of symmetry has proved crucial to high-energy physics. Indeed, much of the recent progress in finding new levels of simplicity in nature has gone hand-in-hand with the elucidation of new kinds of symmetry.

The property of strangeness mentioned in the last chapter surfaced because the so-called strange particles—kaons and lambdas, for example—were always produced in pairs. This happens because the two particles carry equal but opposite amounts of strangeness, +1 and −1, so that the sum before an interaction is the same as the sum after, or 0.

When the strong force governs an interaction as above, strangeness is indeed conserved. But when the weak force gets into the act, strangeness is *not* necessarily conserved. The neutral kaon produced in the process depicted above can decay via the weak force into two pions, both of which

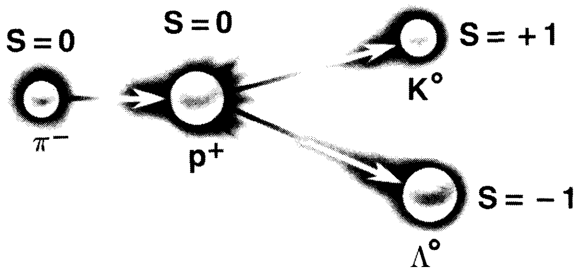

Figure 5. The total amount of strangeness remains the same when a pion and proton collide to produce a kaon and a lambda.

have strangeness 0. Physicists say that the strong force "conserves strangeness" while the weak force need not conserve it.

For years physicists had expected that the laws governing subatomic forces had to be symmetric with respect to reflection in a mirror. Everyday objects might appear different in a mirror, which swaps left for right and vice-versa, but not subatomic processes. If a particle interaction occurred with a given strength, its mirror image ought to occur with equal strength, too, or so most physicists thought. Called the conservation of *parity,* this principle of left-right symmetry indeed holds true for the strong force.

In the summer of 1956 Tsung-Dao Lee and Chen Ning Yang began to examine whether parity conservation actually held true for the weak force, too. After careful study of the existing data, these two Chinese-American physicists concluded that there was no experimental evidence for such a belief; it was merely a strong theoretical expectation. To explain certain odd decays of kaons, Lee and Yang proposed that parity conservation might actually be *violated* by the weak force and suggested ways to test their hypothesis. Their bold proposal was tantamount to saying that the weak force could tell left from right.

This prediction was borne out later that year and in early 1957 by three experiments done by physicists from Columbia, the University of Chicago, and the National Bureau of Standards. Parity conservation is indeed violated in beta decay and in pion decay. The decay particles are emitted in preferred directions that do *not* appear the same under mirror reflection. The proofs were so clear-cut that Lee and Yang won the 1957 Nobel prize in physics, the youngest scientists ever to receive it.

Further experiments at Brookhaven indicated that the weak force violated parity not just a little but *maximally.* Neutrinos emerging from weak decays always have their spin vectors aligned opposite their direction of motion, never along it. Physicists say neutrinos are "left-handed." On the other hand, antineutrinos are "right-handed;" the antiparticle of the neutrino always has its spin vector pointing along its trajectory.

Thus the violation of parity by the weak force was evidence of an asymmetry between the world of matter and that of antimatter. With the strong force alone, things had been fine: matter and antimatter behave the same way. But not when the weak force became involved. To rescue the situation, some theorists proposed that perhaps nature was symmetric under a *combined* operation. "If one performs a mirror reflection and converts all matter into antimatter," wrote Yang in 1959, "then all physical laws remain unchanged." This new symmetry, which became known as "CP invariance," was believed to hold true for all forces—strong, weak, and electromagnetic.

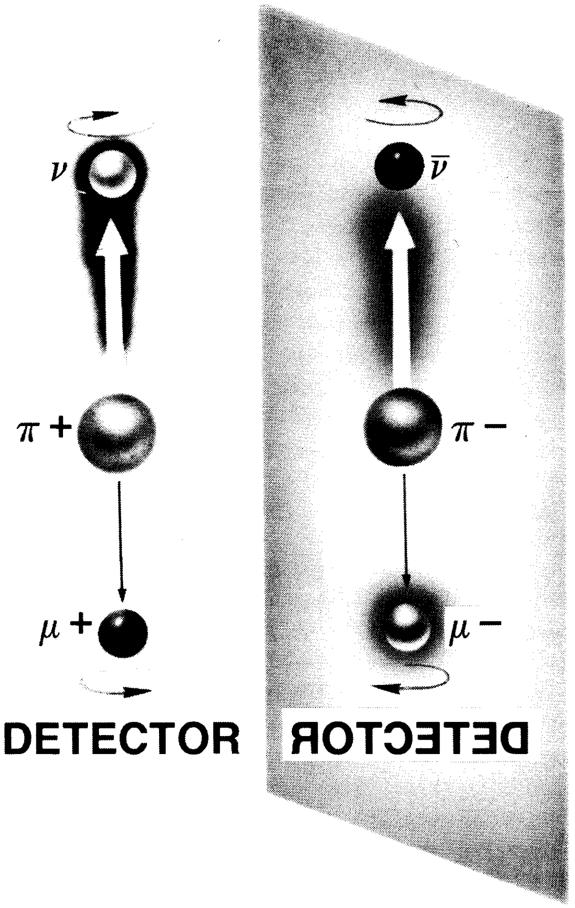

Figure 6. CP invariance in pion decay. If one replaces particles with antiparticles and performs a mirror reflection, the decay occurs at the same rate.

But here again the weak force failed to cooperate. If CP invariance held true, then a long-lived version of the neutral kaon could never decay into a pair of pions. In a 1964 experiment at the Brookhaven AGS, Princeton physicists led by James Cronin and Val Fitch proved that this decay indeed occurred, albeit less than one percent of the time. This small violation of CP invariance by the weak force meant that there remained a tiny asymmetry between matter and antimatter. For this discovery of CP violation, Cronin and Fitch shared the 1980 Nobel prize.

A conservation rule that has never been knowingly violated—that seems to hold true in *every* interaction—is the conservation of electric charge. It is absolute. Nobody has ever observed charge spontaneously appear or disappear. To physicists the conservation of electric charge is proof of an abstract internal symmetry called *gauge invariance*. Loosely speaking, gauge invariance means that the laws of nature do not depend on the calibrations of our measuring sticks—their "gauges."

Both classical electromagnetism (the theory of electromagnetic force) and QED were long known to possess gauge invariance. The electromagnetic force, that is, originates from a charge that is absolutely conserved. In QED the force is carried from one charge to another by a spin-1 particle, the photon. Because QED had worked so well, allowing physicists to make very precise calculations accurate to many decimal places, physicists of the 1950's began to search for similar approaches, called *gauge theories,* to describe the strong and weak nuclear forces.

An early attempt along these lines was the work of Yang and Robert Mills, done at Brookhaven over the summer of 1954. They suggested that the strong force possessed a gauge symmetry and was borne from one hadron to the next by a *triplet* of spin-1 particles they designated B^+, B^-, and B^0—three analogues of the photon.

The analogy with QED and the requirements of gauge invariance meant, however, that these B-particles had to have zero masses like the photon, which posed a severe problem for the Yang-Mills theory. The strong force is a very short-range force, extending outward less than a trillionth of a centimeter. According to the so-called quantum-mechanical uncertainty principle, short-range forces are carried by massive particles. But allowing these particles to have a mass destroyed the beautiful gauge invariance of the theory. Yang and Mills could not surmount this problem, which continued to plague gauge theories for years.

Around this time there were increasing suggestions that the weak force was itself carried by two massive, spin-1 particles: the W^+ and W^-. Because the weak force had an even shorter range than the strong, the mass of these W's was thought to be at least 50 GeV—far too heavy to be produced by accelerators of the day.

In 1956 Julian Schwinger of Harvard University proposed that the Yang-Mills theory might be deployed to unify the theory of the electromagnetic force with that of the weak force. He thought the two forces might be different manifestations of the same fundamental force, much as electricity and magnetism are the two facets of electromagnetism. Schwinger suggested that the triplet proposed by Yang and Mills might actually be the W^+, W^-, and the neutral photon. By assuming the W's to have tremendous masses, he could explain why they acted only over short distances; hence the weak force only *appeared* to be very weak. But his theory foundered for the same reason as that of Yang and Mills: giving the W's a mass destroyed its desirable feature of gauge invariance.

During the 1950's physicists had made a good start in understanding the strong and weak nuclear forces, but by decade's end they still lacked a complete theory. In its stead they had determined a number of conservation rules that provided clues to the underlying symmetries (or lack thereof) of whatever laws of nature were operating on subatomic particles. But various attempts to model the strong and weak forces with QED-like theories had encountered severe difficulties.

4. THE PARTICLE EXPLOSION

The number of different subatomic particles, which had been growing steadily during the 1950's, suddenly began to explode in the early 1960's. By 1964 the total exceeded a hundred different species. Most of these new particles were heavy, short-lived cousins of the lighter mesons and baryons. More than any other factor, a new experimental device was responsible for this great burst of discovery: the *bubble chamber*.

A bubble chamber consists of a large volume of liquid—commonly hydrogen, freon, or propane—maintained extremely close to boiling and exposed to a high-energy beam of subatomic particles. Just as they are about to hit, the pressure on the liquid is suddenly lowered, which boosts the liquid above its boiling point. Tiny bubbles begin to form spontaneously along the trail of a charged particle as it tears through the atoms of the liquid. By flashing a bright light into the bubble chamber at just the right instant, one can photograph the tracks left by charged particles, which appear as lines of tiny bubbles.

The bubble chamber had been invented in 1952 by Donald Glaser, then a research associate at the University of Michigan. His first prototypes were tiny, thimble-sized tubes of liquid ether. Experimental groups at Brookhaven and Berkeley seized on Glaser's novel invention, for which he eventually won the Nobel prize, and built far larger chambers containing liquid propane and hydrogen.

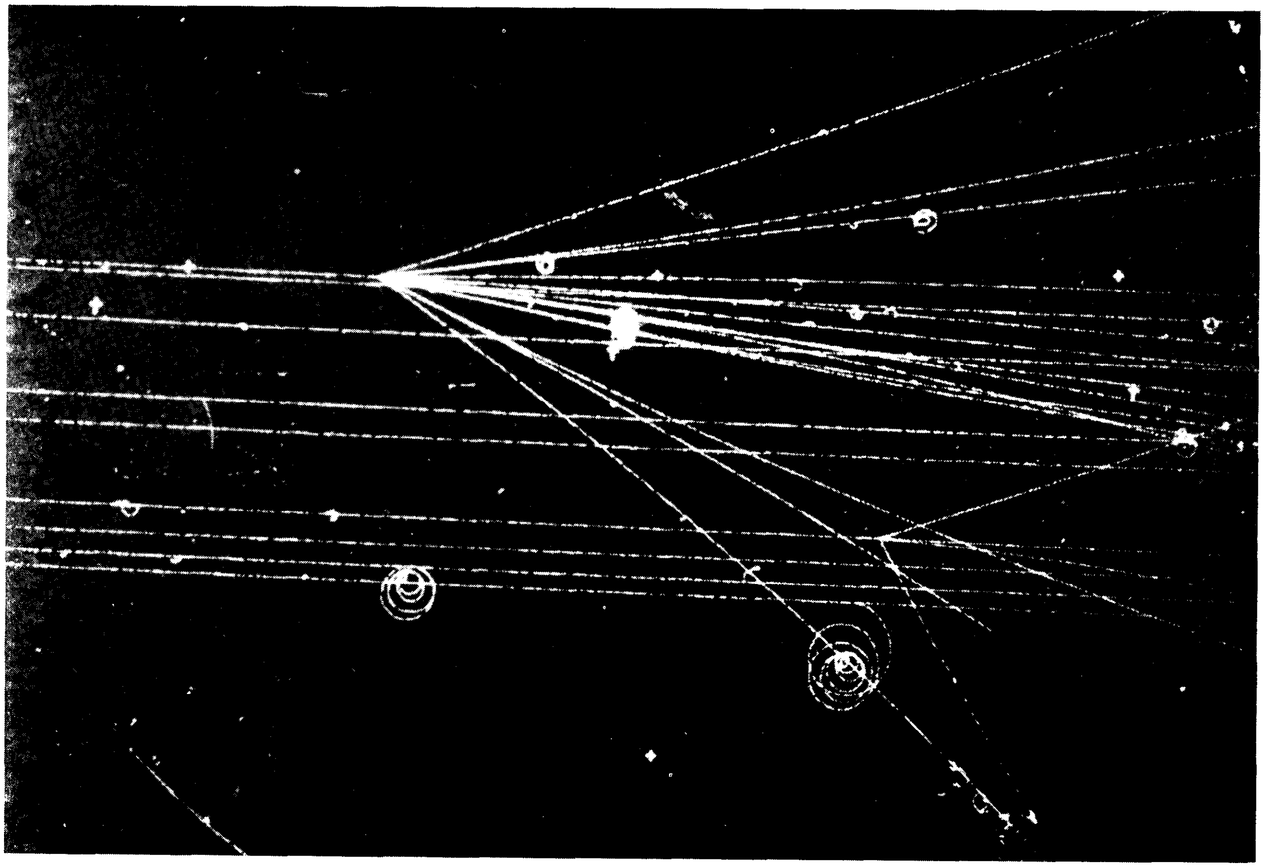

Figure 7. Bubble chamber picture of a pion-proton collision. The pion enters from the left.

By 1960 they were standard equipment at particle accelerators around the globe.

Bubble chambers had several distinct advantages over other particle detectors of the day. Not only did they serve as a large-volume target, but they also enabled experimenters to reconstruct the fine details of collisions in a rapid, straightforward manner. Picture after picture could be snapped and then carried back to home universities, where teams of "scanners" set to work searching the negatives for characteristic patterns.

After Glaser's invention, nobody contributed more to bubble-chamber technology than Luis Alvarez and his group of Berkeley physicists. They built a series of ever-larger chambers at the Bevatron, culminating in a device 72 inches long containing 500 liters of liquid hydrogen. Completed in 1958, this was by far the largest bubble chamber of its day. Surrounded by an enormous electromagnet, it was housed in a separate building adjacent to the Bevatron. For spearheading the development of this immense chamber, and for its contributions to the discovery of new particles, Alvarez won the 1968 Nobel prize in physics.

Bubble chambers were particularly effective in discovering new particles with extremely short lifetimes, such as the resonances mentioned in Chapter 2, which were far too short-lived to leave visible tracks in *any* detector. They travel hardly a trillionth of an inch before decaying into two or three other particles. All one can see in a bubble chamber picture is a spray of tracks emanating from the point where the resonance originated. But by measuring the length, curvature, and starting points of the paths of these telltale offspring, physicists could reconstruct the parent and deduce its intrinsic properties.

A group of spin-1 resonances, predicted during the late 1950's, were discovered during the early 1960's using bubble chambers. The first of these was the K* at a mass of 890 MeV, thought to be a high-energy cousin of the kaon, which was discovered with the 72-inch device in 1960. Many other resonances with a variety of properties soon turned up in bubble chambers at Berkeley and Brookhaven.

To restore order in the particle kingdom, physicists again resorted to taxonomy. Striking regularities could be found among properties of mesons and baryons. The masses of the baryons, for example, seem to increase in rough proportion to their spin. A similar behavior was observed among the mesons. These regularities enabled physicists to group the baryons and mesons along, when plotted on a graph, what were called *Regge trajectories* of related particles.

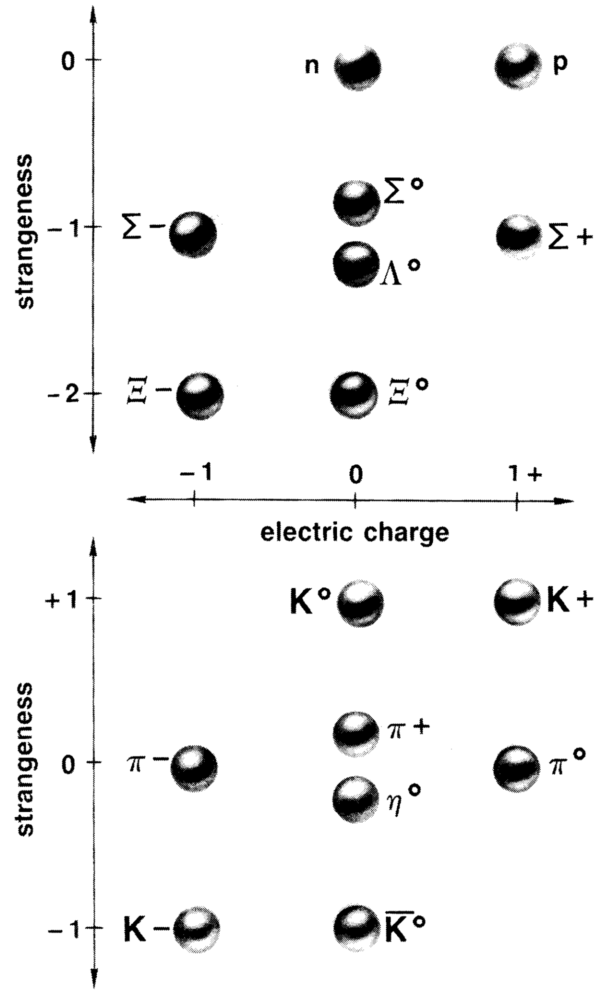

Figure 8. Octets of spin-½ baryons (top) and spin-0 mesons.

Another approach, pioneered in 1961 by Murray Gell-Mann, was to group together those mesons and baryons with identical spins. For example, the proton, neutron, lambda, three sigmas, and two xis are known collectively as the "spin-1/2 baryons." If one plots them on a graph according to their charge and strangeness, a hexagonal pattern of eight members called an *octet* results. A similar pattern emerged among the known spin-0 mesons—the three pions and four kaons—except that at the time there were a total of only seven members.

Based on the discrepancy between these two patterns, Gell-Mann predicted the existence of an

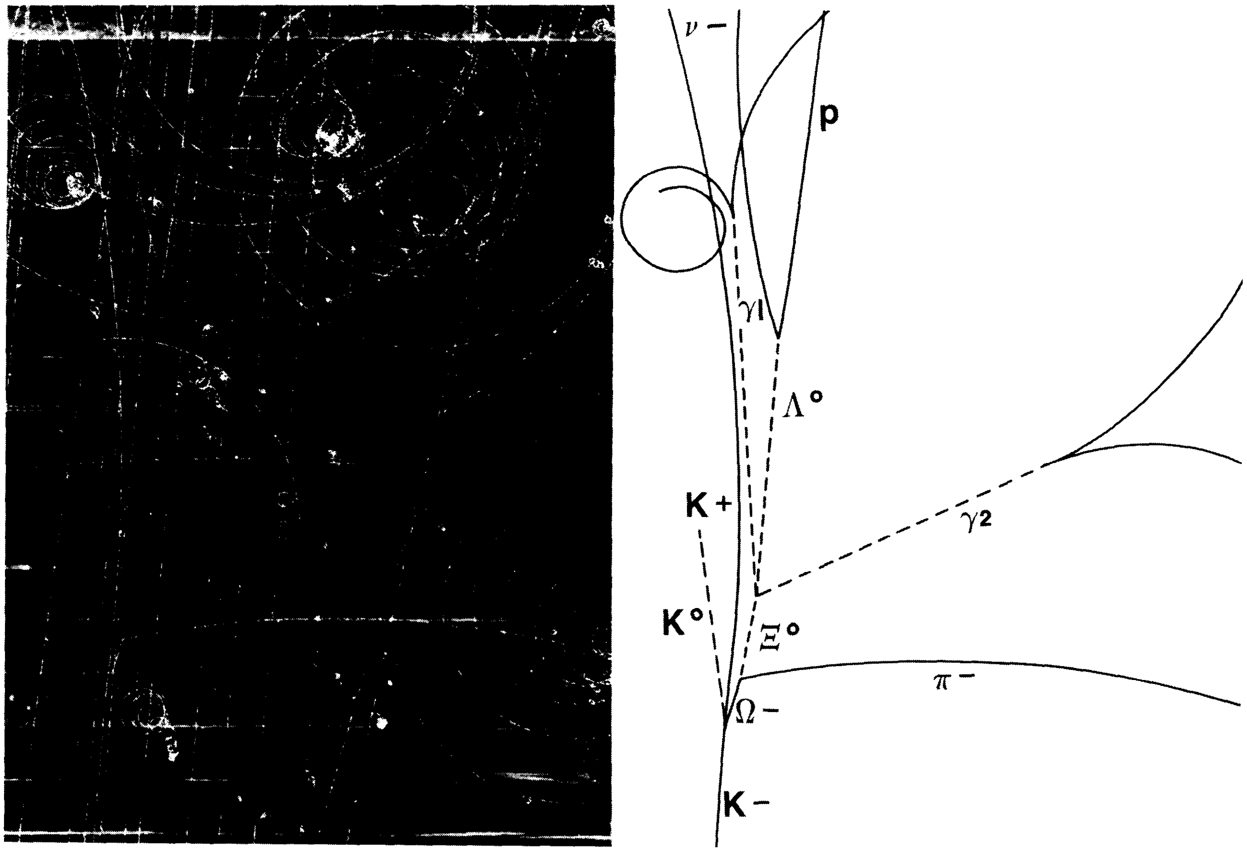

Figure 9. Bubble chamber photo of the first omega-minus event. The omega minus is created at the bottom of the photograph.

eighth spin-0 meson with zero charge and strangeness. Within months it had indeed turned up, with a mass of about 550 MeV, in bubble chamber searches at Berkeley and Brookhaven. Dubbed the *eta meson* (η^0), this new particle completed the octet of spin-0 mesons. Soon another octet, that of spin-1 mesons like the K*, had also been fleshed out.

To Gell-Mann and other physicists of the early 1960's, these regular patterns were concrete evidence of a harmonious grouping of the hadrons called *unitary symmetry* or, more specifically, *SU(3) symmetry*. Although their masses and other properties might appear different, the members of a given octet are closely related to one another by symmetry transformations similar to the rotations of a cube. If you rotate a cube through 90° or 180° about an axis drawn through the centers of two opposite faces, for example, it ends up looking the way it did before you began. The colors of the faces might change as upon rotation, but the final shape is the same.

Unitary symmetry does not require that *every* hadron belong to an octet. There can be groupings of 1, 3, 10, 27, and even more. In fact, it was the verification of the ten-member group, or *decimet,* that convinced most physicists of the validity of this idea. The spin-3/2 baryon resonances were predicted to fall into such a decimet, and by 1962 nine of these particles had indeed been discovered.

Based on the evidence presented at an international conference held that summer, Gell-Mann predicted the existence of the tenth spin-3/2 resonance with a mass of 1,685 MeV and strangeness

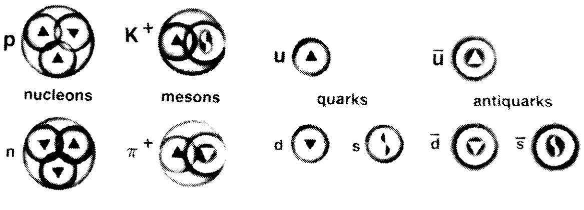

Figure 10. Nucleons are composed of quarks; mesons of quarks and antiquarks.

-3. This negatively charged baryon, which he dubbed the *omega-minus* (Ω^-) after the last letter in the Greek alphabet, would have a lifetime sufficiently long enough to leave a visible track in a bubble chamber photo. Here was the ideal quarry for experimental physicists.

At the time Brookhaven was building a new bubble chamber every bit the equal, if not the superior, of the big Berkeley device. Eighty inches long, it contained 900 liters of liquid hydrogen. To produce the omega-minus, Brookhaven physicists led by Nicholas Samios (the director of this laboratory today) fired a high-energy beam of negative kaons into the chamber. Then they searched through thousands of pictures for a characteristic short track emerging from a kaon-proton collision.

Early in 1964 Samios found just such a track. Detailed studies proved it was indeed the omega-minus, with strangeness -3 and almost exactly the mass Gell-Mann had predicted. After this convincing discovery, SU(3) symmetry was here to stay.

Just as these Brookhaven physicists were finding the omega-minus, a new idea was being published by Gell-Mann. The same idea had occurred simultaneously to George Zweig of the California Institute of Technology, then working at CERN, the European Center for Particle Physics in Geneva, but he had encountered difficulty getting it published. Both of them realized the octets and decimet of SU(3) symmetry followed logically if the mesons and baryons were built up from a set of just three fundamental building blocks, which Gell-Mann dubbed *quarks*. There was an "up" quark u, a "down" quark d, and a "strange" quark s—plus their respective antiparticles. According to Gell-Mann and Zweig, baryons were a combination of three quarks, while mesons had to be made from a quark plus an antiquark. Strange particles contained at least one strange quark that was not balanced by its antiquark, or vice versa.

For this scheme to work, however, the quarks had to have a peculiar property: *fractional* electric charge. The up quark had a charge of $+(2/3)e$, where $-e$ is the charge on an electron, while the down and strange quarks had $-(1/3)e$. Thus the proton charge, $+e$, came out okay if it were composed of two up quarks plus a down quark ($2/3 + 2/3 - 1/3 = 1$). All the allowed combinations of quarks and antiquarks, i.e., the hadrons, in fact, had whole-number charges.

The problem with fractional charge, however, was that it had never been observed. Within experimental errors, every previous measurement of the charge on a subatomic particle had come in as an integral multiple of e. So it was extremely difficult for physicists of the mid-1960's to accept the existence of quarks as real particles. Another severe problem was that putting two or three identical quarks—like two up quarks in a proton or three strange quarks in an omega-minus—together violated a basic tenet of quantum mechanics, the Pauli "exclusion principle" first enunciated by the Austrian theorist Wolfgang Pauli in the 1920's.

Despite these objections, a number of experimenters were game to try searching for quarks. They looked for evidence of fractionally charged particles in all kinds of places—at high-energy accelerators, in cosmic rays, in air, in dust, in sea water, and even in oyster shells! Over 20 such experiments occurred between 1964 and 1966, all without finding a single convincing example of a quark.

So the interest in quarks began to wane. Most physicists of the late 1960's, if they gave quarks any credence at all, considered them to be "mathematical" artifacts. They appeared in the equations describing the behavior of subatomic particles—but there was no experimental evidence for them. The origins of SU(3) symmetry were widely thought to lie elsewhere.

5. DEEP INSIDE THE NUCLEON

During the 1960's a new particle accelerator was under construction that eventually resolved the quark quandary. Built under the direction of Wolfgang Panofsky with $114 million in AEC funds, the Stanford Linear Accelerator was 2 miles long and arrow-straight. Based on microwave technology invented at Stanford University during the late-1930's, this device pushed electrons from 0 to about 20 GeV in a *single* pass along its length. Most other accelerators of the day, like Berkeley's Bevatron and the Brookhaven AGS, imparted small doses of energy to the particles in every circuit as they sped around a circular path many thousands of times per second.

Stanford physicists had pioneered a very different acceleration method. Starting in the late 1940's, they built a series of longer and more pow-

Figure 11. Aerial view of the Stanford Linear Accelerator Center.

erful accelerators based on microwave-generating devices known as *klystrons,* which are now used to power radar installations throughout the world. At Stanford they are employed to deliver short bursts of extremely high-power electromagnetic radiation to a long copper tube through which electrons travel in compact bunches. These bunches ride along on the leading edge of the resulting electromagnetic wave that surges down the interior of the tube at close to the speed of light, imparting energy to the electrons all the way.

Funded by the U.S. Office of Naval Research, the early Stanford work culminated in the Mark III, a linear accelerator that eventually stretched over 300 feet and delivered electrons at energies above 1 GeV. Robert Hofstadter used this machine extensively during the 1950's to discern the structure of atomic nuclei and the nucleons by interpreting the patterns of high-energy electrons as they bounced off these targets. He proved that the proton and neutron are spheres of matter about a tenth of a trillionth of a centimeter across—about a hundred thousand times smaller than an atom. Hofstadter won the 1961 Nobel prize for this important work.

Related *electron scattering* experiments continued at circular accelerators completed during the early 1960's in Cambridge, Massachusetts, at Cornell and near Hamburg, West Germany. These machines pushed electrons to energies as high as 6 GeV. Using these electrons as probes, physicists studied the structure of the nucleons in finer detail, finding no evidence for any "lumpiness" in the distributions of their matter. They still looked like homogeneous mixtures of mass and energy.

When the Stanford Linear Accelerator Center (SLAC) finally began its experimental program in 1966, most high-energy physicists expected its users to continue these nucleon structure measurements to even smaller distances. With electron energies of 20 GeV, the accelerator could be used to probe features about a *quadrillionth* of a centimeter across. But few physicists expected any big surprises. Indeed, results from the the first electron-proton scattering experiment, presented in 1967, proved to be just a smooth continuation of the earlier findings. No lumps.

But in the fall of 1967 a group of physicists from the Massachusetts Institute of Technology (MIT) and SLAC itself began a series of experiments that would give quarks more credence. Led by Jerome Friedman and Henry Kendall of MIT and Richard Taylor of SLAC, this team began to study *inelastic* scattering, whereby the electron produced other particles as it ricocheted from the proton. Most of the earlier work had concentrated on so-called elastic scattering, in which no other particles are produced when the electron bashes into the proton.

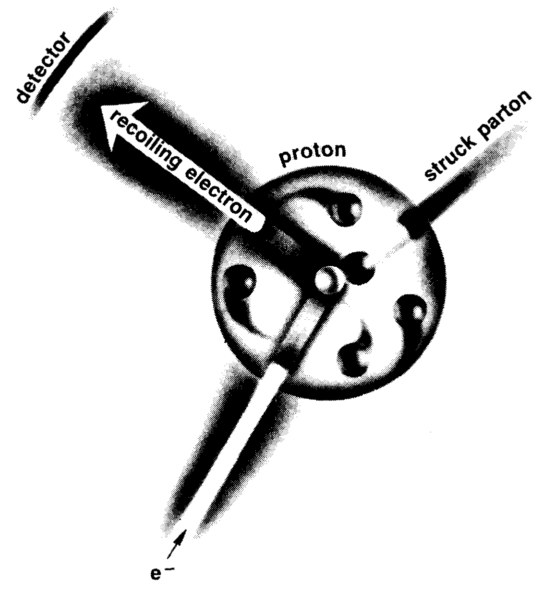

Figure 12. Parton picture of inelastic electron scattering.

Using two large devices called magnetic spectrometers, the MIT-SLAC team soon began to detect far more electrons bouncing off the proton at larger angles than expected—ten to a hundred times as many. One ready interpretation was that the inelastically scattered electrons had encountered tiny lumpms of matter deep inside the proton. It was an experience quite similar to what had occurred half a century earlier to Rutherford and his assistants, when they used beams of alpha particles to discover the atomic nucleus. Then too, physicists had encountered far too many projectiles scattering at large angles and concluded there must be something tiny responsible.

These ideas were assembled into a coherent theoretical framework by theorists James Bjorken of SLAC and Richard Feynman of the California Institute of Technology. Since a year before the MIT-SLAC experiment, Bjorken had been elaborating some of the quark ideas and had actually predicted there might be a large excess of electron scattering in the "deep inelastic" realm. Feynman happened along after the experiment, in mid-1968, and derived Bjorken's abstract results from a much simpler picture in which electrons scattered from individual, freely moving, pointlike objects inside the proton that he dubbed *partons*. Were these partons the same as quarks?

There were other ways to explain the excess of scattered electrons, too, and the "quark-parton model" of Bjorken and Feynman needed added verification. This proof came in over the next 5 years, however, as the MIT-SLAC team went back and made more measurements. Not only did they measure the rate of electron scattering from protons at many different angles, but they also examined inelastic electron scattering from neutrons.

If the electrons were actually hitting quarks inside the proton and neutron, as Bjorken and Feynman had suggested, the rate of scattering from neutrons should be *smaller* than that from protons. And indeed it was, proof that the objects inside both of them had (previously unencountered) fractional charges. The ratio of electrons scattered forward to those ricocheting backwards was another important test. It came in consistent with the hypothesis that the objects ausing the scattering had spin-1/2, as required by the quark and parton ideas.

By the early 1970's other kinds of experiments were beginning to test what was becoming known as the quark-parton model. Beams of neutrinos made at CERN were fired into a huge bubble chamber almost 5 meters long and containing thousands of liters of liquid propane or freon. From just a few thousand neutrino-nucleon collisions, the Europeans confirmed the SLAC discovery, concluding that quarks were responsible. By 1973 they could say that whatever was causing the scattering had fractional charges and spin-1/2, and that there were *three* of them inside both the proton and neutron.

Experiments in high-energy proton-proton scattering gave further evidence for quark substructure. The large numbers of pions flying out at wide angles from these encounters could be explained fairly easily if a quark in one proton had struck a quark or an antiquark in the other. Such "hard-scattering" phenomena became increasingly common during the 1970's as powerful new accelerators supplied very high-energy projectiles able to penetrate deep into the heart of the nucleons.

By the summer of 1973 the quark-parton picture of nucleon structure had begun to take a firm hold upon the thinking of many physicists. Evidence for quark substructure had been found in experiments involving the strong, weak, and electromagnetic forces. Everything seemed to be coming up quarks.

But there was still one puzzling problem that kept everybody wary. No matter how hard one hit the nucleon, a single, solitary quark never emerged all by itself to leave a track in a particle detector. All physicists had ever observed coming out were the usual hadrons—pions, protons, kaons, and other particles feeling the strong force. Lacking any direct observation of an individual quark, many physicists remained skeptical of their existence.

6. THE SEARCH FOR UNITY

High-energy physicists try to describe the universe with the utmost economy. They seek the smallest possible set of fundamental bricks out of which to build matter and the fewest different kinds of mortar that can bind them together. Ideally they would prefer to use only one kind of mortar and a few different bricks, one force acting among just a few elementary particles, as the basis of all existence. The quark model was a major success in this regard; out of a scant three particles, all the teeming variety of hadrons could be built.

By the 1950's it had become clear that there were *four* forces acting upon subatomic particles: electromagnetism, the strong and weak nuclear forces, and gravity. Although such a situation is not bad—4 is far better than 40—it was not good enough for certain physicists, who began to search for deeper connections between these forces. They wanted to know whether two of these forces might be just different manifestations of a single, fundamental force.

Such a quest was hardly radical. In the late 1600's Isaac Newton had accomplished such a "unification" when he showed that apples fell to earth—and moons and planets remained in orbit—because of a single universal force called gravity. Almost two centuries later, the Scottish physicist James Clerk Maxwell achieved a similar unification when he demonstrated that electricity and magnetism were but two facets of the same phenomenon, called electromagnetism. Maxwell's four equations, which predicted the existence of electromagnetic waves (of which light is just one form), supply the theoretical underpinnings of the electronic and communication technologies that are central to modern life.

Recent attempts at unification employed the gauge theory approach that had been eminently successful in describing electromagnetism. In a gauge theory the force on a particle is due to some kind of charge that is absolutely indestructible—like electric charge. As mentioned earlier, Julian Schwinger tried to apply the gauge theory of Yang and Mills to form a unified theory of the weak and electromagnetic forces. It was an audacious idea, because these two forces appear *very* different in practice. Thousands of times feebler than electromagnetism, the weak force extends only over extremely short distances, and does not conserve parity.

Schwinger's attempt ran into severe difficulty, however, when he tried to endow the two weak-force-carrying W particles with mass—which was necessary because short-range forces are usually carried by massive particles. When he tried to graft a mass onto these particles, the desirable gauge invariance of the theory broke down, and infinite quantities began to crop up in his calculations. This "problem of mass" continued to be a source of frustration to physicists working on gauge theory.

One such physicist was Sheldon Glashow, who as Schwinger's graduate student at Harvard, had participated in the attempts to unify the theories of weak and electromagnetic forces. Sympathetic to his mentor's ideas, he was also cognizant of their shortcomings. Working in Copenhagen in 1960, he skirted some problems by postulating a neutral force-carrying particle called the Z in addition to the two W's. Together with the photon, they formed a hypothetical family of four spin-1 vector *bosons* that carried both the weak and electromagnetic forces. By an appropriate choice of masses, Glashow's theory portrayed both a short-range, parity-violating weak force and a long-range, parity-conserving electromagnetic force. But because he had inserted the masses of the vector bosons into the theory in a seemingly arbitrary manner, infinities again cropped up in calculations.

In the early 1960's, theorists were becoming interested in *broken* symmetry. An idea borrowed from solid-state physics, broken symmetry means that the equations describing a physical system remain symmetric even though their physical manifestations—the subatomic particles and the forces between them—do not. The members of the spin-0 meson octet, for example, have fairly different masses ranging from 135 to 550 MeV even though they are all close relatives. Perhaps the symmetry between the particle masses is "broken" by some kind of mechanism, while the underlying equations remain symmetric.

An everyday example of broken symmetry is a bar magnet. Maxwell's equations, which describe the magnetic field permeating the magnet, favor no particular direction. But the bar magnet itself *has* a special direction; like every magnet, it has a north and south pole. This polarization occurs because the iron atoms in the bar are themselves tiny magnets whose preference is to line up with one another—reinforcing each other's magnetism. So although the underlying equations are symmetric, their physical manifestation is not.

Broken symmetries, however, had a highly undesirable feature. In 1961 Yoichiro Nambu of the University of Chicago and Jeffrey Goldstone of Cambridge University showed that they required the existence of massless spin-0 particles, later called *Nambu-Goldstone bosons*. As no such particles had ever been observed, the ideas of broken symmetry seemed to have little relevance to particle physics.

Then in 1964 a number of physicists solved this problem. They discovered a mechanism whereby these unwanted bosons would automatically disappear from the theory while the spin-1 vector bosons in a theory could have masses. Most noteworthy was the work of Edinburgh University theorist Peter Higgs, who showed that in *gauge* theories the troublesome spin-0 bosons might go away when the symmetry is broken. Several other theorists then demonstrated how the force carriers in gauge theory could possess mass—as though they had somehow "gobbled up" the Nambu-Goldstone bosons.

In 1967 Steven Weinberg, a Berkeley physicist on leave at MIT, first realized that this "Higgs mechanism" might provide a way to unify the weak and electromagnetic forces. By incorporating the mechanism in a Yang-Mills gauge theory, he could allow the W and Z particles to acquire their masses "naturally." He published his ideas in a short paper titled "A Model of the Leptons." In 1968 the same idea occurred independently to Abdus Salam of the Imperial College in London. But neither physicist could prove that the resulting *electroweak* theory was in fact calculable—that it did not have the same infinities that always seemed to crop up when masses were introduced.

The proof that the electroweak theory could lead to calculable results, that it was indeed *renormalizable* in physicists' language, was finally made in 1970 by two Dutch theorists. Martinus Veltman of Utrecht had developed a number of calculation techniques that his graduate student, Gerard't Hooft, applied to Yang-Mills gauge theory. If the masses of the vector bosons in this theory were generated by the Higgs mechanism, they showed, then the physical quantities of the theory—particle masses and other properties—were indeed calculable. Only then did the infinities that had plagued gauge theories for years go away.

Armed with this electroweak theory, physicists began making testable predictions. A leader of these efforts was Weinberg, who showed how to extend his "model of the leptons" to include the weak interactions of the hadrons. The clearest evidence for the new theory would be a proof that the Z particle indeed existed. But with a mass thought to exceed 40 GeV, this boson was impossible to produce at accelerators of the day. Its *indirect* effects, however, could still turn up in weak interactions.

Experimenters began to look for indirect effects of the Z in neutrino collisions with matter. Because neutrinos interact only through the weak force, this was an ideal place to search for such subtle effects, which would have been overwhelmed if neutrinos had strong or electromagnetic interactions. In particular, physicists were searching for events in which a neutrino glanced off an atomic electron or nucleus and remained a neutrino afterwards. Such *neutral current* events could occur if the weak force between the neutrino and the atom had actually been carried by a neutral boson like the Z instead of charged bosons like the W^+ and W^-. It was a crucial test of the electroweak theory.

Neutrino scattering experiments were among the first to be planned for the big proton synchrotron then under construction at the new Fermi National Accelerator Laboratory (Fermilab) just west of Chicago. Built under the leadership of Robert Wilson and with $250 million in AEC funding, this 4 mile ring was the largest particle accelerator in the world when it began operations early in 1972. At the time it could boost protons to energies of 200 GeV, setting a new world record. Its performance has steadily improved over the years until today it supplies them at almost 1,000 GeV, or 1 TeV—still the world's highest energy particles.

In 1972 a collaboration of physicists from Harvard, Pennsylvania, and Wisconsin began to use the Fermilab accelerator to search for evidence of

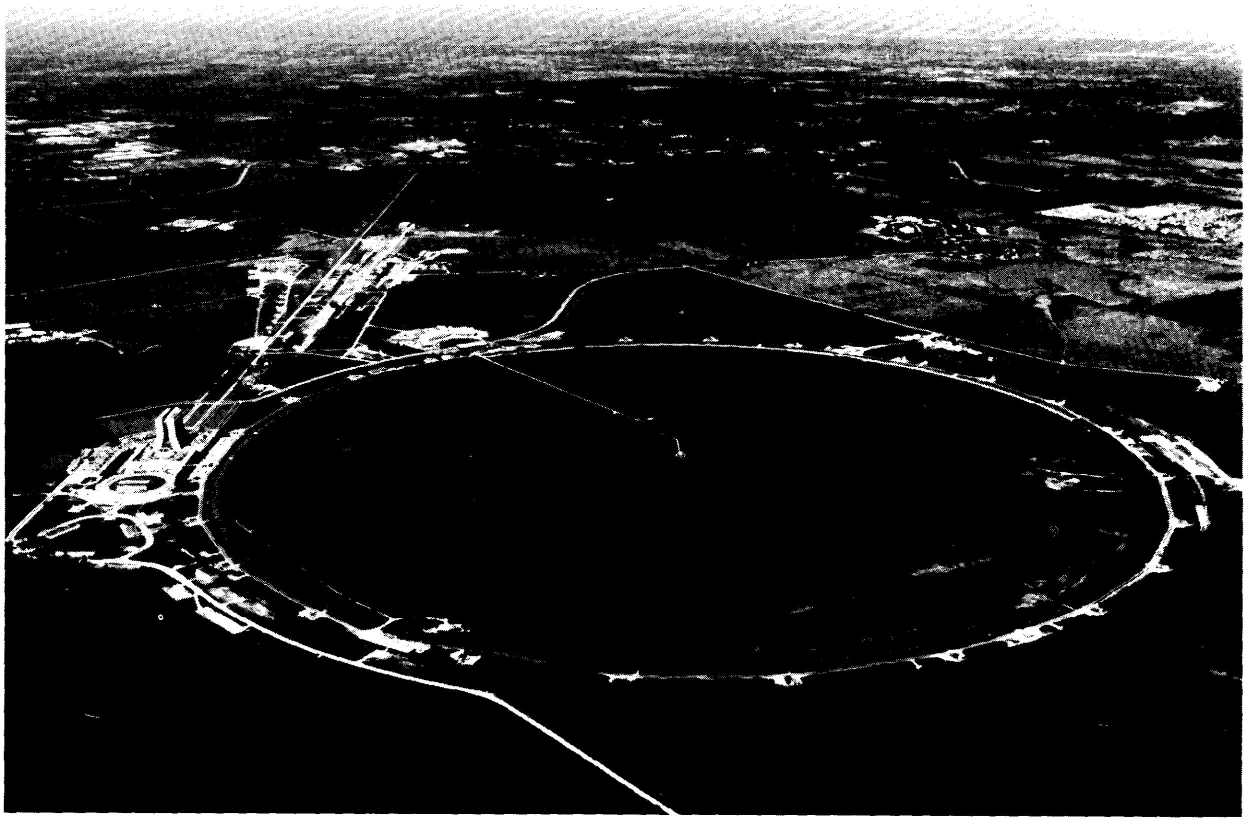

Figure 13. Aerial view of the Fermi National Accelerator Laboratory.

the Z. They made a beam of neutrinos by crashing high-energy protons into metal targets and filtering out all the other debris; then they directed this neutrino beam onto a massive detector to see whether any rebounded. But European physicists had already performed a similar experiment at CERN, using much lower-energy neutrinos, and found the first candidate for a neutral current event, in which a neutrino had apparently knocked a single electron out of its atom.

Other neutral current events, in which a neutrino collided with an atomic nucleus and rebounded sharply, also began to turn up in increasing numbers at both Fermilab and CERN. The Europeans had been working with their detector for several years, however, and knew its behavior better than the American group understood their newer equipment. CERN was the first to announce conclusive evidence for neutral currents, in the summer of 1973, and the Fermilab team soon confirmed the find. With this discovery of neutral currents, the case for a unified gauge theory of the weak and electromagnetic forces became much stronger.

The electroweak theory says that the charged leptons—the electron and muon—must be paired with their respective neutrinos. When an electron neutrino interacts with anything, either a W^+ or Z conveys the weak force. If a W^+ conveys the force, the neutrino converts into an electron. Similarly, a muon neutrino can only change into a muon. Both neutrinos retain their identities, however, if a Z is involved.

What's more, the electroweak theory permits only *left-handed* leptons—those whose spin vectors are aligned opposite their direction of motion—to participate in these exchanges. Right-handed *anti*leptons like the positron can take part, too, but right-handed leptons and left-handed antileptons cannot. No such restrictions apply when these particles feel the electromagnetic force carried by a photon. Thus the electroweak theory explains how the weak force violates parity, distinguishing between left and right, while the electromagnetic force does not.

When quarks were first proposed in 1964, a number of physicists figured they should be closely related to the leptons. Prominent among them were Glashow and Bjorken, who postulated another, fourth quark they called the *charmed* quark (c).

Many physicists felt that symmetry between quarks and leptons was required—that there had to be equal numbers of both. As a fourth lepton—the muon neutrino—had just been discovered at Brookhaven, a fourth quark was needed.

Not much came of this prediction until 1970, when Glashow and two European physicists visiting him at Harvard used this hypothetical fourth quark to help explain why neutral kaons hardly ever decayed into a pair of muons. If there were only three quarks, this process should have occurred at a small but steady rate. But such an event had never been observed. With a charmed quark in the picture, however, in theory there were *two* pathways by which the kaon could decay in this way. And through an idiosyncrasy of nature, the two processes might easily cancel one another out, yielding zero net result!

A fourth quark fitted very nicely into the electroweak theory, too. The up quark can be paired with the down quark, and the charmed quark with the strange. (Actually, the relationship is more complex than with leptons, but that need not concern us here.) As with the leptons, only left-handed quarks and right-handed antiquarks feel the weak force.

Thus a beautiful, compact picture of the subatomic world had begun to emerge after the discovery of neutral currents in 1973. What was needed to clinch matters was the discovery of the charmed quark itself.

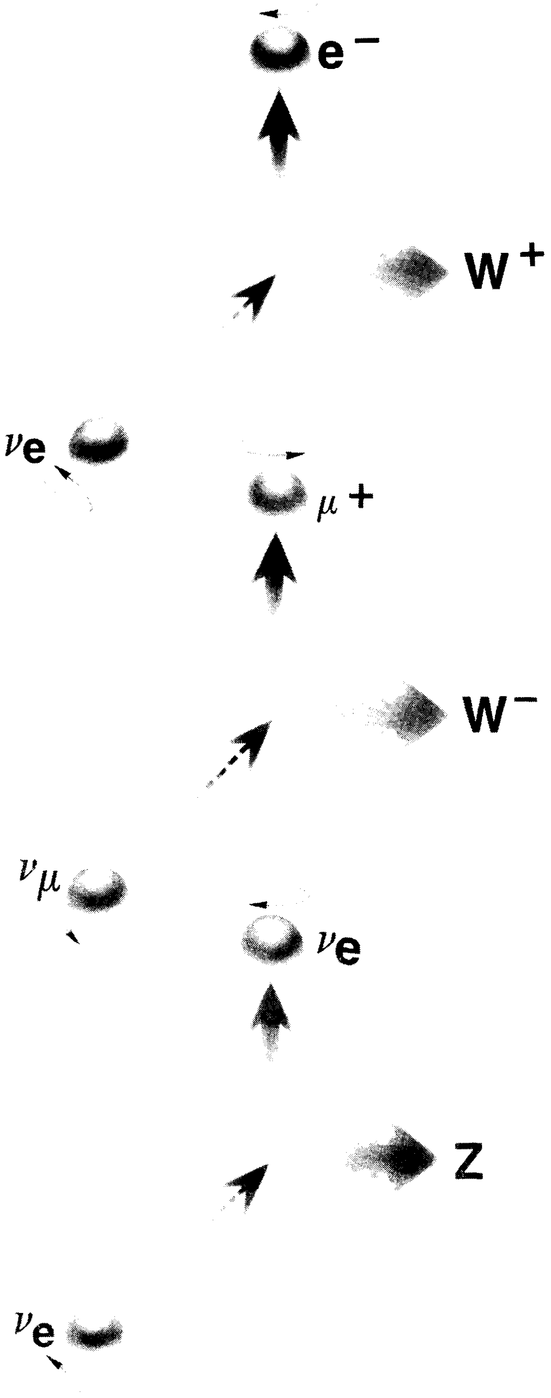

Figure 14. **Neutrinos and antineutrinos interact by exchanging W and Z particles.**

7. PHYSICS IN COLLISION

In the early 1970's another innovation in accelerator technology led to a jump in available energy that helped U.S. physicists discover the fourth quark. Until that time almost all important high-energy physics research had employed what are known as *fixed-target* facilities. Physicists smashed energetic subatomic particles into stationary targets and examined the debris thrown forward into detectors. Although this approach has certain advantages, such as being able to place huge volumes of material in the path of weakly interacting particles like neutrinos, it also has a number of key drawbacks.

At energies where relativity becomes important, most of the probing particle's energy is used to fling collision fragments away, somewhat like clobbering a Volkswagen with a trailer truck. The fraction of the energy available for making new, exotic, and *heavy* particles— such as the massive W and Z bosons—becomes smaller and smaller as the energy grows. Even though Fermilab's synchrotron could accelerate protons to 300 GeV by 1973, for example, less than 8 percent of this figure, or 24 GeV, was available to make new particles. The rest was simply wasted on the debris.

By the late 1950's a few physicists had recognized this inherent limitation of fixed-target machines and begun to seek alternatives. If one instead took *two* beams of particles of equal energy and passed each beam through the other, they figured, almost all of the combined energy of any two colliding particles would be available to make new things happen. It would be somewhat like two trailer trucks colliding head-on.

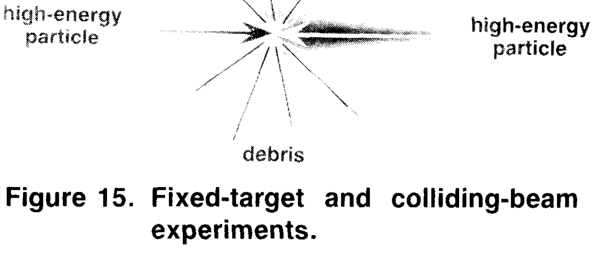

Figure 15. Fixed-target and colliding-beam experiments.

Given the incredibly small sizes of subatomic particles, however, the chances of a head-on collision occurring in a single crossing are miniscule. There is so much empty space between the individual particles in each bunch that they merely zoom past one another without interacting. But by putting the particles into circular devices called storage *rings* and circulating them in intersecting beams for hours at a stretch, physicists could improve their chances. With millions of beam-beam encounters per minute, smash-ups occur often enough to do experiments.

Only stable, charged particles such as the electron and proton can be stored in these rings. The first storage ring was built in 1958 by a small collaboration of Princeton and Stanford physicists. Shaped like the figure 8, it stored 500 MeV electrons in two separate rings and brought them into collision at a single cross-over point.

In the early 1960's Italian physicists demonstrated how to store both electron and positron beams in the *same* ring. One circulates clockwise at almost the speed of light, the other counterclockwise. Head-on collisions occur at a few fixed *interaction regions* around the ring, where physicists set up their detectors to examine the debris. Occasionally an electron and a positron annihilate each other, creating a momentary fireball of pure energy that quickly materializes as leptons or hadrons.

The first results from the Italian storage ring ADONE, which came in during the early 1970's, showed far greater production of hadrons in these electron-positron annihilations than most physicists had imagined. It was welcome news to the small but growing company who believed in quarks. The excess production of hadrons was a key piece of evidence that quarks carry an important new property.

One of the problems with the original quark hypothesis had to do with the difficulty of putting three quarks inside a baryon. According to Pauli's exclusion principle, two identical spin-1/2 particles cannot occupy the exact same turf. This is the main reason solid materials are so hard and impenetrable even though they are mostly empty space. But with certain baryons like the omega-minus, physicists needed to put *three* identical quarks into the same pot.

One way around this difficulty was to suppose that these quarks were not really identical, after all, rather they carried some additional property that was in fact *different* from one quark to the next. Not much was made of this idea until 1971, however, when Gell-Mann used it to explain why the neutral pion disintegrated nine times faster than first expected. If each type of quark—up, down, and strange—came in three distinct varieties, then the exclusion principle would not be violated by baryons, and the pion decay rate would increase by a factor of 3^2, or 9, as observed.

Gell-Mann dubbed the new, threefold property *color*. Quarks, he said, came in three different colors, arbitrarily chosen to be red, green, or blue. Thus the three strange quarks inside the omega-minus are in fact different: one red, one green, and one blue. The *combination* of these three colors—like the combination of red, green, and blue light on a television screen—results in zero net color. The mesons and baryons that leave deposits in particle detectors are completely colorless.

With the help of color, the quark model could readily explain the large numbers of hadrons being produced in electron-positron collisions. A quark and its antiquark could be created and subsequently metamorphose into hadrons that strike the detectors. Without color the quark model prediction still came in a factor of 3 below the observed rate of hadron production. With color, however, there are three times as many ways to make quark-antiquark pairs, and the rate increases accordingly.

A segment called the CEA Bypass, added to the Cambridge Electron Accelerator in the late 1960's, made it the first electron-positron storage ring to be built in the United States. By 1973 the CEA was able to extend the Italian measurements to higher energies. The rate of hadron production now proved to be greater than expected in the quark model, even if one assumed three kinds of quarks and three colors of each. Some physicists began to claim that this excess was evidence for a fourth quark, such as the charmed quark, but most preferred to wait for better data.

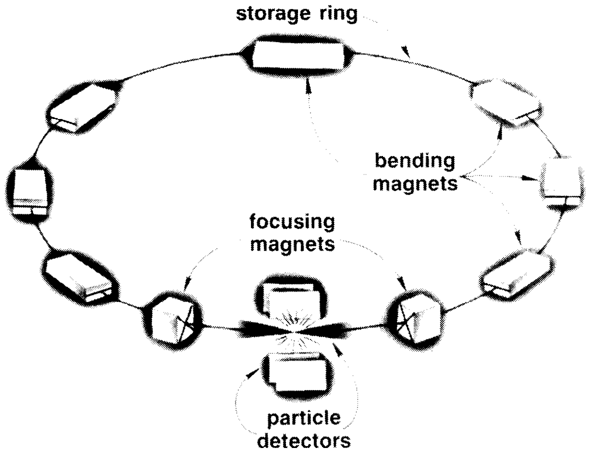

Figure 16. An electron-positron storage ring with detectors positioned near an interaction region.

Just coming on line that year at SLAC was a new storage ring called SPEAR, an oval tube 200 yards in circumference that was fed electrons and positrons from the linear accelerator. Built under the leadership of SLAC physicist Burton Richter, a member of the original Stanford-Princeton group (and now Director of SLAC), it was designed to operate at total energies between 2 and 8 GeV and to generate a far greater number of collisions than previously possible.

In addition, Richter insisted that a new kind of particle detector be built at one of the two SPEAR interaction regions. The Mark I detector surrounded most of the collision point and had a strong magnetic field inside to help identify the particles produced and measure their properties. Earlier detectors at storage rings had been lacking on both counts, with consequent ambiguities in the interpretation of their results.

By the end of 1973 the first set of SPEAR measurements were complete, confirming the steady rise in the rate of hadron production at total energies above 3 GeV. As the rate was well beyond expectations based on three kinds of quarks with three colors, the case for a fourth quark became stronger.

In November 1974, while rechecking a few measurements at 3.1 GeV, SLAC and Berkeley physicists working on the Mark I detector discov-

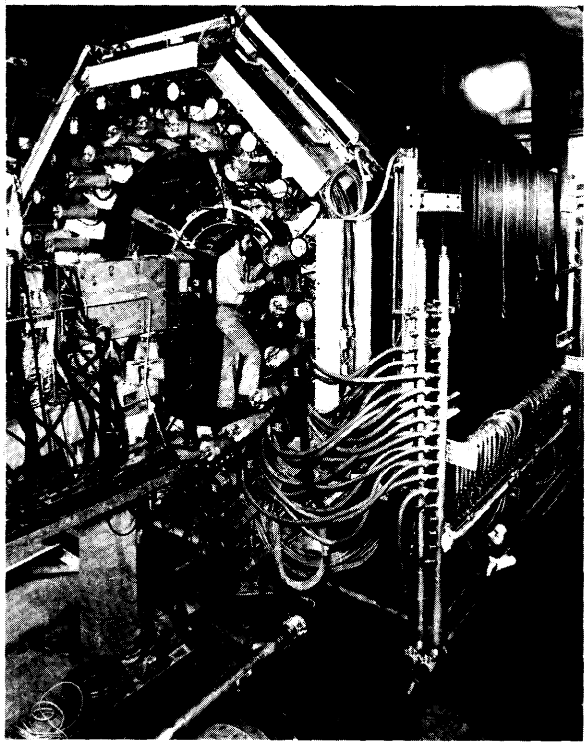

Figure 17. The Mark I detector at the SPEAR storage ring.

ered a tremendous increase in hadrons produced at that energy, which proved to be the signature of an astounding new particle. Electrons and positrons were feverishly annihilating one another to form an electrically neutral particle with a mass-energy of 3.1 GeV; it decayed into hadrons, a pair of muons, or another electron-positron pair. They named their discovery the *psi* ("ps-eye") particle.

Unknown to the SPEAR group, the exact same particle had turned up the previous month in a Brookhaven experiment led by Samuel Ting of MIT. Working on the AGS, his team examined what particles were produced when 29 GeV protons smashed into beryllium nuclei; they detected the new particle by careful study of its decay into electron-positron pairs. Ting called his discovery the *J* particle. The two discoveries were announced simultaneously at SLAC on November 11, 1974—a red-letter day in high-energy physics.

What was particularly striking about this particle was the fact that it survived about a thousand times longer than it should have, based on its large mass. Many physicists took this fact to suggest that the J/psi, as it has come to be known, carried some completely new property of matter never before encountered.

Advocates of the charmed quark were elated. They figured their hypothesis had been confirmed at last—especially after a second psi particle was discovered at SPEAR two weeks later with a mass of 3.7 GeV. These new objects, they argued, consisted of a charmed quark paired with its corresponding antiquark. To confirm this interpretation beyond a shadow of doubt, however, physicists needed to find a particle with "naked" charm, within which a charmed quark was *not* paired with its antiquark. Well before the J/psi discovery, Glashow and others had predicted such charmed mesons and baryons, containing a single, unpaired charmed quark, would turn up in high-energy experiments.

At accelerators around the globe experimenters raced to search for charmed particles. The first evidence for a charmed baryon was reported in early 1975 by a group of Brookhaven physicists working in neutrino scattering. Over a year later Berkeley and SLAC physicists found solid evidence for charmed mesons produced inside the Mark I detector. It was convincing proof that the charmed quark truly existed. In recognition of their key roles in the discovery of a whole new family of particles, Richter and Ting received the 1976 Nobel prize in physics.

Further evidence for quarks came in that year from SPEAR. Using a sophisticated computer analysis, SLAC physicists demonstrated that the hadrons emerging from electron-positron collisions were spewing out in back-to-back sprays, or *jets*. This pattern occurs naturally when a quark and its antiquark are produced in the ensuing fireball—and convert almost immediately into hadrons. Jets are the observable "footprints" left by quarks.

By the end of 1976, the physics community worldwide had come to believe in leptons and quarks as the fundamental basis of all matter. Although no quark had ever left a track in a particle detector, the evidence for them—which came largely from the MIT-SLAC and the SPEAR experiments—was undeniable. In addition to the four leptons, there were four known quarks: up, down, strange, and charmed.

During the excitement over the SPEAR discoveries, another group of SLAC physicists had been concentrating on a different kind of signal. Led by Martin Perl, they were searching for events in which an electron appeared in the Mark I detector together with a single muon, which would be evidence for the production of a lepton heavier than the muon. With over a hundred such events in hand by the summer of 1976, Perl's group announced the discovery of the *tau* (τ) lepton at a mass of about 1.8 GeV. Detailed analyses also showed that a new and different neutrino, called the *tau neutrino* (ν_τ), was being produced when the tau decayed. Thus there was a *third* pair of leptons to be reckoned with.

Advocates of quark-lepton symmetry therefore postulated another pair of quarks, and experimenters at Fermilab were not long in finding the first one. Led by Leon Lederman (who later became Director of Fermilab), a group of physicists was ramming high-energy protons into stationary metal targets and searching for muon pairs among the debris. By the summer of 1977 they had accumulated sufficient evidence to announce the discovery of three *upsilon* particles with masses near 10 GeV. Like the J/psi, these particles were neutral and survived a long time by subatomic standards. Theorists immediately figured these upsilons were combinations of a *fifth* quark paired with its antiquark. Detailed measurements made in Germany later that year and in 1978 showed that the charge of this quark had to be -1/3, like that of the down and strange quarks. The new quark was dubbed *bottom* or *beauty* (*b*).

Particles known as B-mesons, containing a bottom quark plus an up or down quark, were first discovered in 1983 at the Cornell Energy Storage Ring. Physicists working at CESR have pioneered the studies of these particles, which may be the key to understanding CP violations.

Once the fifth quark had been discovered, the search began for the sixth, called *top* or *truth* (*t*). New accelerators and storage rings have been built during the past 10 years whose primary goal was to find this quark, but it has not turned up as yet (early-1990). Still, few physicists doubt it will eventually be found, once a powerful enough machine is built. So firm is the belief that quarks and leptons come in pairs, that they figure the top quark must simply be too massive to be produced at existing devices.

This is a telling measure of how seriously quarks are taken today—and a tribute to the performance of American high-energy physicists. Not only was the quark model, and much of the electroweak theory, developed by U.S. physicists, but crucial work in confirming these ideas was carried out at each of the three national laboratories—Brookhaven, Fermilab, and SLAC.

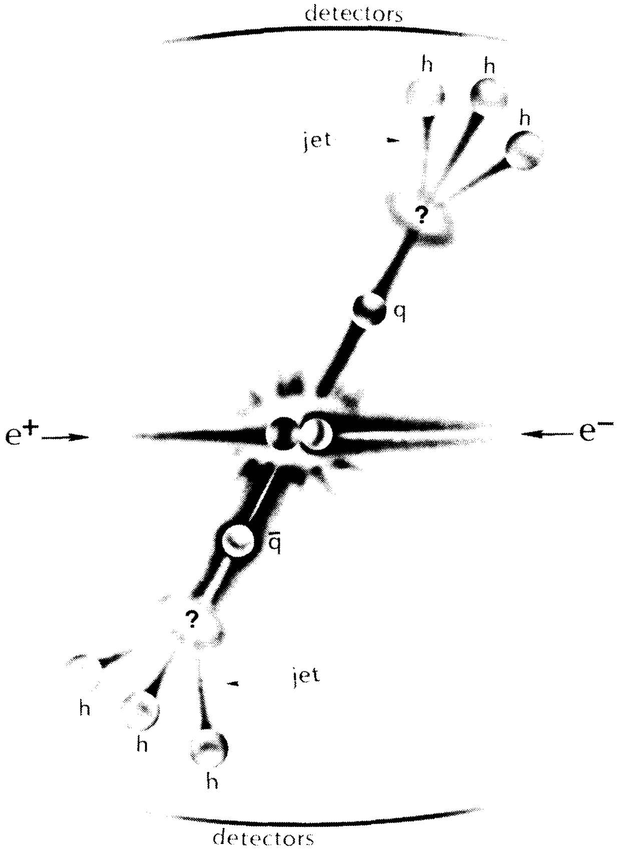

Figure 18. **Back-to-back jets of hadrons arising from quark-antiquark product in an electron-positron collision.**

8. THE STANDARD MODEL

Thanks to the work of theoretical and experimental physicists, all known features of the subatomic world can be explained in terms of what is called the Standard Model. A grand achievement of modern physics, this model incorporates all the major advances of the past three decades. With the discovery of a third family of quarks and leptons in the late 1970's, the Standard Model was nearly complete. But a few more elements were needed to fill out the picture—like a way to lash quarks together inside hadrons.

From scattering experiments physicists knew that quarks inside a hadron acted like individual particles—like pairs or trios of colorful marbles rattling around in a bag. But some unfamiliar force was confining these quarks so that they never emerged individually. As subatomic forces are conveyed by particles, there had to be a particle (or a group of them), which physicists called the *gluon* (g), carrying the force that imprisoned them inside hadrons. Quarks would attract one another by swapping gluons.

Describing this interquark force in detail, however, was not a simple feat. Physicists still cannot isolate a single quark and study its interaction with known forces—as can be done, for example, with an electron in electric or magnetic fields. They must always work with ensembles of two or three quarks, which complicates matters enormously.

An important theoretical breakthrough occurred in the spring of 1973. Three Americans—David Politzer of Harvard, and David Gross and Frank Wilczek at Princeton—independently showed that Yang-Mills gauge theories predicted that the force between two particles *decreases* as they approach one another. It is somewhat like the force exerted on two marbles by a rubber band connecting them, which slackens as they come closer together. Such behavior is contrary to normal expectations based on forces like gravity and electromagnetism, which increase at close quarters, but it is vary much how quarks behave. Politzer, Gross and Wilczek had discovered the correct theoretical framework needed to describe such a force.

The force between quarks becomes feeble at short distances, like those separating quarks inside a proton. When one of them is struck by a high-energy probe, such as an electron, the quark behaves like a relatively free, unbound particle—as does one marble when hit by another. As the struck quark begins to fly away from its siblings, however, the force between them gets stronger: the "rubber band" becomes more taut. One of two things now happens. Either the force yanks the truant quark back into the fold, or the quark has sufficient energy to break free. In the latter case, however, it does so only after acquiring enough energy to create a new quark to take its place and a corresponding antiquark bound to itself. We are still left with hadrons: a baryon made of three quarks and a meson composed of a quark-antiquark pair.

In gauge theories, forces are due to some kind of "charge." During the summer of 1973 several physicists suggested that the new property of color—originally proposed to distinguish one quark from

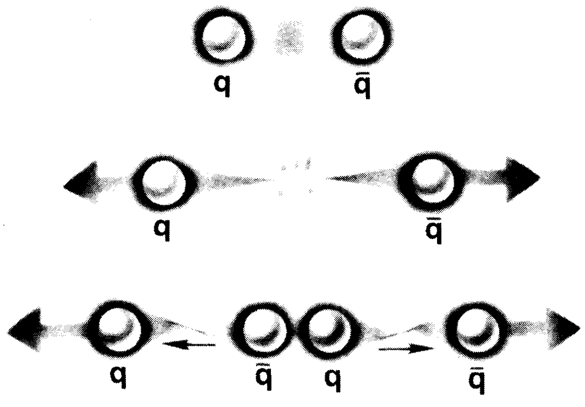

Figure 19. The force between two quarks grows stronger as they separate. They can break free of one another only by creating a quark-antiquark pair.

another—is precisely what gives rise to the interquark force. The gluons, then, are the bearers of this property. Eight neutral, massless, spin-1 gluons are responsible for conveying the force between quarks, actually *carrying color* from one quark to another. In analogy with quantum electrodynamics, Gell-Mann dubbed this new gauge theory *quantum chromodynamics,* or *QCD* for short.

Experimental tests of QCD, however, were hard to come by. Like quarks, gluons should be trapped inside hadrons and be thus unobservable in particle detectors. Any proofs therefore had to be indirect. If gluons did exist, there would be slight deviations from free quark behavior inside a hadron; quarks would not act *exactly* like free marbles inside bags. Traces of that slackened "rubber band" ought to be detectable, for example, in deep inelastic scattering of leptons from nucleons. Such deviations were indeed reported in 1975 by sensitive experiments at SLAC and Fermilab. Detailed confirmation of this behavior came later from CERN.

Another proof of QCD occurred at a new storage ring in Germany, in which electrons and positrons collided at combined energies of 30 GeV or more. Experimenters at this facility noticed trios of jets emerging from some collisions. Two of these were clearly the visible footprints of a quark and its antiquark, but the third jet was interpreted as the track of a gluon emitted by one of them. Similar three-jet events soon turned up at other storage rings. By the following year, the evidence was conclusive that the object responsible for the third jet was a spin-1 particle, as expected in QCD. The gluon had been discovered.

In 1980 another storage ring called Positron-Electron Project (PEP) began operations at SLAC. More than 2 kilometers in circumference, this ring circulated electrons and positrons at energies up to 18 GeV. Collisions occurred at six points around the ring, where large particle detectors sampled the debris. From the frequency of the three-jet events, scientists working at PEP were able to measure, for the first time, the *strength* of the QCD force carried by gluons.

Thanks to all this work, stretching over an entire decade, physicists now have a working description of the force binding quarks within hadrons. Though weak at close quarters, it becomes tremendous at large distances. To pull two quarks a foot apart (if that were possible) would require the same energy as needed to lift an automobile a foot off the ground. The "strong" force between hadrons is just the residual force remaining after the quarks inside have essentially neutralized their immense attraction for one another.

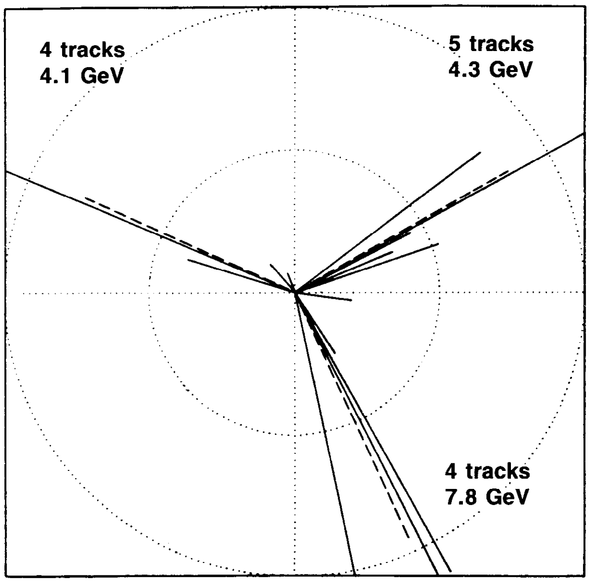

Figure 20. One of the first three-jet events witnessed at electron-positron storage rings.

By the late 1970's particle physicists were also reaching consensus on a theory of the electroweak force. After the experiments at CERN and Fermilab had proved the existence of neutral currents (see Chapter 6), there followed a period of confusion over which particular gauge theory was most appropriate. The one proposed by Glashow, Salam, and Weinberg—known as the GSW theory—was but the simplest of many possibilities. Experimental anomalies that cropped up in the mid-1970's seemed to require more complex theories to explain them.

If the GSW theory were indeed true, electrons had to violate parity occasionally. Because left-handed electrons could sometimes feel the force carried by a Z boson, they would interact a little more often than right-handed electrons, which could not. It was a tiny effect, however, only about 1 part in 10,000. Until 1978 nobody had been able to find evidence for it.

That year a team of SLAC and Yale physicists shot beams of *polarized* electrons—those with their spin vectors aligned either along or opposite the beam direction—at a target of liquid deuterium, a heavy form of hydrogen. It was a difficult experiment requiring extreme precision all along the two-mile accelerator. But the SLAC-Yale team finally proved that left-handed electrons scattered a bit more often, in complete accord with predictions of the GSW theory. The very next year Glashow, Salam, and Weinberg shared the Nobel prize in physics for their pivotal contributions to the unified theory of electromagnetic and weak interactions—an epochal feat.

The SLAC-Yale experiment also provided an accurate measurement of a key quantity in the GSW theory, from which one could deduce the masses of the W and Z particles. The W mass had to be about 80 GeV and the Z mass about 90 GeV. These particles finally turned up in an experiment performed by a large collaboration of European and American physicists. Led by Carlo Rubbia of CERN and Harvard and Simon Van der Meer of CERN, this team found several W and Z particles in the debris of proton-antiproton collisions. Their masses came in at about what was expected, and the rate of their production was close to what had been predicted by QCD. Rubbia and Van der Meer shared the 1984 Nobel prize for this discovery.

All known features of the subatomic world, down to distances a thousandth the size of a proton, can now be explained in terms of the Standard Model. According to this picture, matter is subdivided into quarks and leptons, and forces are described by gauge theories. Matter particles come in three families of four spin-1/2 members each—a pair of quarks and a pair of leptons. Forces are carried by spin-1 particles: the electromagnetic force by the photon, the weak force by the W and Z bosons, and the QCD force by gluons.

One more piece is needed to complete this Standard Model. Accepting the Higgs mechanism, which gives the W and Z particles their tremendous masses, means there should exist at least one massive, spin-0 particle called the *Higgs boson*. This particle is also thought to endow the various quarks and leptons with their different masses. The simplest theory, the Standard Model, calls for only one Higgs boson, but more complex theories allow for more.

Finding a Higgs boson would be a major step forward in explaining why there are so many different quark and lepton masses; now these are just externally determined properties one must plug into equations of the Standard Model. Low-energy searches at existing accelerators have not yet turned up any convincing candidates for a Higgs boson, so experimenters have begun to focus attention on the very highest energies.

During the late 1980's, a pair of powerful colliders began operations—the Stanford Linear Collider (SLC) at SLAC and the Tevatron at Fermilab—able to create particles with masses of 100 GeV or more. The SLC brings 50 GeV electrons and positrons into collision after a single trip down the SLAC accelerator. The Tevatron boosts protons and antiprotons inside the Fermilab ring to energies of almost 1,000 GeV, or 1 TeV, and smashes them together inside a huge particle detector four stories high. Using these two colliders, American physicists made the first precision measurements of the massive W and Z particles, thereby providing key tests of the Standard Model.

Designed to create the Z particle in quantity, the SLC produced about 500 by the end of 1989, enabling physicists at SLAC to establish its mass to be 91.1 GeV. From the apparent yield of Z particles when the electron and positron beams were tuned to a total energy close to this value, the same scientists also concluded that there are no more conventional families of quarks and leptons beyond the three families already known to exist. Meanwhile, physicists working on the Tevatron at

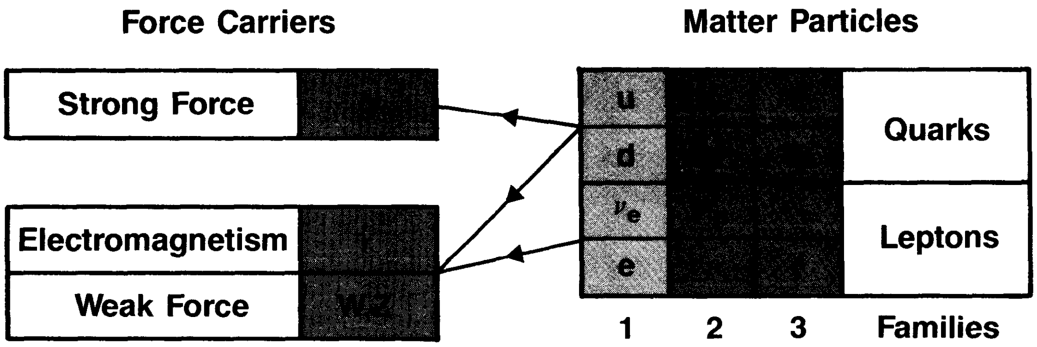

Figure 21. The elementary particles of the Standard Model. Quarks exert both strong and electroweak forces, but leptons feel only the latter.

Fermilab established the mass of the W particle to be 80.0 GeV—the world's most accurate measurement of this important Standard Model parameter.

Still undiscovered by end of the 1980's, however, were the elusive top quark (needed to fill out the third and final quark-lepton family) and the Higgs boson. According to Fermilab measurements, the top quark has to be heavier than 78 GeV, and indications are that it may be much more massive than that. If its mass is less than 200 GeV as expected, the top quark should eventually turn up at the Tevatron, which is the only collider in the world that can presently be used to produce it.

The Standard Model is a vast improvement over the situation that existed as late as the 1960's. It has withstood repeated experimental tests. But it is still too complex for most physicists, who seek to explain nature in the simplest possible terms, using only a few (if any) arbitrary parameters. Including the quark and lepton masses, there are at least 19 unexplained parameters in the Standard Model—a highly unsatisfactory situation.

For at least a decade, therefore, theoretical physicists have been trying to reach *beyond* the Standard Model. Based on little more than mathematical insight, they are attempting to predict how matter might behave and what particles might be discovered at energies above a thousand GeV, or 1 TeV, the current limit of existing accelerators. From previous experience at lower energies, they expect nature will reveal a common origin for the strong and electroweak forces, which would simplify matters enormously and help explain the complexity remaining today.

Perhaps the commonest path taken is the quest for what physicists dub a *grand unified theory,* or *GUT,* of the interparticle forces. Extending their Yang-Mills gauge theories, physicists have proposed that strong and the electroweak forces are, in turn, just two different low-energy manifestations of a single, grander unified force—two sides of the same coin. At the extremely high energies where this unity supposedly takes hold, estimated to be many trillions of GeV, these forces become one and quarks and leptons become indistinguishable from one another.

Because such energies are completely inaccessible at earthbound particle accelerators, experimenters have had to seek other, novel methods of testing grand unified theories. One way is to see if the proton decays. Long thought to be absolutely stable, the proton can decay according to GUTs because one of its quarks can change into a lepton through what physicists call a *quantum fluctuation.* The mean lifetime of a proton would still be incredibly long, however, perhaps a billion trillion times the age of the universe. The only feasible way to observe proton decay is to gather a lot of them—a thousand tons or more—in one place and wait patiently for a few to expire.

In the early 1980's experimenters around the world began to set up huge detectors in underground locations (to screen out cosmic rays, which can mimic the signals of proton decay) to search for such events. The largest and most sensitive of these underground experiments is built around a tank containing 8,000 tons of extremely pure water situated deep in a salt mine near Cleveland, Ohio. A collaboration of physicists surrounded the tank with over 2,000 phototubes, seeking to detect the faint flashes of blue light that would be generated in this water if a proton suddenly disintegrated.

In over 5 years of waiting and watching, they have recorded no such events, leading to the conclusion that the proton lifetime is greater than a million trillion trillion (or 10^{33}) years. This null result excludes the simplest grand unified theory. More complex GUTs, however, predict longer proton lifetimes that cannot be ruled out yet.

Grand unified theories make another prediction that can be tested by experiments. If they are true, then neutrinos are not massless particles as previously thought, but have a tiny mass. In such a case, the three known types of neutrinos can "*quantum oscillate*" one into another. A muon neutrino might become an electron neutrino, or vice-versa. So far, searches have turned up no conclusive evidence either for neutrino mass or for neutrino oscillations. But more sensitive searches are continuing in these areas, as much remains to be done. The quest for a grander unity has only just begun.

Whether or not grand unification holds true, however, the springboard that made these kinds of theories conceivable—the Standard Model—will certainly remain as one of the greatest intellectual achievements of this century.

9. PARTICLES AND THE COSMOS

The vast knowledge gained in the last few decades of high-energy physics has had a major impact on the fields of astrophysics and cosmology. So grand are its accomplishments that scientists can begin to make credible statements about the birth and death of the universe. To understand its earliest moments and some of its most exotic objects and processes, such as neutron stars and supernovae, they need to know how matter behaves at high energies and at short distances—exactly what has been studied for decades at particle accelerators and colliders.

In a similar vein, observations of the cosmos and its astrophysical objects have given particle physicists heavenly laboratories where they can test theories like GUTs, by providing conditions that cannot be replicated on earth. If a theory predicts that the universe or the sun behaves in a certain manner, and that behavior is not observed, the theory must be rejected or modified. By turning to the heavens like this, physicists have been able to study matter at energies, densities, and distance scales that are impossible to produce in earthbound laboratories.

Since the mid-1960's scientists have recognized that we live in an expanding universe, which began about 15 billion years ago in a tremendous explosion called the *Big Bang*. The faint afterglow of that titanic blast was discovered in 1964 by Arno Penzias and Robert Wilson of the Bell Telephone Laboratory. They found that the temperature of this relic radiation was only 3 degrees above absolute zero, or minus 270°C, which can be thought of as the average temperature of the universe today.

If we go back in time to the early moments of the universe, things get steadily hotter and matter becomes increasingly dense. When it was hardly 100,000 years old, the temperature was several thousand degrees—about that of the sun's surface. At this temperature, normal atoms disintegrate into their constituent electrons and nuclei; the universe then was a hot soup of atomic fragments. Still earlier, at about 1 second, it was far too hot (about 10 billion degrees) for even the simplest nuclei like helium to hold together. Under such conditions the universal soup consisted of individual protons, neutrons, electrons, neutrinos, and photons.

Between 1 second and 3 minutes, however, the universe cooled down enough so that the lightest nuclei could begin to form. From knowledge of nuclear and particle physics, scientists from the University of Chicago and Fermilab have calculated the relative amounts of deuterium, helium, and lithium nuclei that should have coalesced. The fact that the abundance of these elements, as measured by astronomers, correspond closely to the calculations is a key proof that the universe began in a hot Big Bang.

One of the assumptions used in these calculations, however, was that there are only *three* families of leptons and quarks having a light (or massless) neutrino as a member. If there were more than four different kinds of light neutrinos, the calculated abundance of helium is too high to be compatible with that measured. Thus cosmology was able to place a constraint on the Standard Model: there could be at most one light neutrino in addition to the three known kinds.

Originally published in the early 1980's, these striking predictions were borne out by the 1989 measurements of the Z particle at the SLC at SLAC. Additional neutrinos would allow the Z ways to disintegrate without leaving a visible trace in the surrounding detector—thus lowering the apparent yield of this massive particle. No such deficit was found. Thus the results are compatible with the three known species of neutrinos, and they exclude the possibility of a fourth.

Predictions of the Standard Model go back even further in time, to tiny fractions of a second after the birth of the universe. At about 0.00001 second (or 10^{-5} second, in scientific notation), conditions were so ultrahot that even hadrons could not survive, disintegrating into quarks and gluons. At earlier moments the universe was a superhot, superdense, seething plasma of quarks, leptons, photons, and gluons. At a trillionth of a second, or 10^{-12} second, it was so blistering that the massive W and Z particles existed in great profusion.

The Standard Model fully describes the behavior of matter and the evolution of the universe after this moment. But to understand what occurred *before* this instant, we have to call upon speculative theories like GUTs that take us beyond the Standard Model, where superhigh energies and ultrashort distances are the norm. There are several important questions whose answers must lie in these earliest moments of creation. Where did all the matter in the universe come from? How did it become structured the way it is? Why is it so smoothly distributed on the average?

Although the answers given by these speculative theories must be taken as conditional, the general outlines of this earliest trillionth of a second have begun to take shape over the past decade. The excess of matter (over antimatter) in the universe, for example, is thought to be closely tied, in part, to the phenomenon of CP violation discovered in 1964 (see Chapter 3). This slight asymmetry between processes involving matter and antimatter, when combined with conditions that should have occurred at about 10^{-34} second, could have produced such an excess—together with the vast quantities of photons that fill the universe. The ratio of photons to matter particles, in turn, helps physicists distinguish among various unified theories.

The overall smoothness of the universe is now thought to have arisen at about the same instant due to a unique phenomenon known as *inflation*. It was discovered in 1980 by Alan Guth, a particle theorist then working at SLAC, who was applying GUTs to the early universe. According to the inflation idea, the entire universe observable today compressed to a size smaller than a trillionth the diameter of a proton at 10^{-35} second, but it exploded violently to at least the size of a grapefruit (and perhaps a billion billion times bigger!) in the blink of an eye. The fabric of space was stretched so rapidly, like a balloon suddenly inflated, that it became extremely smooth.

Despite its overall smoothness, however, matter was somehow able to collect into the galaxies and clusters of galaxies now sprinkled about the universe. To accomplish such a feat, there had to be some kind of primeval lumpiness that survived this inflationary epoch—to supply the necessary "seeds" toward which matter could begin to gravitate.

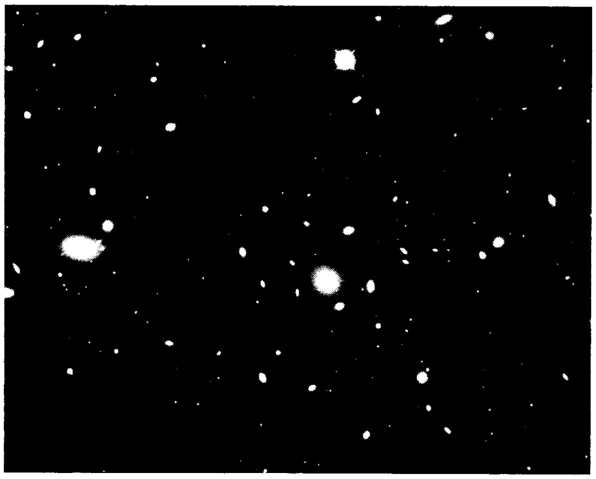

Figure 22. A cluster of galaxies in the constellation Coma Berenices.

Gauge theories propose two ways this lumpiness might have arisen. Quantum fluctuations during inflation could have produced tiny ripples in the otherwise smooth density of primordial matter. Or other phenomena resembling ruptures might have occurred in space itself—incredibly massive loops and filaments known as *cosmic strings*. In the billions of intervening years, matter would have swarmed toward seeds like these, producing the huge blobs and spirals we call galaxies.

While solving the smoothness and structure problems, however, inflation posed another riddle for cosmologists. It requires that there be far more matter around than has yet been spotted by astronomers—10 to 100 times as much. In the 1970's astronomers had begun to suspect that there was indeed more matter in the universe than what was visible. The luminous stuff seen with telescopes is about 10 times less than what is needed to explain the pinwheel motions of the spiral galaxies. Some form of as yet unseen *dark matter* has to exist in intergalactic space, causing this rapid rotation. But until inflation was proposed, this dark matter could have simply been baryons that had not been detected yet, normal matter that somehow does not shine.

Inflation requires there be so much matter around that, if true, the dark portion cannot be composed merely of baryons. Something else must contribute at least 90 percent of it. A possibility consistent with GUTs is that at least one type of neutrino has a non-zero mass. There are tremendous numbers of neutrinos—about a billion for every proton. If just one type has a mass only 0.01 percent of the electron's, neutrinos would *dominate* the total mass of the universe. Precise measurements made at Los Alamos National Laboratory and elsewhere have thus far shown that the electron neutrino falls short of the mark. Attention has begun to focus on the others.

There is no shortage of new and hitherto undiscovered particles predicted by speculative theories that reach beyond the Standard Model. Some of them are massive and interact weakly with normal matter, making them likely candidates for dark matter. One of these is the *axion*, a light particle predicted by U.S. physicists in the late 1970's to explain why the strong force obeys CP conservation. Although thought to be less than a *billionth* as massive as the electron, there can be far more of them in the universe than even photons or neutrinos. And because they would move at speeds far slower than that of light, axions could collect around galaxies and lead to their apparent "halos" of dark matter.

Other possible dark-matter particles arise in grand unified theories with a property known as *supersymmetry*. For every particle in the Standard Model, these theories require there be a so-called supersymmetric partner—a *squark* for every quark, a *slepton* for every lepton, a *photino* for the photon, etc. What's more, at least one of these exotic particles has to be stable and indestructible, with the current favorite being the photino. Massive, neutral, slow-moving, and interacting very feebly, it is an ideal candidate for the dark matter in galaxy halos.

Searches for axions, photinos, massive neutrinos, and other possible dark-matter particles are now under way at laboratories around the globe. Particle accelerators and colliders have been used to look for photinos, for example, which are thought to be far more massive than the proton. So far they have not turned up, but searches for them remain high on the list of objectives for physicists working on the SLC and Tevatron, which can both produce conditions resembling those that occurred when the universe was a trillionth of a second old.

Dark-matter searches can also be made by small teams of physicists working in their own laboratories. New detection methods, often involving superconducting materials, may soon enable one of these groups to record the extremely faint signal that would occur if a dark-matter particle originating in the halo of our own Milky Way dislodged a proton or neutron. Another promising method uses a superconducting magnet surrounding a copper cavity to try to convert axions from our galactic halo into detectable microwave photons.

The underground detectors originally built to search for proton decay (see Chapter 8) are finding increasing use in dark-matter research. They are particularly useful when neutrinos are involved, because these are the only known particles that can penetrate to such depths. If a photino encountered its antiparticle near the earth—inside the sun, for example—two high-energy neutrinos could emerge after they annihilated. One of these neutrinos might be detected in the underground detectors. So far no high-energy neutrinos attributable to photinos have been observed, but the search continues.

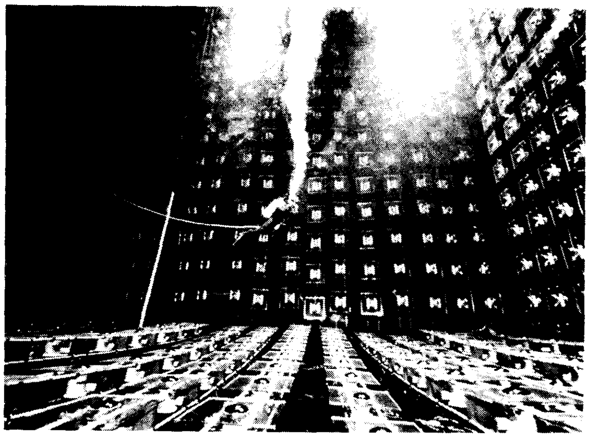

Figure 23. A skin diver checking phototubes inside the IMB underground detector.

The IMB detector near Cleveland did, however, witness a burst of low-energy neutrinos emanating from the 1987 supernova in the Large Magellanic Cloud—as did another underground detector in Japan. This was the first time that neutrinos from a supernova had been recorded. Of the many trillions of neutrinos that swept through these two enormous tanks of water during this 10 second burst, only 20 or so interacted, but this scant few revealed plenty. Because neutrinos are produced copiously in the core of a collapsing star, and most escape without interacting, they provide a unique "window" on one of the most violent processes occurring in the universe today.

From the duration of the neutrino burst as it reached earth, physicists concluded that the electron neutrino must have a mass-energy less than 20 eV—or about 0.004 percent of the electron's mass. This limit is almost as good as what has been obtained after years of painstaking research in terrestrial laboratories.

These stunning observations have focused much recent attention on the use of these underground detectors as "neutrino telescopes." Originally meant to study proton decay, they are beginning to sample the energetic neutrinos emerging from the superhot cores of nearby astrophysical objects like the sun. The fledgling scientific field of neutrino astronomy, which received a great boost from this fortuitous event, owes its existence to the foundations laid by the last three decades of high-energy physics.

10. PRACTICAL BENEFITS

The knowledge gained from high-energy physics research is used not only in other scientific fields but increasingly in advanced technology and engineering. Although the principal aim of this research is to understand the fundamental nature of matter and energy, the information gained often has immediate practical applications. Large markets may take decades to emerge, but so-called spin-offs—positive effects such as new products, quality improvements, and productivity increases—take place every year. And high-energy physics often serves as a proving ground for risky new technologies not yet ready for the marketplace.

Often, it takes years for the results of basic research in particle physics to find mass applications. The particle physics of the 1920's, which led to quantum mechanics and a precise theory of atomic structure, was crucial to the invention of the transistor and lasers in the 1940's and the 1950's. Hardly a decade elapsed, however, between the first experiment on controlled nuclear fission and its use in submarine propulsion. One cannot say for sure how soon technological advances will come from recent research in high-energy physics, but history suggests it will not be long.

Money invested in high-energy physics research also produces more immediate benefits to society. In the course of their work, researchers develop devices, instruments, and technologies that can be used for practical purposes outside the domain of pure research; most frequently these applications occur in the area of medical diagnosis and treatment. And by working hand in hand with various industries to develop state-of-the-art equipment, high-energy physicists help them improve their processes and speed technology to the marketplace.

Advanced medical technologies have traditionally been quick to take advantage of high-energy physics research. Particle beams, for example, find widespread use in cancer therapy. Electron accelerators using linear accelerators like those developed for the Los Alamos Meson Physics Facility in the 1970's, were quickly developed into clinical instruments by commercial vendors. They and other machines using concepts developed for physics accelerators, are employed in nearly 1,000 hospitals around the United States. Intense beams of x-rays and gamma rays produced by these devices are crucial for radiation therapy. The production and use of these devices is a multi-billion dollar industry.

While energetic photons from these machines are a good choice for treating most cancers, other particles are better for more localized treatments. Focused beams of pions, protons, and heavy ions supplied by cyclotrons or small synchrotrons provide the sharper scalpel needed in such cases. The energies of these charged particles can be adjusted to pass through the skin and outer tissues and deposit most of their energy at a specific depth within the body without unduly harming the healthy surrounding tissue.

Energetic beams of protons have become the preferred treatment for tumor growths inside the eye (ocular melanomas), with a 95 percent success rate. These particles spare the sensitive tissue of the eye and the optic nerve, preserving the patient's vision. Loma Linda University Medical Center, in southern California, has a proton therapy facility containing the first particle accelerator built specifically for proton beam therapy. With a machine designed and constructed by Fermilab, which helped pioneer this treatment during the 1970's, the Center is expanding the technique to all body sites and to many more patients. Japan, Sweden, and the Soviet Union have also begun to use proton therapy extensively.

Beams of charged ions (atoms with less than their full complement of electrons) heavier than protons provide still sharper scalpels. Heavy ions do even less damage in passing through healthy tissues and deposit almost all of their energy when they finally come to rest. By adjusting the initial energy, doctors can tune the ion beams so that they stop precisely in the tumors they wish to excise.

Particle beams are also used for purposes besides cancer therapy. Treatment of growth disorders due to hyperactive pituitary glands with protons and heavy ions was first achieved at Lawrence Berkeley Laboratory using its synchrocyclotron. In 85 percent of the cases, patients returned to normal growth rates with far less risk than in other treatments. This procedure has since become a standard clinical procedure that can be performed routinely at facilities like Harvard's 160 MeV cyclotron.

Other medical applications of high-energy physics involve diagnosis rather than therapy. Computed Axial Tomography (CAT scanners) and Magnetic Resonance Imaging devices (MRI scanners) have revolutionized diagnosis of disorders of soft tissues, especially disorders of the head and brain. Rare is the shock-trauma unit or major neurological clinic that does not have one of these machines on-site or at its immediate disposal. The sophisticated mathematical techniques used to reconstruct the images of organs and tissues that doctors see with these amazing diagnostic instruments—as well as in positron emission tomographs discussed below—originated in particle detection methods developed by high-energy physicists.

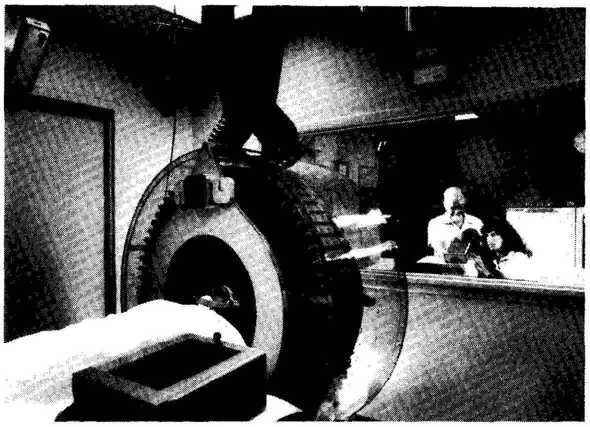

Figure 24. Brookhaven's facility for positron emission tomography.

Allan Cormack, a high-energy physicist at Tufts University, shared the 1979 Nobel prize in physiology and medicine for his key work in developing these methods for CAT scanners which are widely regarded as the most significant advance in medical radiography since the 1895 discovery of x-rays. His physics research was directed towards replacing bubble chambers and similar particle detectors with digital electronic instruments.

In positron emission tomography or PET, as with the other scanners, doctors see a precise image of a cross section of the tissue and can detect any change or abnormality that has occurred. A radioactive isotope that decays by emitting positrons is administered to the patient and collects in tissues. Two energetic gamma rays shoot out back-to-back when a nucleus of these isotopes decays. Crystals of bismuth germinate, first developed for high-energy physics particle detectors, are used to detect these photons, and a computer helps to reconstruct the image.

In medical scanners and some particle detectors, photons or particles moving in different directions pass through a target volume and are received by an array of surrounding detectors. The detector measurements tell how much of the original radiation was absorbed during the passage. The computer uses this information, together with data on how materials absorb radiation, to reconstruct an image of an interior slice of the target.

Positron emission tomography has provided physicians a new and powerful tool. It has proved to be a non-invasive way to observe changes as they are occurring in the body. This kind of imaging is important for the study, diagnosis, and treatment of brain tumors, strokes, Alzheimer's disease, schizophrenia, and heart disease. PET scans are also being used to distinguish the two major types of breast cancer. Since one type requires early, aggressive treatment, learning the distinction is vital.

Integrated circuit technology has provided yet another channel through which particle physics research affects commercial technologies. One of the most important of these has been ion implantation. In this technique, particle beams are used to embed a thin layer of ions near the surface of a semiconductor material to alter its chemical structure. According to the National Research Council, "Every IC [integrated circuit] now made employs ion implantation .... the remarkable growth in integrated circuit technology is difficult to envision without ion implantation." Ion implantation also has been used to reduce the wear of artificial hip joints by 400 times, saving replacement operations.

One of the most promising technologies for the analysis and creation of new integrated circuit chips is synchrotron radiation—energetic photons spun off tangentially by electrons as they whip around inside a storage ring. Physicists first viewed synchrotron radiation as an undesirable but unavoidable energy drain on accelerators and designed storage rings to minimize it. Early research at the SPEAR storage ring soon showed it to be an extremely intense, tunable source of useful x-rays that cannot be duplicated elsewhere.

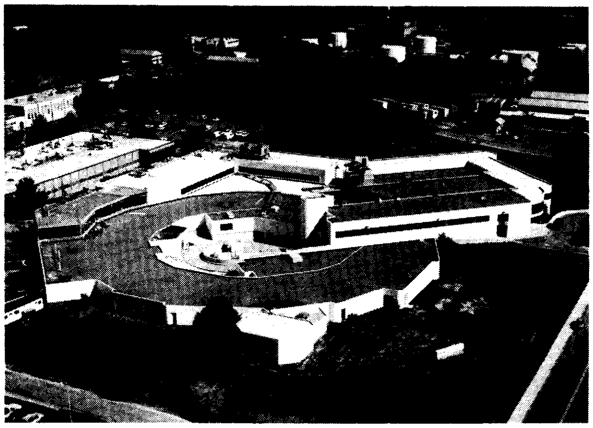

Figure 25. Aerial view of the National Synchrotron Light Source at Brookhaven.

This method of producing short wavelength x-rays has proved so important for research in crystallography, chemistry, biology, and materials science that the DOE funded storage rings dedicated to producing it, such as the National Synchrotron Light Source at Brookhaven. Others are in planning or currently under construction in the U.S., Europe, Japan, and the Soviet Union. These facilities, some costing hundreds of millions of dollars, are designed and operated by accelerator specialists who received their training in the field of high-energy physics. New techniques using devices called *wigglers* and *undulators* that surround the circulating beam have increased x-ray intensities a million fold over the past decade.

At these particle accelerators, industrial researchers have used intense beams of x-rays to make chips with tiny features less than a micron (a millionth of a meter) across. The goal of x-ray lithography, as the technique is known, is to etch finer semiconductor circuits than ever before. If manufacturing techniques being developed by IBM and other companies are perfected, the process would cram far more components onto fingernail-sized chips. While the best chips today bristle with a million or so circuit elements, future ones created with x-rays conceivably might hold up to a billion.

In recent years, accelerators have become increasingly important sources of radioisotopes for clinical and research medicine. Commercial production of radioisotopes was pioneered by New England Nuclear, now part of DuPont Chemical. It now operates four cyclotrons and a 45 MeV linear accelerator for commercial production of isotopes for both industrial and medical purposes. Industrial isotopes are used to measure wear on surfaces in motion, for thickness gauges, and other specialized applications. Other private radioisotope producers using cyclotrons include Mallinkrodt (a subsidiary of Avon) and Medi Physics.

High-energy physics often requires a significant fraction of the outputs of such high technology industries as very low temperature refrigeration equipment, high vacuum equipment, and superconducting magnets. Purchases of equipment for research reduces production costs through learning. Costs of additional units are lowered by incremental improvements in production technology, a process that may be further aided by researcher assistance in solving production problems. When these products are offered for sale in commercial markets their prices are lower, their quality is higher and their markets are likely to be larger.

Over a thousand electromagnets are used at Fermilab to confine the high-energy beams of protons within a slender tube 4 miles in circumference. The original magnets were tremendous consumers of electric power, soaking up a fair fraction of the laboratory's total operating cost. During the late 1970's, in an ambitious attempt to slash these costs and double the proton energy, Fermilab scientists began an extensive project to install magnets with windings made of superconducting materials throughout the entire ring. Because a superconductor offers no resistance to an electric current, its use can cut power consumption drastically.

There were many technological hurdles to overcome before this dream could become reality. Cable made from wires of just the right superconductor had to be developed to withstand the extreme stresses involved, and new methods were required to bind the magnet windings about their cores. Otherwise, the tremendous magnetic forces would have literally torn the magnets apart. Refrigeration systems of unprecedented scale and reliability were needed to cool and keep the superconducting elements at the temperature of liquid helium. But the challenges were met, and by 1983 the Tevatron was completed—the world's most powerful accelerator.

The construction of the Tevatron—with its 650 miles of superconducting cable—represents the first

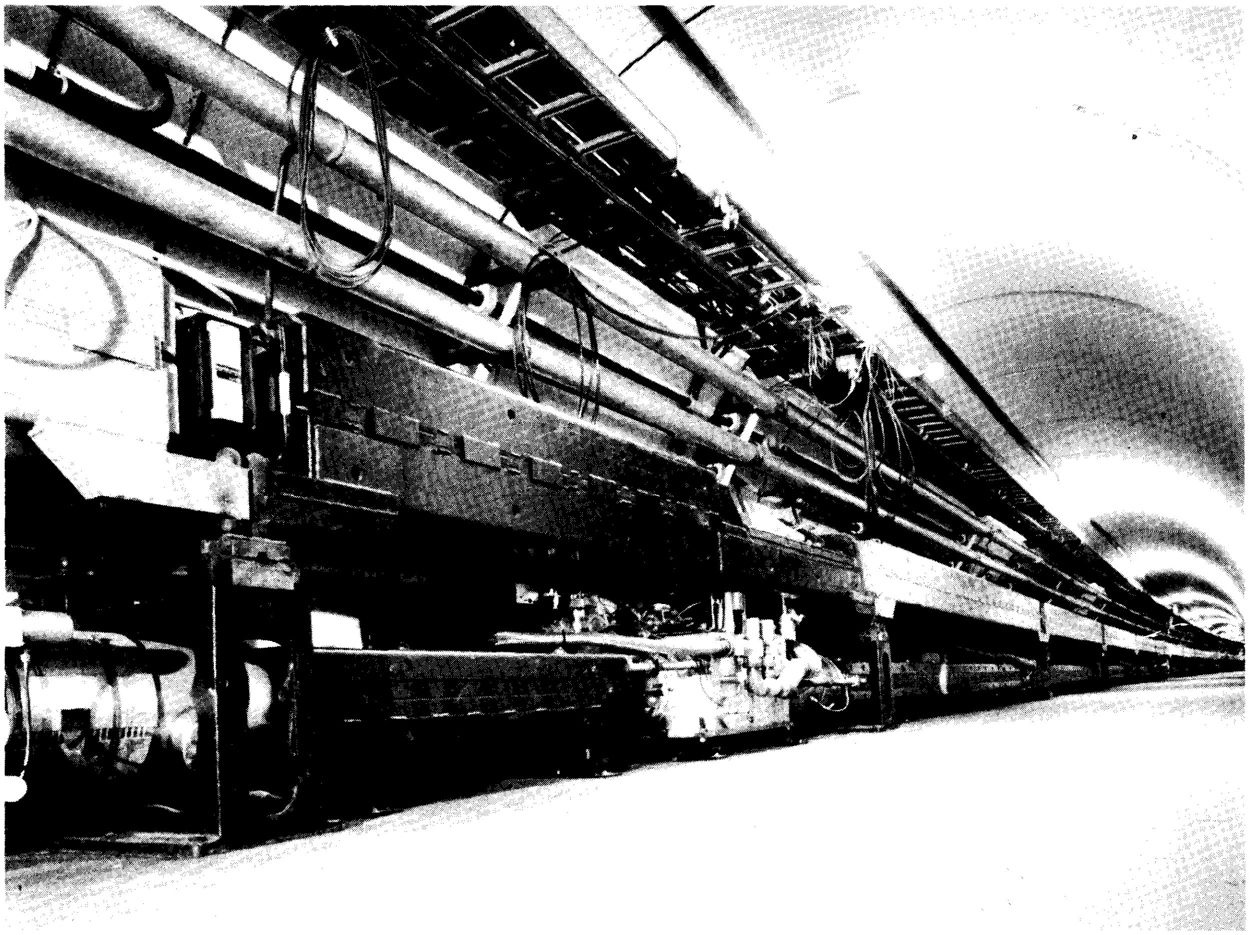

Figure 26. Interior view of Fermilab's main ring. The lower magnets are superconducting magnets used to boost protons from about 400 GeV to almost 1 TeV.

successful use of superconductivity on an industrial scale anywhere in the world. It has laid the foundations for the U.S. superconducting magnet industry, which promises to rival the size of the liquid nitrogen industry and have applications in diverse sectors of the economy. Superconducting magnets are already used, for example, in hundreds of whole-body MRI scanners in hospitals around the country. Applications of superconductors are being envisioned for power transmission and storage, high-speed rail transport, supercomputers, and even for metal and garbage separation.

Other state-of-the-art devices originally developed by high-energy physicists have been adopted for industrial purposes. High-power microwave technology, including klystrons like those originally designed for the SLAC accelerator, are the basis for this country's defense and air-traffic radar. An apparatus designed for the collection and concentration of extremely dim light emitted by particle detectors has been developed into a solar hot water heater. Its inventor, a theoretical particle physicist, now pioneers the use of *non-imaging concentrators* for increasing the collection of the sun's radiation to generate electricity, produce high-temperature process heat, and provide high radiant flux for use in chemical processes.

No formal studies have attempted to evaluate the aggregate benefits to U.S. industry, but CERN commissioned such a study of European industry several years ago. The manufacturing firms involved in CERN contracts, it revealed, received three Swiss francs in additional sales revenues in related product lines for every Swiss franc in sales to high-energy physics. What's more, 75 percent of the total added value came in applications outside of high-energy physics—in areas as diverse as railways, shipbuilding, power generation and distribution, and automobile design.

High energy physics, its products, and the knowledge gained from this basic research program are used in medicine for diagnosis and treatment of illness, in the food industry for sterilization, in construction for inspection of structural defects, in law enforcement for the analysis of evidence, in computers and computer science, and in the making of computer chips. They are applied in electronics, cryogenics, copier technology, synchrotron light sources, petroleum exploration and recovery, pulsed power sources, computer control of large-scale systems control, and superconducting magnets and microwave sources development.

Science and technology outgrowths of this effort see daily use in telecommunications, power generation and distribution, vacuum technology, optics, precision mechanics, magnet technology, welding, car design, railways, shipbuilding, subway control, refrigeration, material storage, television, and solar energy. They serve the Nation's economy in nondestructive testing by electron beams, in ion implantation of semiconductors and artificial joints, and in high-resolution electron microscopy, heavy ion fusion research, monitoring and control of thin films, and industrial radiography.

Microchips and lasers were not contained, even implicitly, in the textbooks and handbooks of physicists who, in the 1920's and 1930's laid the groundwork for their development. Nor were they tripped over "by accident" in some laboratory. Accelerator designers of the 1940's and 1950's had no expectation that the understanding they were achieving would lead to CAT and MRI scanners, and to the diagnosis and treatment of a large number of human afflictions. Yet, it is hard to think of any practical technology important to our economic competitiveness or our standard of living that is not being bolstered, directly or indirectly, by high-energy physics research into fundamental aspects of matter and energy.