Fundamental Particles with Charm

The search for particles with this quantum-mechanical property has been a preoccupation of high-energy physics. A few such particles have now been seen in the debris of electron-positron annihilations

by Roy F. Schwitters

At the level of elementary particles the properties of matter are remarkably few. A particle can have mass, or energy, and it can have momentum, including the intrinsic angular momentum called spin. It can have electric charge. There are more arcane properties, such as the one called strangeness, but not very many. In most cases a list of half a dozen attributes completely describes a particle. Nothing more can be said about it.

Because there are so few fundamental properties of matter the discovery of a new one is a major event in physics. Such a new property has recently been found: it has the whimsical name charm. The atoms of ordinary matter have no charm; the property can be observed only in the debris of high-energy collisions between particles.

The first hint that charm exists came in 1974, when particles were discovered that have charm in a hidden or latent form. More recently particles with overt charm have been detected. These new particles are unquestionably among the most important discoveries of high-energy physics in the past decade. What is more, in unraveling the story of charm physicists have learned much about the structure of ordinary matter.

Most of the particles observed in nature fall into one of two classes, the leptons and the hadrons. The leptons include just four known particles: the electron, the muon and two kinds of neutrino. The electron and the muon both have an electric charge of -1, and they are also essentially alike in all other properties with the exception of mass. (The muon is about 200 times heavier than the electron.) The neutrinos have no electric charge and seem to have no mass. There are also four antileptons, which are identical to the corresponding leptons in certain respects, such as mass, but have other properties that are exactly opposite those of the leptons. For example, the antielectron, or positron, has an electric charge of $+1$.

Leptons are considered elementary because they cannot be broken down into smaller entities. They have no measurable size and give no hint of any internal structure. Hadrons, on the other hand, are complex objects, and there is strong evidence they do have an internal structure. More than 100 kinds of hadron have been identified, the most familiar being the proton and the neutron, the constituents of atomic nuclei. Both the multiplicity of the hadrons and their properties as individual particles set them apart from the leptons.

A theory that is now widely accepted seems to explain these differences. It does so by stating that hadrons are not elementary particles at all but composite entities consisting of a few simpler constituents called quarks. In many of their properties the quarks are thought to be quite similar to leptons; for example, they ought to be simple and pointlike particles. There is no question, however, that the quarks are in a class apart from the leptons. Interactions between quarks are dominated by a force that does not affect leptons at all.

Physicists recognize four basic forces in nature; in order of increasing strength they are the gravitational, the weak, the electromagnetic and the strong forces. Gravitation influences all particles and its range is unlimited, but its effects on subatomic particles are negligible. The weak force also affects all kinds of matter. Although the weak force is many orders of magnitude stronger than gravitation, it is still feeble enough for it to be observable only when stronger interactions are inhibited.

The electromagnetic force acts exclusively on particles that have an electric charge; among those particles are the electron and the muon and all the quarks. Electromagnetic forces bind atoms together and are responsible for almost all the gross properties of matter, including chemical properties.

It is the strong force that distinguishes between leptons and hadrons or, according to theory, between leptons and quarks. None of the leptons is sensitive to the strong force in any way; only quarks and hadrons (which are assumed to be made up of quarks) feel its influence. Quarks can interact with leptons through the weak and electromagnetic forces, but with each other they interact almost exclusively through the strong force. That force is more than 100 times stronger than the electromagnetic force, and at energies studied today it is about 10^{10} times stronger than the weak force.

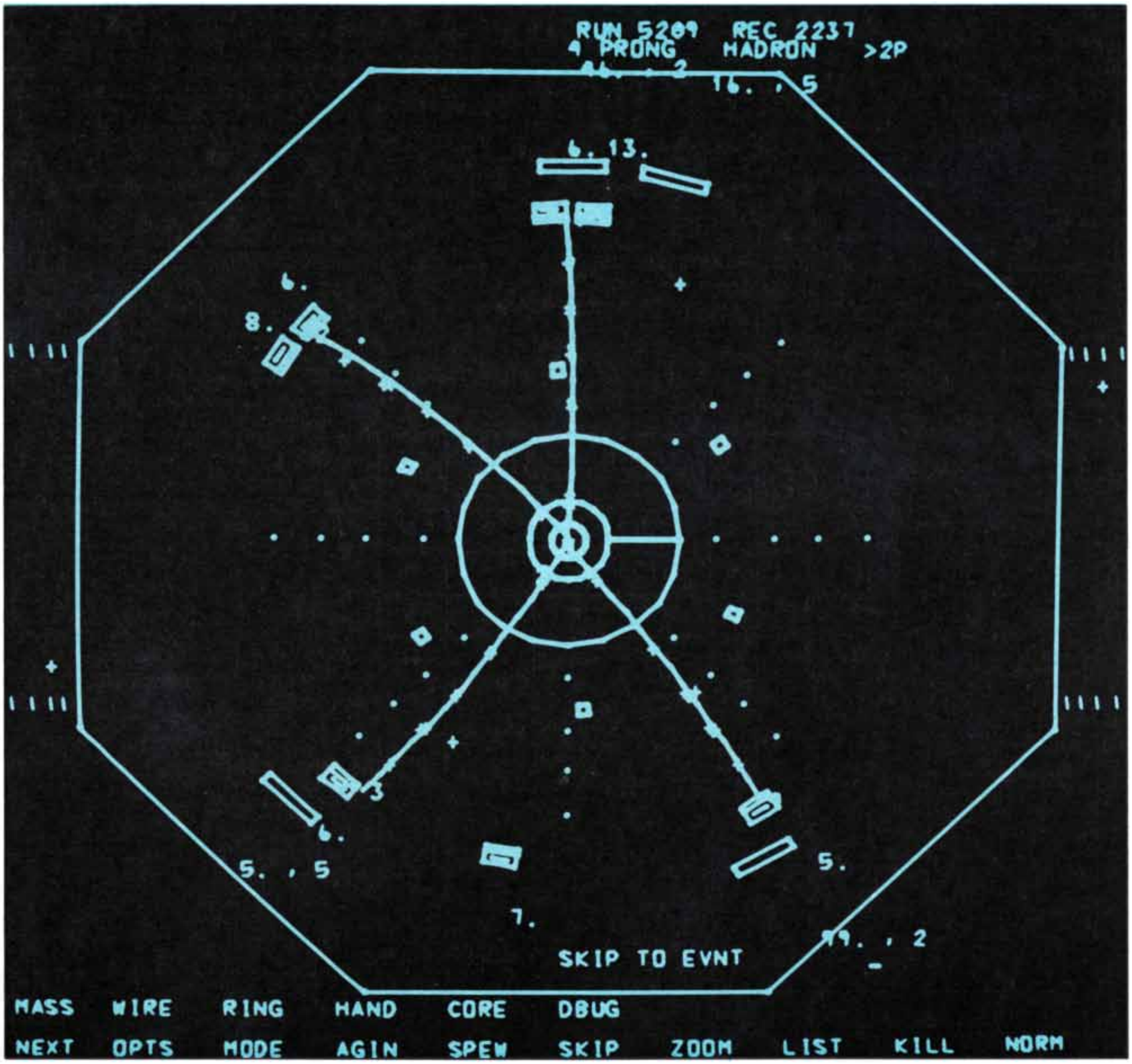
A theory that accounts for all the varieties of matter with just a few quarks and leptons has an appealing economy, but a significant disclaimer is necessary. Although the theory has gained widespread acceptance, there is no evidence at all that quarks exist in isolation. So far no one has been able to extract a quark from a hadron. Indeed, some theorists suggest that quarks may be so tightly entwined within hadrons that they may never be separated in the laboratory. The question of the existence of quarks will not be pursued here; instead the quarks will be considered as a means for interpreting relations between particles observed experimentally.

The quark hypothesis was proposed independently in 1963 by Murray Gell-Mann and George Zweig, both of the California Institute of Technology. In the original version of the concept there were three kinds of quark, given the labels u, d and s, for "up," "down" and "strange," and three corresponding antiquarks, designated $\bar{u}$, $\bar{d}$ and $\bar{s}$. Hadrons are formed by combining the quarks and antiquarks according to simple rules. One possibility is for a quark and an antiquark to bind together; the resulting particle is a member of the class of hadrons called mesons. An example is the positively charged pion (π^+), which is made up of a u quark and a $\bar{d}$ antiquark. Another allowed combination consists of three quarks in a bound system. Hadrons formed in this way are called baryons, and they include the proton (with the quark composition *uud*) and the neutron (*udd*). Finally, antibaryons can be formed from combinations of three antiquarks.

These are the only permissible ways of combining quarks to form hadrons. It is easy enough to imagine other combinations, such as particles made up of two quarks or of one quark and two antiquarks, but such hadrons do not exist.

The observed properties of hadrons are explained in a straightforward way by the properties assigned to their constituent quarks. With the exception of mass, all the properties of matter needed to identify a given elementary particle appear only in discrete units, or quanta, and they can therefore be measured in terms of the integers and simple fractions called quantum numbers. Spin angular momentum, for example, is observed only in integer and half-integer quantities (when it is measured in natural units); intermediate values are not possible. In all observed particles electric charge exists only in integer units of the electron's charge.

Most quantum numbers of a hadron



DECAY OF A CHARMED PARTICLE is reconstructed in a computer-generated display on a cathode-ray tube. The display includes a schematic cross section of the particle detector in which the event took place. The octagon is the basic form of the detector; the rows of four dots give the radial positions of four cylindrical spark chambers; the innermost circle at the center of the image represents the beam pipe in which electrons and their antiparticles, positrons, collide to produce other particles. The trajectories of particles are plotted from the triggering of discharges in the spark chambers and from two concentric rings of scintillation counters, the inner ones being represented by small boxes and the outer ones by larger, flat boxes. In this event the particle track at the 12 o'clock position has been identified as that of a negatively charged *K* meson (K^-) and the track at the seven o'clock position is that of a positively charged pion (π^+). These two particles are thought to be the decay products of a particle, designated D^0, that bears the new property of matter called charm. The D^0 itself decays too quickly for it to be detected directly. In electron-positron collisions charmed particles can be created only in combination with charmed antiparticles, and in this case the antimatter companion of the D^0 is thought to be an excited state, the $\bar{D}^{*0}$, whose decay products have been identified only tentatively. The scintillation counter near the bottom of the display, which has no associated particle track, might have been triggered by a gamma ray emitted when the $\bar{D}^{*0}$ decayed to a $\bar{D}^0$. This particle might have decayed to yield a muon (μ^-) at the 10 o'clock position, a *K* meson (K^+) at the five o'clock position and a neutrino that would have escaped detection.

LEPTONS	MASS (GeV)	SPIN	ELECTRIC CHARGE
ELECTRON NEUTRINO ν_e	0	½	0
ELECTRON e^-	.0005	½	−1
MUON NEUTRINO ν_μ	0	½	0
MUON μ^-	.105	½	−1

QUARKS	MASS (GeV)	SPIN	ELECTRIC CHARGE	STRANGENESS	CHARM
u	.1	½	+⅔	0	0
d	.1	½	−⅓	0	0
s	.4	½	−⅓	−1	0
c	1.5	½	+⅔	0	+1

LEPTONS AND QUARKS are the only major classes of particles now thought to be elementary. Both seem to be simple and pointlike entities, with no internal structure and no measurable size. There are four known leptons, arranged in pairs. In the initial formulation of the quark theory there were only three quarks: those labeled *u* and *d* formed a pair but the *s* quark had no companion. The charm hypothesis establishes a symmetry between leptons and quarks by adding a fourth quark, designated *c*. A special relation must exist between the *s* quark, which carries the property of matter called strangeness, and the *c* quark, which has the similar property charm. For each of the leptons and quarks there is an antiparticle with exactly opposite properties. Quarks have not been isolated, but they seem to be constituents of other particles.

	HADRON	SYMBOL	QUARK COMPOSITION	MASS (GeV)	SPIN	LIFETIME (SECONDS)	ELECTRIC CHARGE	STRANGENESS	CHARM
BARYONS	PROTON	p	uud	.938	½	STABLE	+1	0	0
BARYONS	NEUTRON	n	udd	.940	½	10^3	0	0	0
BARYONS	LAMBDA	Λ	uds	1.116	½	10^{-10}	0	−1	0
BARYONS	CHARMED LAMBDA	Λ_c	udc	2.260	½	?	0	0	+1
MESONS	PI MESONS	π^+	$u\bar{d}$	.140	0	10^{-8}	+1	0	0
MESONS	PI MESONS	π^-	$d\bar{u}$	.140	0	10^{-8}	−1	0	0
MESONS	PI MESONS	π^0	$u\bar{u} + d\bar{d}$	.135	0	10^{-16}	0	0	0
MESONS	K MESONS	K^+	$u\bar{s}$	.494	0	10^{-8}	+1	−1	0
MESONS	K MESONS	K^-	$s\bar{u}$	.494	0	10^{-8}	−1	+1	0
MESONS	PHI	ϕ	$s\bar{s}$	1.020	1	10^{-22}	0	0	0
MESONS	PSI	ψ	$c\bar{c}$	3.095	1	10^{-20}	0	0	0
MESONS	CHARMED MESONS	D^0	$c\bar{u}$	1.863	0	?	0	0	+1
MESONS	CHARMED MESONS	D^+	$c\bar{d}$	1.868	0	?	+1	0	+1
MESONS	CHARMED MESONS	F^+	$c\bar{s}$	?	0	?	+1	+1	+1

HADRONS are the particles constructed of quarks. Those called mesons are made up of a quark and an antiquark, the latter being represented by the symbol for a quark with a bar over it. Baryons consist of three quarks bound together; there are also antibaryons that combine three antiquarks. The properties of the hadrons (and of other particles) are accounted for in terms of the integers and simple fractions called quantum numbers. The first hadron that hinted at the existence of charm was the psi meson, with the quark constitution $c\bar{c}$, but since the charm quantum numbers of this quark and antiquark cancel, the net charm of the psi is zero. The lowest-mass hadrons that exhibit overt charm are the D^0, D^+ and F^+ mesons, and the first two of these have been observed. There is also suggestive evidence for a charmed baryon, named Λ_c.

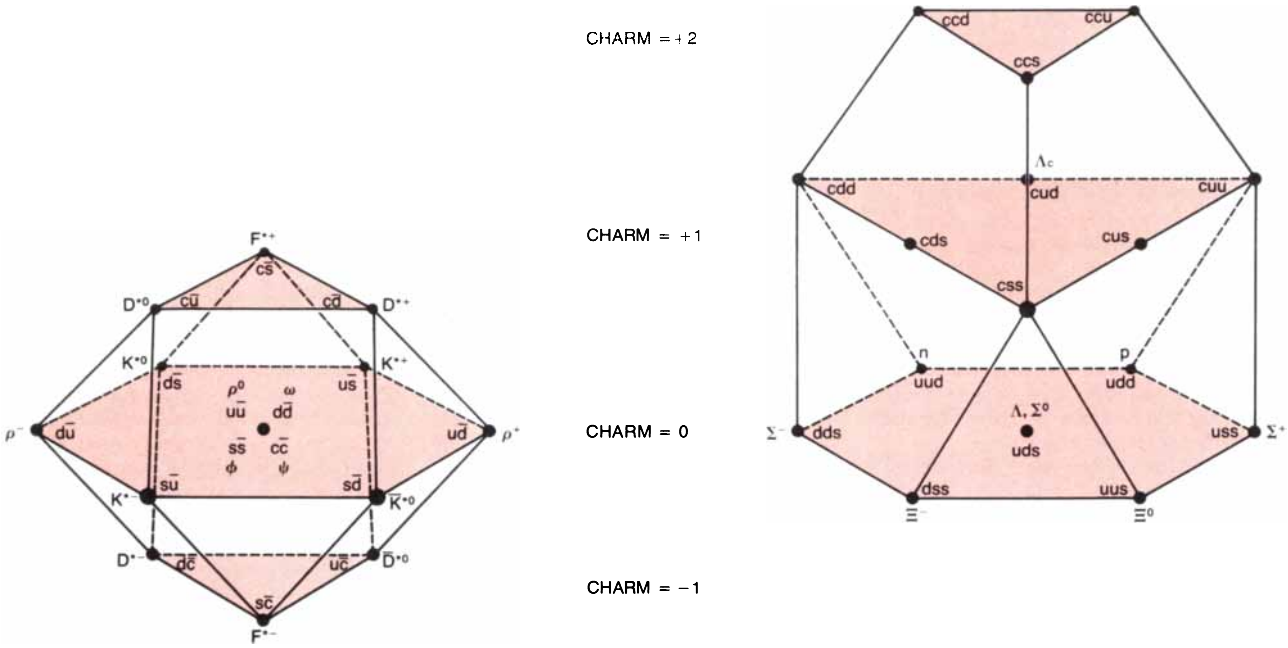
are determined by simply adding up the quantum numbers of the constituent quarks. In the case of electric charge this procedure requires that the quarks be assigned some rather bizarre quantum numbers: they must have fractional electric charge. The *u* quark has a charge of +2/3; the *d* and *s* quarks both have a charge of −1/3. Antiquarks have the opposite charges. Thus in the positively charged pion, made up of a *u* quark and a $\bar{d}$ antiquark, the charges of +2/3 and +1/3 add up to +1. The *uud* quarks of the proton, with charges of +2/3, +2/3 and −1/3, also give a sum of +1. In the neutron (*udd*) the charges of +2/3, −1/3 and −1/3 have a sum of zero. All these results are in agreement with the known electric charges of the hadrons.

Other quantum numbers can be treated in a similar way. Strangeness, for example, is a quantum number assigned to certain hadrons that have anomalously long lifetimes. In the quark model these particles are distinguished by the presence of an *s* quark or an $\bar{s}$ antiquark, which respectively carry strangeness quantum numbers of −1 and +1; the other quarks have zero strangeness. The strangeness of a hadron is then determined by adding up the strangeness quantum numbers of all its constituent quarks. The positively charged *K* meson (K^+), made up of a *u* quark and an $\bar{s}$ antiquark, has a strangeness of +1.

The concept of strangeness was introduced as an explanation for the slow decay of certain hadrons discovered in the 1950's. Massive hadrons generally decay through the strong force, which acts very quickly; in a sense the force is said to be strong precisely because it is so fast. A strongly decaying hadron exists for only 10^{-23} second before it breaks up into less massive hadrons. All the properties of matter must remain unchanged by this process; for example, the net electric charge of the decay products must be equal to the electric charge of the decaying particle. This requirement is expressed by saying that all quantum numbers must be conserved.

Strange hadrons can take part in such decays provided the strangeness quantum number can be conserved. In terms of the quark model the need to conserve strangeness implies that the strange *s* quark must be passed along intact to the decay products. The more massive strange particles do decay to lighter strange particles in this way, and their lifetimes are not substantially longer than those of other strongly decaying hadrons. Ultimately, however, there must be a set of lightest strange particles, which have no states of lower mass to which they can give the *s* quark. These are the *K* mesons and the lambda baryon (Λ).

The *K* and lambda particles cannot decay through the strong interaction. Indeed, they could not decay at all if it



FAMILIES OF HADRONS define all allowed combinations of quarks. There are separate families for each possible value of intrinsic spin angular momentum; those shown here are the mesons with one unit of spin and the baryons with 1/2 unit of spin. Until recently only the particles in the plane marked "Charm = 0" had been observed, but the discovery of charmed particles implies that all the others must also exist. The psi particle completes a group of four particles at the center of the array of spin-1 mesons. The D^0, D^+ and F^+ are members of another family of mesons, those with zero spin, but they are represented in the spin-1 group by excited states denoted D^{*0}, D^{*+} and F^{*+}. The D^{*0}, the D^{*+} and their antiparticles have been found. As yet, there is little evidence for the observation of charmed baryons.

were not for a remarkable feature of weak interactions: some conservation laws that are strictly obeyed in all strong and electromagnetic interactions can be ignored in weak interactions. Strangeness is among these approximately conserved quantum numbers; as a result weak interactions can convert an *s* quark into a *u* or a *d* quark and strange particles can decay through weak interactions into lighter nonstrange hadrons or into leptons. Particles that can decay only through the weak interaction, however, have much longer lifetimes than strongly decaying hadrons; the *K* and lambda particles have lifetimes ranging from 10^{-10} second to 10^{-8} second.

A few quantum numbers require a slightly more elaborate system of bookkeeping than electric charge and strangeness do. Most notable among them is spin angular momentum. All quarks and leptons are expected to have the same quantity of spin, namely 1/2 unit; rules of quantum mechanics require that such particles can have their spin axes aligned in only two possible directions (with respect to any arbitrary frame of reference). Thus the quark and antiquark in a meson can have their spins pointing in the same direction or in opposite directions. In the first case the net angular momentum of the meson is 1; in the second it is 0. From these rules it follows that mesons always have integer spin. In a baryon there are also two possible spin configurations: the spins of all three quarks can be parallel or the spin of one quark can be aligned in the opposite direction. The corresponding spins of the baryon are 1/2 and 3/2, and baryon spins are invariably half-integers. Further complicating the situation, a bound system of quarks can have orbital angular momentum in addition to spin: the quarks can revolve around each other or around their common center of mass as well as spin individually on their axes. Orbital angular momentum adds integer increments to the total angular momentum of the hadron. Because there are many possible spin states a single combination of quarks can give rise to numerous particles with various quantities of angular momentum and also with different energies, or masses. They are distinct states of matter even though they are made up of the same quarks.

By observing the rules for combining the quarks and for tallying their quantum numbers one can account for all the properties of hadrons. Every known hadron can be explained as a combination of either a quark and an antiquark or of three quarks. What is more, every allowed combination of quarks corresponds to a known hadron. There are no vacancies.

It was the very completeness of this scheme for classifying the hadrons that was challenged with the discovery of a new particle in 1974. The particle was a hadron, but it could not be formed by any allowed combination of the three quarks since all those combinations were accounted for.

The new particle was discovered independently and at about the same time by two groups of experimenters employing vastly different techniques. One group, whose members were from the Massachusetts Institute of Technology and the Brookhaven National Laboratory, found the particle during an experiment conducted at Brookhaven and gave it the name *J*. The other group, of which I was a member, was made up of physicists from the Stanford Linear Accelerator Center (SLAC) and the Lawrence Berkeley Laboratory. Our evidence for the new particle was obtained in an experiment at SLAC, and we chose to designate the particle by the Greek letter psi (ψ). Here I shall adopt the latter name. Last year the leaders of the two groups, Samuel C. C. Ting of M.I.T. and Burton Richter of SLAC, shared a Nobel prize for their discovery.

The new particle has a mass of about 3.1 billion electron volts (3.1 GeV). That is more than three times the mass of the proton, making the psi one of the heaviest particles known. Those of its quantum numbers that could be measured were found to be quite conventional. The psi has a spin angular momentum of 1, the integer unit indicating the particle must be a meson. It is electrically neutral, and it has zero strangeness. The products of its decay are familiar particles such as pions, electrons and muons. With these properties the psi might have passed for an ordinary hadron, quite unexceptional except for its mass. The problem was that all states of matter with the quantum numbers of the psi had long since been identified with other hadrons. In a world made of three quarks there was no need for the psi; there was not even room for it.

Experimentally the one distinctive trait of the psi is its lifetime, which is exceptionally long. Many hadrons with large masses are known, but almost all of them decay very rapidly through strong interactions; their lifetimes are generally on the order of 10^{-23} second. The psi particle also decays through the strong interaction, but it has a lifetime of about 10^{-20} second, 1,000 times longer than the lifetime of a typical hadron of comparable mass. Some explanation of its longevity is required.

A suggestive precedent for the long lifetime of the psi is found in another particle discovered some years earlier: the phi meson (ϕ). The phi meson is made up of a strange quark bound to a strange antiquark, and since the strangeness quantum numbers of the quark and antiquark cancel, it has a net strangeness of zero. The phi can decay through the strong interaction; all that is required is that the quark and the antiquark annihilate each other. This process conserves all quantum numbers, but it nonetheless seems to be inhibited. The lifetime of the phi is roughly 10 times longer than might have been expected.

The simplest way to provide a place among the hadrons for the psi particle is to assume it is a meson made up of a new, massive quark bound to the corresponding antiquark. This structure automatically accounts for the quantum numbers of the psi. The long lifetime might be explained by a mechanism similar to that which retards the decay of the phi meson: strong decays would be allowed but they might be slowed somewhat.

A bound state of a new quark and a new antiquark was the leading explanation for the psi particle from the time of its discovery. In large measure this hypothesis was credible only because the existence of a fourth quark had been proposed long before and on grounds that had nothing to do with the discovery of new hadrons.

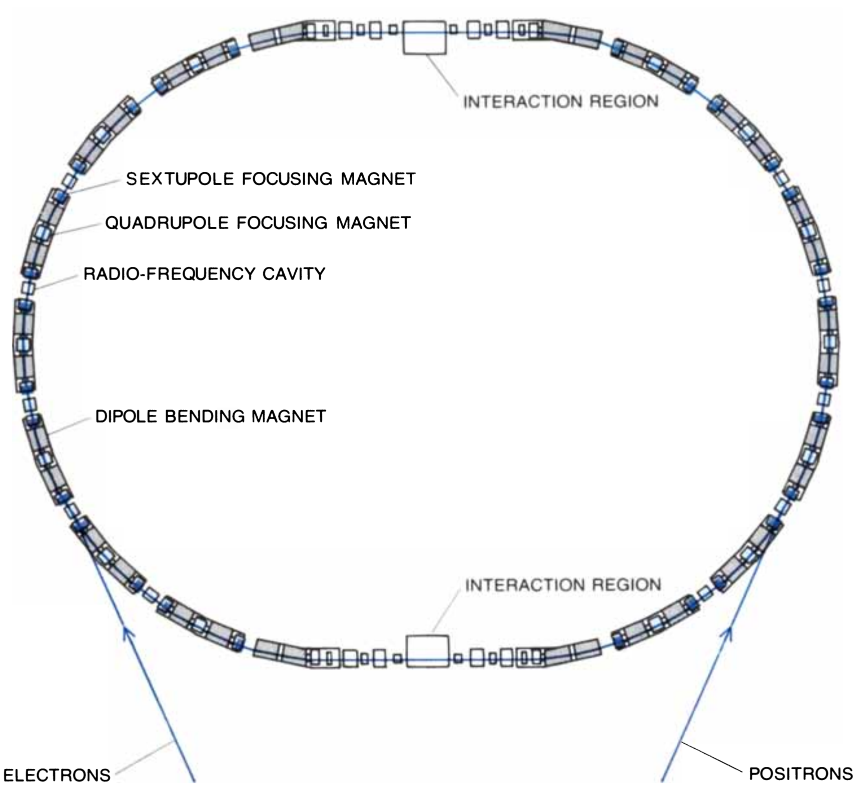
The new quark was suggested by a number of theorists as a natural extension of the model formulated by Gell-Mann and Zweig. Initially it was supported by an esthetic argument based on the notion that there may be a deep connection between leptons and quarks. Since there are four known leptons, it was argued, the spectrum of elementary particles would be far more attractive if there were also four quarks. The leptons come in pairs, the electron being associated with one neutrino and the muon with the other. The *u* and *d* quarks form a similar pair, but the *s* quark is without a companion. The new quark was designed to fill this gap. In order to do so it must have an electric charge of +2/3 and some new quantum number that would distinguish it from the known quarks. James D. Bjorken of SLAC and Sheldon Lee Glashow of Harvard University gave the quantum number the name charm. The charmed quark is designated *c*, the charmed antiquark $\bar{c}$.

Charm is a property much like strangeness: it must be conserved in all strong and electromagnetic interactions but not in weak ones. Hence the lightest charmed particles should decay only through the weak interaction, and they should have commensurately long lifetimes. The psi particle, however, is exempt from this rule because its net charm is zero. It consists of a *c* quark and a $\bar{c}$ antiquark whose charm quantum numbers cancel.

A substantial theoretical argument for the charmed quark was made in 1970 by Glashow in collaboration with John Iliopoulos and Luciano Maiani. It was based on observations that did not directly concern charmed particles at all but involved certain weak interactions of strange particles. Weak interactions can proceed either with or without a transfer of electric charge between the interacting particles. By 1970 a puzzling correlation had been established experimentally: with very rare exceptions strangeness is changed in weak interactions only when electric charge is transferred. The so-called neutral weak currents, which do not transfer charge, also seemed not to alter strangeness.

In the three-quark model there was no obvious connection between charge-transfer and strangeness-changing. Glashow, Iliopoulos and Maiani pointed out that the addition of a fourth, *c*, quark closely associated with the *s* quark could account for the suppression. How it does so involves a rather subtle quantum-mechanical argument. The fourth quark does not directly impede the interactions that change strangeness without transferring charge. Instead it provides an alternative channel for those interactions but in such a way that the effects of the two channels cancel.

By the time the psi was discovered charmed particles were already prominent items on a long list of entities that had been predicted to exist but had never been observed. The charm hypothesis could explain the properties of the psi, but so might other theories. On the other hand, the charm model predicts much more than a single new particle; if charmed quarks exist, there must be an



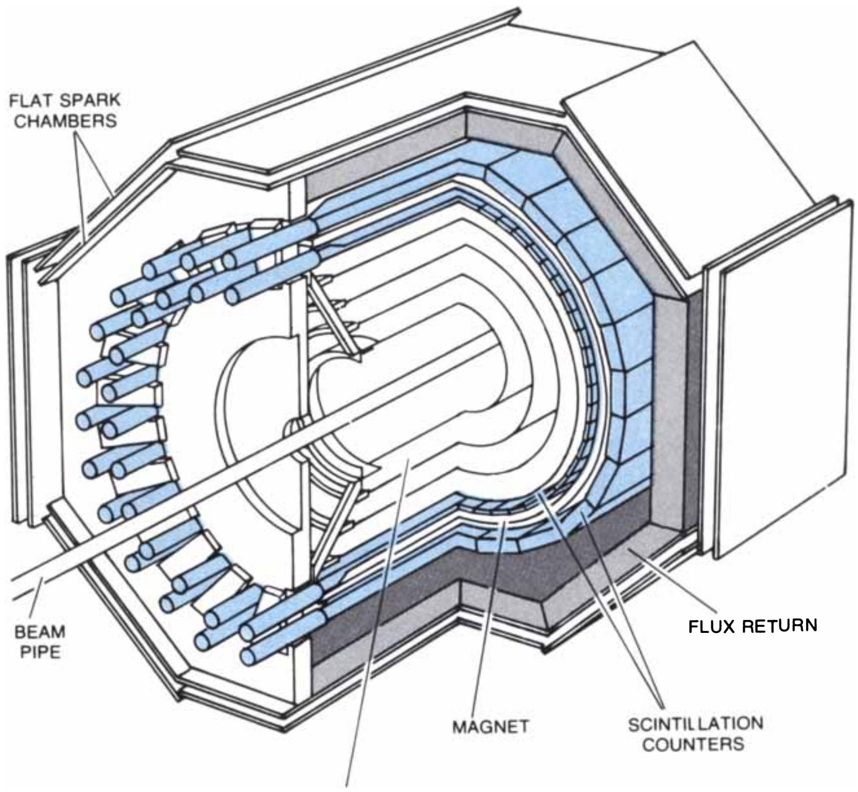
PARTICLE-STORAGE RING at the Stanford Linear Accelerator Center (SLAC) was one of the devices with which the psi particle was discovered and, more recently, where charmed mesons have been observed. The oval ring, which is called SPEAR, is supplied with electrons and positrons by the two-mile accelerator at SLAC. Counterrotating electrons and positrons are confined to the ring by magnets that bend the particles' trajectories and focus the beams into needle-shaped "bunches." Each bunch is made up of about 10^{11} particles, and the bunches are synchronized so that they pass through each other in the two straight sections of the ring. Energy lost by the particles is replenished by the radio-frequency cavities. The magnets confine particles moving in opposite directions since electrons and positrons have opposite charges.

entire spectrum of new states of matter. Some of these states are closely related to the psi: they consist of a c quark and a $\bar{c}$ antiquark, but they have different masses and different values of angular momentum. The charmed quark must also combine with the original three quarks to form dozens of new hadrons with overt charm. By searching for these particles we could determine whether or not the psi particle actually contains a new kind of quark and whether or not that quark possesses the proposed quantum number charm.

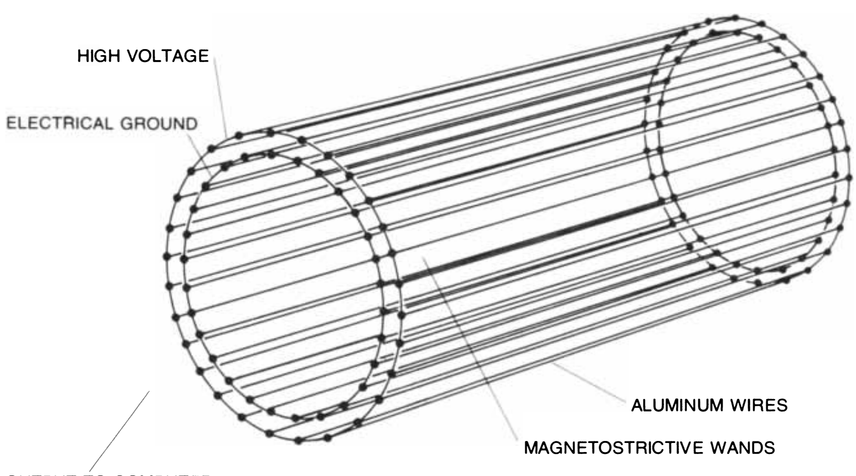
At SLAC the experiment in which the psi was discovered and subsequent searches for other particles containing charmed quarks were carried out by the same basic technique. Electrons and their antiparticles, positrons, are made to collide at high energy. The particles of interest are then found by sorting through the debris of the collisions.

The collisions take place in a device called a storage ring, in which electrons and positrons circulate in opposite directions at nearly the speed of light. The storage ring at SLAC is called SPEAR; it was built in 1971 and 1972 under the direction of Burton Richter and John Rees. At the heart of the SPEAR ring is a toroidal aluminum vacuum chamber with a mean diameter of 80 meters and a cross section of a few inches. When the ring is operating, about 10^{11} electrons circle it clockwise in a needle-shaped "bunch" a few centimeters long and less than a millimeter thick. A similar bunch of positrons circulates counterclockwise. The bunches cross twice during each revolution, and their orbits are timed so that the collisions take place in two short straight sections of the ring where particle detectors are emplaced. Elsewhere on the circumference of the ring the vacuum chamber is encased in large electromagnets, which bend the trajectories of the particles to the circular path and keep the bunches focused. There are also four cavities where radio-frequency energy is supplied to replenish the energy lost by the circulating electrons and positrons.

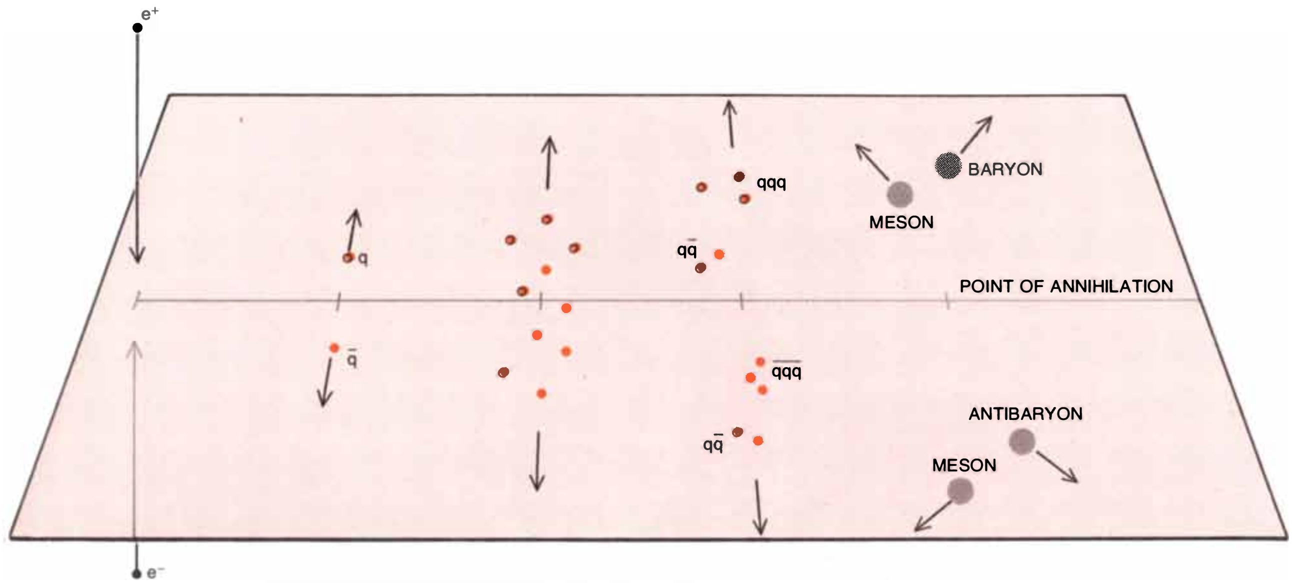
The electrons and positrons are generated by the two-mile-long linear accelerator at SLAC. At the far end of the accelerator electrons are boiled off a hot filament, much as they are in an ordinary vacuum tube. The electrons are injected into SPEAR merely by accelerating them and diverting them into the ring. Supplying positrons requires a slightly more elaborate procedure. First the electrons are propelled through a third the length of the accelerator, where they collide with a copper target, generating a shower of secondary particles that includes electrons, positrons and gamma rays. The remaining length of the accelerator is then adjusted to accelerate only the positrons. Replenishing the stored beams takes only a few



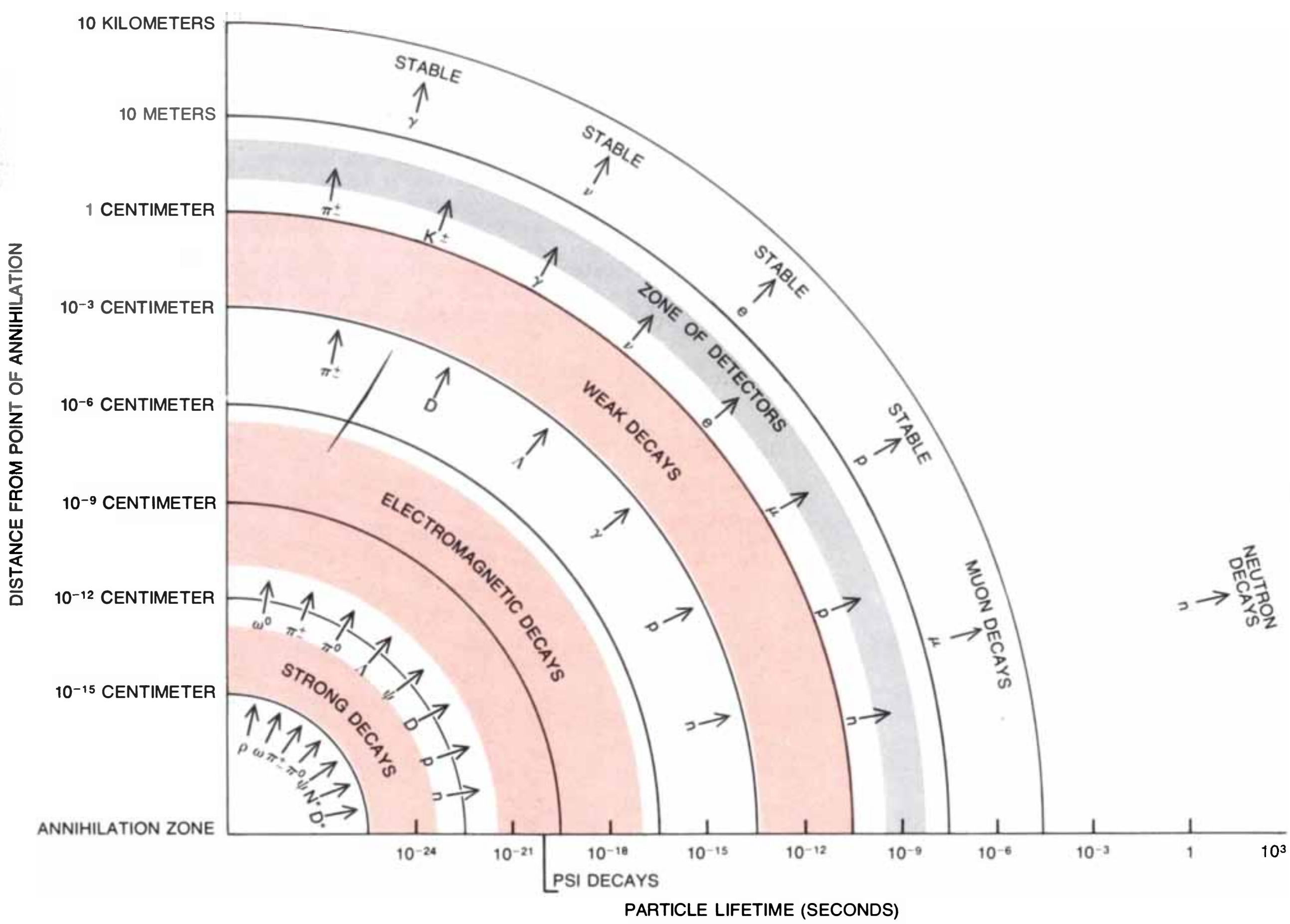
MAGNETIC DETECTOR at SPEAR was crucial to the discovery of the psi particle and of charmed mesons. The detector includes two kinds of device: spark chambers and scintillation counters. Both are sensitive to electrically charged particles emitted in electron-positron collisions at the center of the detector. A strong magnetic field bends the trajectories of the charged particles, and from the amount of bending their momentum can be determined. The scintillation counters are made of a plastic that emits a flash of light when a particle passes through it; they measure a particle's time of flight and hence its velocity. From the momentum and the velocity of a particle its rest mass can be estimated, providing an important clue to its identity.



SPARK CHAMBERS in the magnetic detector consist of concentric layers of fine aluminum wires; when the detector is triggered, a high voltage is applied across the layers. Only two layers are shown here; each chamber actually has four layers and there are four chambers, for a total of about 100,000 wires. When the spark chamber is in operation the wires are immersed in a noble gas that is readily ionized by the passage of an electrically charged particle. The ionized atoms left behind provide a conductive path for a spark between wires in the oppositely charged layers, thereby marking the position at which the particle passed through the cylindrical chamber. The positional information is recorded through a system of magnetostrictive "wands" laid down perpendicular to the aluminum wires at the end of the chamber. The surge of current that flows through the active wire when a spark is triggered gives rise to a pulse in the magnetostrictive wand, which propagates as a sound wave that can be detected and timed.



ANNIHILATION of an electron and a positron gives rise to equal numbers of particles and antiparticles. When hadrons are created as a result of a collision, the initial product is a single quark and an antiquark of the same type. From the energy imparted to this pair, other quarks and antiquarks materialize, and ultimately they coalesce in pairs and triplets to form hadrons. Only the hadrons can be detected.



SEQUENCE OF DECAYS following an electron-positron annihilation converts the great variety of particles created into a few stable or nearly stable species. Most hadrons that can decay through strong interactions have completed their decays within 10^{-23} second, when they have traveled only about 10^{-13} centimeter from the point of collision. The psi particle is an exception: it decays through the strong interaction but requires about 10^{-20} second. The products of the strong decays are longer-lived hadrons, some of which subsequently decay electromagnetically, yielding still other hadrons along with gamma rays (γ). Weak decays are the slowest, but most of them are completed before the particles have traveled more than a centimeter. After the weak decays only leptons, gamma rays and the longest-lived hadrons survive. Detectors cannot be placed closer than a few centimeters to the annihilation zone, and so they detect the products of a collision only after most decays have been completed. Nevertheless, collision products can often be identified. Gamma rays indicate that a particle has decayed electromagnetically, and leptons are evidence for a weak decay. *K* mesons signal the presence of a strange hadron.

minutes, after which they circulate stably for periods of up to several hours.

The energy of the stored beams can be adjusted between 1.2 GeV and 4 GeV. One of the principal motivations for employing storage rings is that all this energy is available for the creation of new particles. When an electron and a positron collide, both particles are annihilated and all their mass and kinetic energy is converted into a state of pure energy. Thus the machine has the potential for creating sets of particles with total masses of up to 8 GeV.

The energy liberated by the annihilation is confined to a small region of space, with dimensions of 10^{-15} to 10^{-14} centimeter. In an unmeasurably brief interval—the time required for light to traverse such a region—the energy is transformed into material particles, which then fly away from the point of annihilation. There are few constraints on the kinds of particle that can be created from this dense bundle of energy. One obvious requirement is that energy must be conserved: the rest masses of the particles created cannot exceed the sum of the electron and positron energies. Quantum numbers must also be conserved, but this requirement is less restrictive than it might seem at first.

The annihilation of an electron and a positron is mediated by the electromagnetic force and the immediate product is a photon, a quantum of electromagnetic energy. The photon decays so quickly it can never be detected, even in principle (it is called a virtual particle), but it nonetheless determines the properties of all subsequent states of the system. If all the decay products of the virtual photon are detected and their quantum numbers added up, the totals must be equal to the quantum numbers of the photon. The psi particle can be created in these events because its quantum numbers are precisely those of the photon: it has one unit of angular momentum but all its additive quantum numbers—those determined by simply adding up the quantum numbers of the constituent quarks—are zero. Why this should be so becomes apparent when the quark composition of the psi is considered. It consists of a quark bound to its own antiquark, and all quantum numbers except angular momentum exactly cancel.

In this context what had seemed a restrictive demand that the properties of the photon be conserved is seen to confer almost complete freedom for the creation of any particle as long as it is accompanied by its own antiparticle. In the psi the particle-antiparticle pair is internal, but it need not be so. For example, a charmed meson could be produced in combination with another meson having the opposite charm quantum number. Given enough beam energy almost any state of matter (and antimatter) could be formed. Collisions at SPEAR are energetic enough to yield up to 50 pions (half π^+ and half π^-) or four protons together with four antiprotons or even a complete atom of helium and an atom of antihelium.

As particles emerge from the annihilation region at speeds near the speed of light they commonly decay through several generations to lighter and longer-lived daughter particles. Most of the massive hadrons have undergone strong decays by the time they have traveled 10^{-13} centimeter, which is approximately equal to the diameter of a hadron. The products of these decays are lighter hadrons, such as pions, *K* mesons and protons and neutrons. Hadrons that decay electromagnetically generally travel less than 10^{-6} centimeter before they emit a photon and are thereby converted into lower-mass hadrons. Most weakly decaying particles, such as the strange lambda baryon, travel a few centimeters before they are transformed into the lowest-mass hadrons, such as protons, neutrons and pions, along with leptons. Ten centimeters from the point of interaction most of the surviving particles are protons and neutrons, electrically charged pions and *K* mesons, gamma rays and leptons. Within a few meters the pions and *K* mesons decay to leptons, leaving only protons, neutrons, gamma rays, electrons, muons and neutrinos. Much farther along the neutrons and the muons decay.

It is the goal of the experimenter to detect as many of these particles as possible and to extract a maximum amount of information from them. In practice the closest a detector can approach the interaction region is a few centimeters, and so there is no hope of seeing particles before both strong and electromagnetic decays are completed. At the other end of the scale detectors larger than a few meters in diameter become too costly and unwieldy to be practical. Even within this limited range of distances it is generally only the charged particles and in some cases the gamma rays that can be detected. Nevertheless, it is often possible from the particles detected to reconstruct the chain of events that gave rise to them. For example, the presence of *K* mesons among the decay products can be read as a sign that strange particles were created. Gamma rays indicate that an electromagnetic decay has taken place and leptons are a clue to the passage of a weakly decaying particle.

The detector in which the psi was discovered surrounds one of the interaction regions at SPEAR. It was built by physicists from SLAC and from the Lawrence Berkeley Laboratory while SPEAR was under construction. Various individuals and small groups from both laboratories had responsibility for components of the detector and for its computer programs.

The core of the detector is a 150-ton solenoid magnet whose useful field volume is a cylinder three meters in diameter and three meters long. Within the field are four cylindrical shells of spark chambers, which record the trajectories of charged particles as they pass through the detector. The spark chambers contain a total of 100,000 aluminum wires, which sense the momentary ionization of an inert gas caused by the passage of a particle. The magnetic field deflects charged particles, and by measuring the curvature of their trajectories one can determine the momentum of the particles.

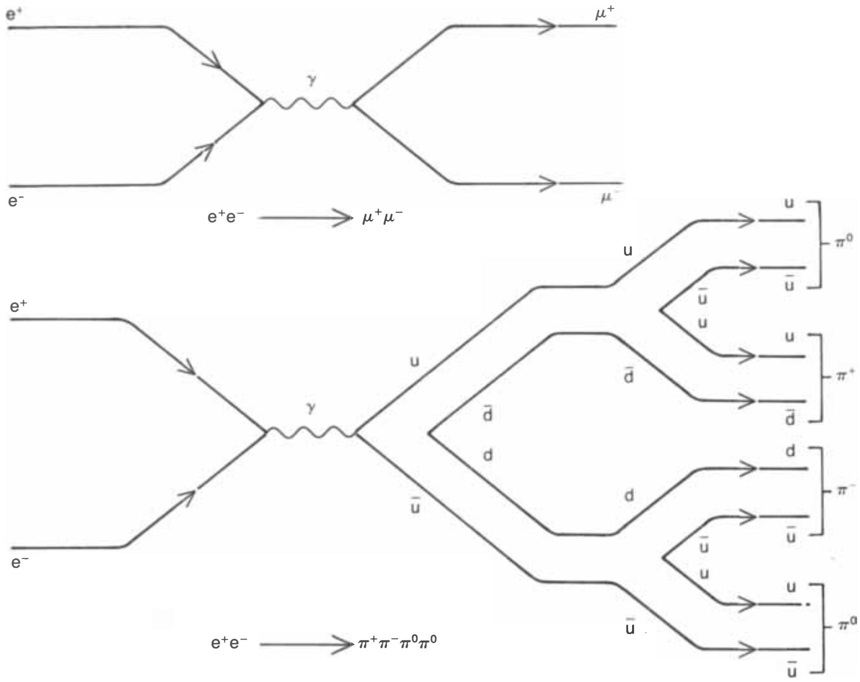
Beyond the spark chambers are scintillation counters, where brief flashes of light emitted when a particle penetrates a strip of phosphorescing plastic are detected photoelectrically. The scintillations can be timed precisely, and so the time of flight and the velocity of the particles can be calculated. Knowing the velocity of a particle and its momentum, one can deduce its rest mass, an important clue to its identity. The comparison of velocity and momentum is our principal means for distinguishing between the three charged hadrons that survive long enough to be detected, namely pions, *K* mesons and protons.

A final peripheral array of scintillation counters and spark chambers is shielded from the interior of the detector by filtering layers of lead and iron. The differential abilities of various particles to penetrate these metals allow us to discriminate between hadrons and leptons and, among the leptons, between electrons and muons.

Most of the time the electron and positron beams pass through each other without interacting at all. Even though each bunch contains 100 billion particles, the leptons are so small—indeed, their size has so far proved unmeasurable—that the probability of a collision is low. On the other hand, the beams move so rapidly, circling the ring more than a million times a second, that practical rates of data collection can be achieved.

The detector is triggered whenever two or more charged particles coming from the vicinity of the interaction region strike scintillation counters simultaneously with the passage of the beams through the detector. When a triggering event is recorded, all the information from the spark chambers and the scintillation counters is transferred to a computer, where it is recorded on magnetic tape. The detector is triggered about once a second, but only a few percent of these events derive from electron-positron annihilations. The rest are caused by cosmic rays and by interactions between the particle beams and residual gas molecules in the vacuum chamber.

The data collected on tape are analyzed with the aid of another computer. Background events are identified and discarded and for the more interesting events the trajectories of the particles



ANNIHILATION EVENTS can be divided into two broad categories: those that give rise to a pair of leptons, such as a positive and a negative muon, and those that lead to the creation of a quark and an antiquark, which eventually appear as a cluster of hadrons. If both leptons and quarks have a pointlike distribution of electric charge, then the rates of production can be calculated; the rates are determined by the number of kinds of leptons and quarks and by the squares of their charges. Measurements of the rate of hadron production therefore test various quark models, discriminating, for example, between those that include charmed quarks and those that do not. In practice the absolute production rates are not measured; instead the ratio of hadron production to muon production is determined, a ratio designated by the letter *R*.

are reconstructed. In a typical event involving hadrons four or five particles may be detected; their momenta and velocities are measured, and if possible the particles are identified.

At any given time approximately 35 physicists are involved with the operation of the detector and data analysis. Although our number varies as students and visitors come and go, without the dedication and talents of a great many individuals in our collaboration, this large detection and analysis apparatus could not function.

When the psi particle was discovered in 1974 we were not searching for charmed particles but were engaged in a much broader inquiry into the structure of hadrons. We were attempting to test the assumption that hadrons are made up of electrically charged, pointlike particles, such as the quarks are supposed to be.

Quantum electrodynamics, a theory that has been verified with great precision, is able to predict the rates at which particles are created in electron-positron annihilations provided the particles have a pointlike distribution of electric charge. The rate is proportional to the sum of the squares of the particles' charges. This prediction has been tested for electrons and for muons, with good agreement between experiment and theory. Quarks are thought to behave exactly like leptons in electromagnetic interactions, and so the same rule should predict their rate of production also.

Of course, we cannot directly observe the quarks created in the aftermath of an electron-positron collision, but it turns out this is no impediment to measuring their rate of production. When hadrons appear among the final products of an annihilation, it is assumed they all derive ultimately from a single quark-antiquark pair. Hence the rate of quark production is given simply by the number of events in which any hadrons appear. In practice the absolute rate is not measured. It is more convenient to measure the ratio of hadron production to muon production, a ratio that by convention is designated by the letter *R*. If the quark hypothesis is valid, then *R* should be equal to the sum of the squares of the quark charges, and it should be approximately constant, independent of the collision energy.

The experimental measurement of *R* is a straightforward procedure. At the energies of the SPEAR storage ring, events in which hadrons appear almost always have three or more particles in the final state, whereas muons are produced strictly in pairs, which leave the interaction with equal but opposite momentum. An excellent estimate of *R* can therefore be obtained simply by adding up the number of events in which more than two particles are detected and dividing by the number of two-body, back-to-back events.

The ratio *R* is an important test of quark theories. Because *R* is determined by the sum of the squares of the quark charges it can discriminate between variants of the quark model having different numbers of quarks or different charge assignments.

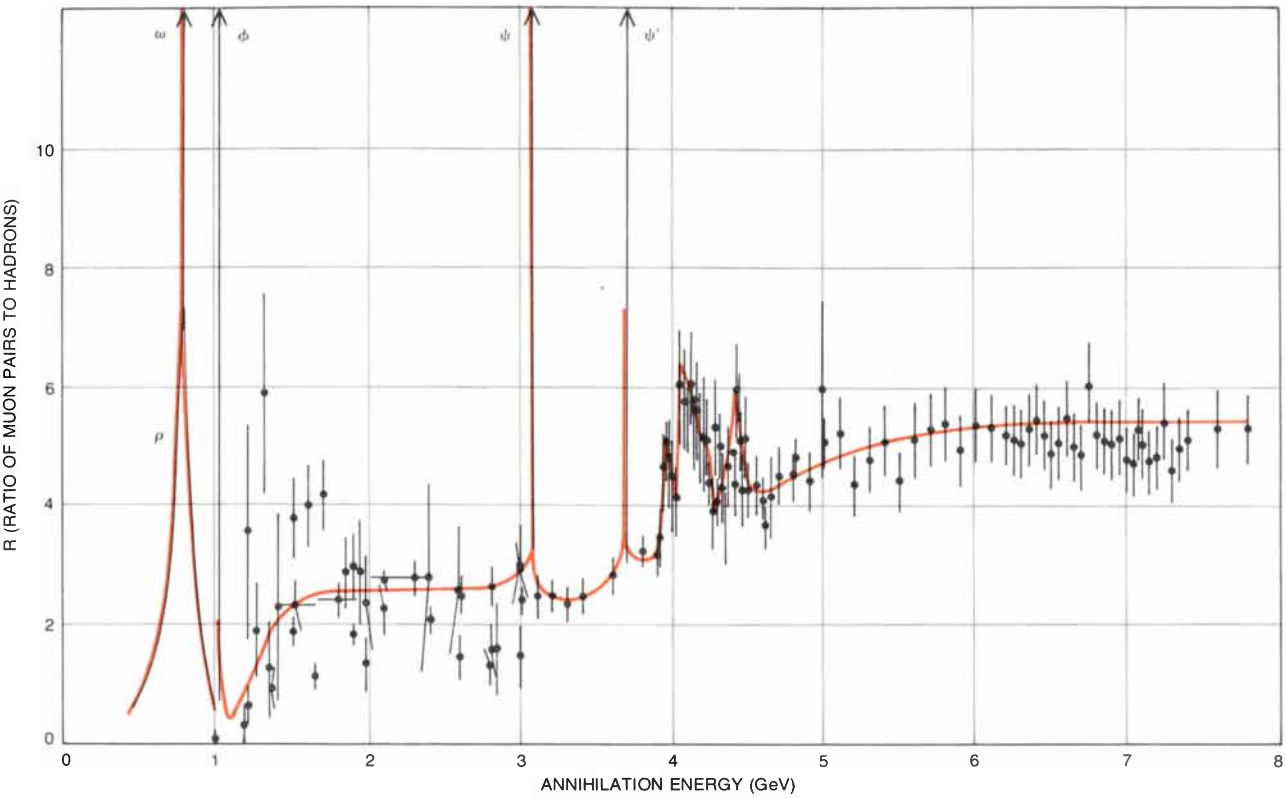
Experimentally determined values of *R* have an interesting history: they have consistently been too large for the fashionable theories of the day. In the original model of Gell-Mann and Zweig, with three quarks, *R* should have been equal to $(2/3)^2 + (1/3)^2 + (1/3)^2$, which adds up to 2/3. That value of *R* implies that for every two events involving hadrons there should have been three muon pairs produced. The first measurements of *R* were made with the storage ring called ADONE at Frascati in Italy. These measurements, all made at energies below 3 GeV, gave values not of 2/3 but of approximately 2; in other words, there were twice as many hadronic events as muon pairs.

Shortly thereafter theory briefly caught up with experiment. It was proposed, and it is now widely accepted, that each of the quarks must come in three varieties in order to accommodate a new quantum number, generally called color. Unless a quark can be isolated the color quantum number will remain permanently hidden from view. Color has proved to be an exceptionally fruitful concept in explaining the interactions of quarks, but it is a purely "internal" quantum number and it predicts no additional hadrons. Indeed, one of the few ways in which it impinges on experimental results is in the value of *R*. By tripling the number of quarks, *R* is also tripled—to a value of 2.

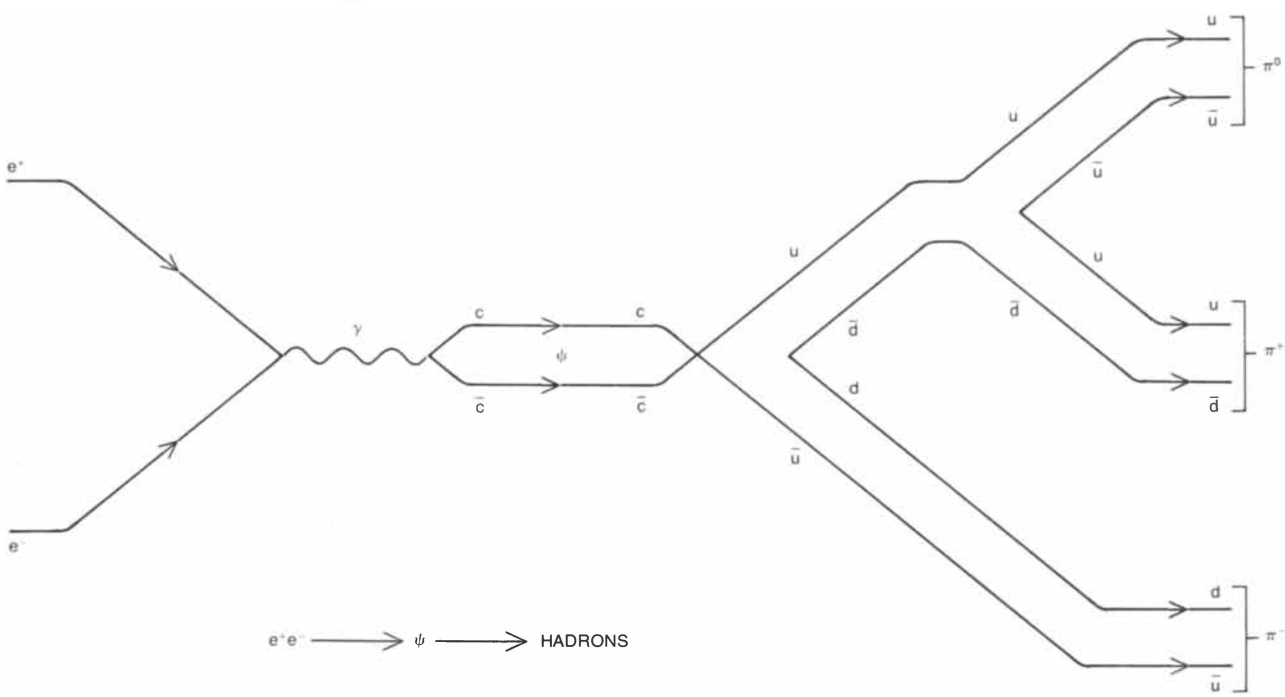
There was little time to gloat over this result. In the early 1970's two more tantalizing measurements of *R* were made at higher energy with a storage ring at the Cambridge Electron Accelerator. They showed that at 4 GeV *R* is 4, and at 5 GeV it rises almost to 6.

The Cambridge Electron Accelerator was shut down shortly after these measurements were made, but the initial program of experiments at SPEAR, beginning in the fall of 1973, confirmed and extended the results. *R* was measured at several energies separated by fairly wide intervals. Below about 3 GeV the value is 2.5, reasonably close to the value of 2 expected if there are three quarks and each comes in three colors. Above about 4 GeV, however, the ratio rises steeply, then above 5 GeV it levels off at a value of about 5.5. Clearly some new phenomenon must be making itself known. Even charm may not be sufficient to explain the behavior of the curve. Adding the charmed quark to the model (in three colors) raises the expected value of *R* only to 3.3.

These disconcerting results aroused



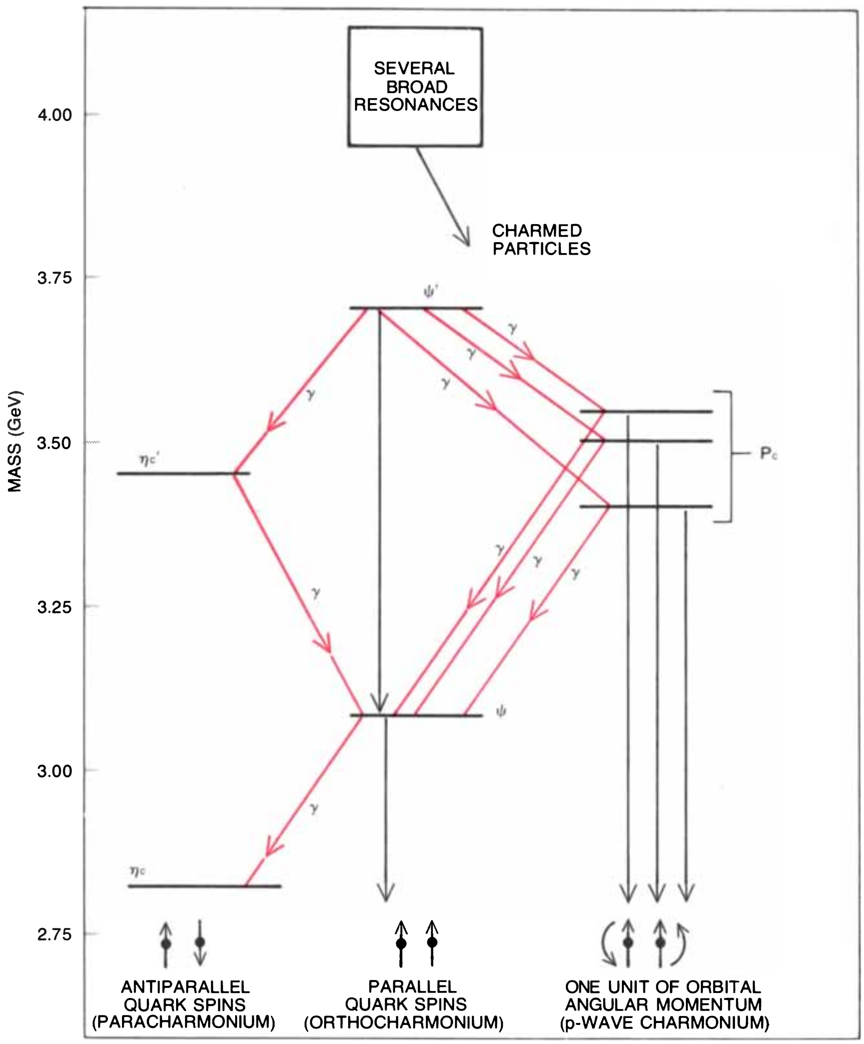
RATIO *R* **rises from about 2.5 at energies below 3 billion electron volts (3 GeV) to about 5.5 at energies above 5 GeV. The most plausible interpretation of the increase is that a threshold for the creation of a new kind of quark has been crossed in this interval. What is more remarkable than the overall increase in the ratio is that the curve has a series of tall and extraordinarily narrow peaks. The three peaks clustered near 1 GeV represent production of the rho (ρ), omega (ω) and phi (ϕ) mesons, which have quark compositions involving combinations of $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$. The spike at 3.1 GeV is the psi meson (ψ), made up of a $c\bar{c}$ quark-antiquark pair. The psi was discovered in 1974 during a measurement of** ***R;*** **the psi prime (ψ′), which is an excited state of the same $c\bar{c}$ system, was found 10 days later. The broader peak at 4 GeV represents several short-lived particles and is now recognized as the threshold for the creation of a pair of charmed mesons.**



PSI PARTICLE can be created singly in electron-positron annihilations because it consists of a quark and an antiquark of the same type. The immediate product of the electron-positron collision is always a photon, but the photon invariably decays to other particles before it can be observed. The photon has one unit of spin angular momentum but all its other quantum numbers are zero; any particle created from the photon must have the same quantum numbers. The psi is one such particle; the rho, omega and phi mesons are others. The psi decays through the annihilation of the charmed quark and antiquark, giving rise to ordinary hadrons such as the three pions shown here.

much interest, but they were soon overshadowed by another feature discovered in the R curve: the peak that signaled the presence of the psi particle. In a graph of R the psi appears as a narrow spike of enormous height at an energy of 3.095 GeV. If the spike could be perfectly resolved, it would be seen to rise above the background level by a factor of 3,000; in other words, at 3.095 GeV hadrons are 3,000 times more likely to be created than they are at neighboring energies. Such an enhancement in hadron production is called a resonance. When the collision energy of the electron and positron exactly matches the mass of the psi particle, the probability is high that a psi will be created. The subsequent decay of the psi yields the hadrons that are detected as a resonance. At energies even slightly higher or lower than that of the resonance, energy and momentum can no longer be balanced to produce only the psi and the rate of hadron production declines.

Even more remarkable than the height of the psi resonance is its extreme narrowness, a property related to the lifetime of the particle. In fact, it is only from measurements of the width of the resonance that the lifetime can be deduced. Part of the observed width results from the finite resolution of the experimental apparatus. Even with perfect apparatus, however, the peak could not be confined to a single uniquely defined energy. The range of energies over which the peak is distributed can be interpreted in quantum mechanics as representing a residual uncertainty in the actual energy of the particle, and that uncertainty is related to the lifetime. The shorter the lifetime, the greater the uncertainty. It is as if there were not enough time before the particle decayed to make an accurate measurement of its energy. Most resonances in this mass region are very broad enhancements hundreds of millions of electron volts wide; the width of the psi resonance is 67,000 electron volts, or about .002 percent of its total energy.



SPECTRUM OF PARTICLES that includes the psi consists of at least seven states. All of them are made up of a charmed quark and a charmed antiquark, but they are distinguished by various combinations of spin and orbital angular momentum. Only the psi and the psi prime can be created directly from electron-positron annihilations because only those states have the same quantum numbers as the photon. The quark spins in the psi are oriented in the same direction and they add to give the meson one unit of spin. Two states of somewhat lower energy, designated η_c and η'_c, are formed when the quark spins are antiparallel. Three states of intermediate mass, called *p*-wave excitations, are formed when a pair of quarks with parallel spins acquires a unit of orbital angular momentum. The bound system of a charmed quark and a charmed antiquark in many ways resembles a simple atom, and the name "charmonium" has been applied to all the states of this system. As in the spectrum of energy levels in an atom, one state can be transformed into another of lower energy through the emission of a photon.

The unexpected discovery of such a narrow peak in the graph of the ratio R prompted a change in the mode of operating storage rings. Instead of sampling hadron production at a few widely separated energies, high-resolution surveys were made with the smallest possible increment between sampled energies. By far the most successful high-resolution survey made at SPEAR was the very first one: 10 days after the discovery of the psi it disclosed a second, closely related particle with a mass of 3.684 GeV. This second particle was given the name psi prime (ψ'). Like the psi itself, psi prime is electrically neutral and has one unit of spin; it is not quite as long-lived as the psi, but the resonance width of 228,000 electron volts is still much narrower than most.

Further exploration of the R curve revealed a third feature in the vicinity of 4.1 GeV. This peak is much less distinct; it is an enhancement with a width of about 200 MeV. How it should be interpreted was not immediately apparent.

A bound system of a charmed quark and a charmed antiquark has much in common with simple atoms such as the hydrogen atom. Just before the discovery of the psi, Thomas Appelquist and H. David Politzer of Harvard proposed the name "charmonium" for this bound system. The name implies an analogy with another exotic atomlike species, positronium, which is a bound state of an electron and a positron.

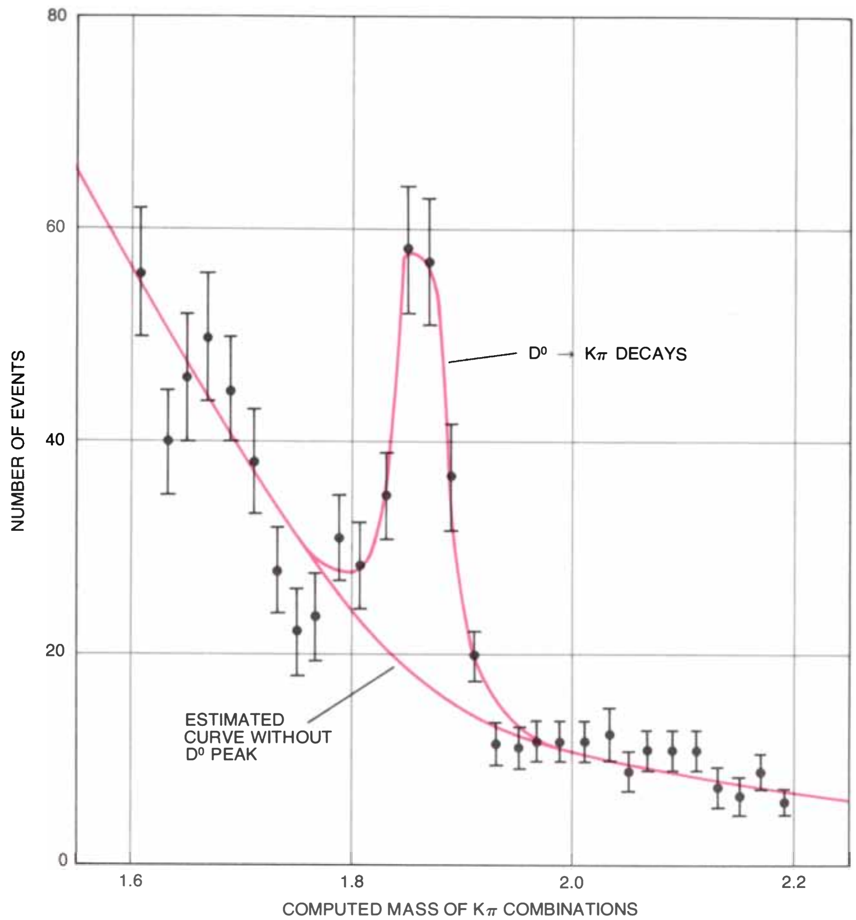
According to the charmonium model, the quark and the antiquark in the psi particle have their spins aligned in parallel, but they have no orbital angular momentum. The psi prime is an excited state of this system, analogous to one of the excited states of a hydrogen atom. In this state too the quark spins are parallel and there is no orbital angular momentum. The parallel quark spins combine to give each meson one unit of spin. This arrangement of spins is known in atomic physics as the "ortho" configuration, and the psi and psi prime particles can together be called orthocharmonium.

Continuing to argue from the principles of atomic physics, Appelquist and Politzer were able to predict additional forms of charmonium. For example, there should be states without orbital angular momentum and with the quark spins antiparallel. The oppositely directed spins are subtracted, with the result that the particle as a whole has zero angular momentum. This configuration is denoted by the prefix "para," and it has a lower overall energy than the ortho configuration. Thus there should be a paracharmonium state with a mass slightly less than that of the psi and another with a mass slightly less than that of the psi prime. The quark and the antiquark should also combine with parallel spins and with one unit of orbital angular momentum. Three such states are expected, known collectively as *p*-wave charmonium (another term borrowed from atomic physics). Their masses should all lie between that of the psi and that of the psi prime.

Because the quantum numbers of the photon must be conserved, electron-positron annihilations can give rise to quark-antiquark pairs only in the ortho configuration, and so neither paracharmonium nor *p*-wave charmonium can be observed as peaks in the ratio R. It should be possible to produce them, however, through electromagnetic transitions from the psi and psi prime states. Once again these transitions are analogous to events in atomic physics, where an atom can move from an excited state to a state of lesser energy by emitting a photon. In the atomic transitions the photons emitted are typically in the visible portion of the electromagnetic spectrum; in the transitions between charmonium states the photons are high-energy gamma rays.

The most straightforward approach to finding these states is to produce psi prime particles copiously, then search among their decay products for telltale gamma rays. Such experiments were undertaken at SPEAR and at the storage ring called DORIS associated with the German Electron Synchrotron near Hamburg.

The main difficulty in recognizing the gamma rays is in distinguishing them from numerous other photons emitted by unrelated processes. One aid to discrimination is that all the photons emitted during transitions between two given states have the same energy, so that they should stand out above the background events, which have a wide range of energies. In the initial experiments the background was further reduced by selecting for examination only those events that seemed to conform to a particular sequence of decays. We decided to study events in which a psi prime particle emits a photon and decays to some intermediate state, which then emits another photon and yields a psi particle. We were thus able to exclude from consideration all events except those in which the presence of a psi could be deduced and in which exactly two gamma rays were present. Such procedures for



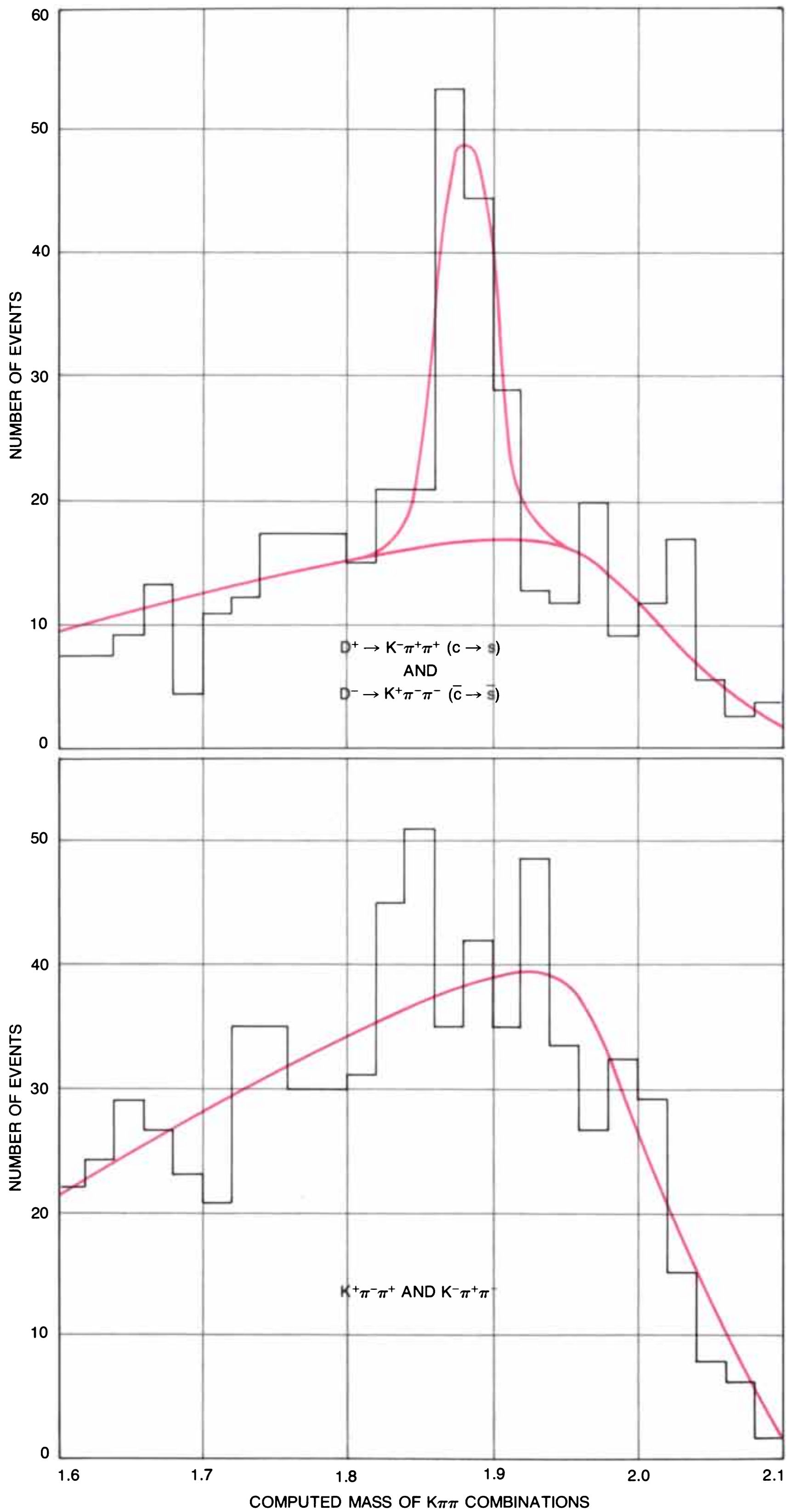
FIRST CHARMED PARTICLE to be discovered was the D^0, composed of a c quark and a $\bar{u}$ antiquark. Unlike the psi, the D^0 has overt charm: the quantum numbers of the c quark are not canceled by those of a $\bar{c}$ antiquark in the same hadron. As the lightest charmed meson, the D^0 can decay only through the weak interaction, which can transform the charmed quark into a quark of another type. Because of the special relation that exists between strangeness and charm, the charmed quark is usually converted into a "strange" quark; consequently strange hadrons (such as K mesons) are expected among the decay products. The D^0 was discovered as a bump in the energy distribution of K mesons and pions that have a net electric charge of zero ($K^+\pi^-$ or $K^-\pi^+$). Such combinations can be produced by many unrelated processes, but their number should decline smoothly as the mass of the pair increases. The presence of a bump at a given energy indicates that a particle with that mass is decaying into the $K\pi$ combination.

"cutting" data are common in high-energy physics; they can reduce hundreds of thousands of recorded interactions to a handful of interesting events.

The first results were reported by a group of experimenters working at DORIS; they found 14 events that met the criteria. Shortly thereafter our group at SPEAR contributed several more candidates. These few events retained one important item of information that was not a mere artifact of the selection process, namely the energies of the two photons. In most of the events one of the gamma rays had an energy near 170 MeV; by subtracting this energy from the mass of the psi prime we deduced that the psi prime was decaying at least part of the time into an intermediate state with a mass near 3.5 GeV. The intermediate state subsequently decays to yield a psi particle. The 3.5-GeV particle has turned out to be one of the states of *p*-wave charmonium, those with a unit of orbital angular momentum. The group at DORIS named it P_c. Since then more examples of this so-called cascade decay have been collected at both SPEAR and DORIS and the two related *p*-wave states, which have slightly different masses, have been found.

A second major search for gamma-ray transitions was undertaken by our group at SPEAR. We sought evidence for psi prime decays in which the final state included a particular ensemble of hadrons and a single gamma ray. These decay products would be the signature of an intermediate charmonium state that decayed not to a psi particle but to ordinary hadrons. We were gratified to discover that the photons again clustered at certain discrete energies, two of which coincided with energies observed in the cascade decays.

Within a year of the discovery of the psi particle a spectrum of closely related



D^+ MESON provides the strongest evidence that the new particles being observed have the property of charm. The charmed quark in the D^+ must decay into a strange s quark, which is a constituent of the K^- meson. The antiparticle of the D^+, the D^-, contains a charmed antiquark that must give rise to a strange antiquark, $\bar{s}$, found in the K^+ meson. Combinations of K mesons and pions consistent with this decay mode (*top*) show a distinct bump at an energy near 1.87 GeV. What is equally important, combinations that would arise from the forbidden transition from charmed quark to strange antiquark show no enhancement at that energy (*bottom*).

states had emerged. These included not only the *p*-wave excitations but also the paracharmonium state just below the psi prime. Two groups of experimenters working at DORIS also obtained evidence for the paracharmonium state below the psi itself; this is the lowest-mass state of charmonium. Finally, in 1976, most of the peaks in the gamma-ray spectrum of the psi prime were observed in a single measurement, made by physicists from five institutions: the University of Maryland, the University of California at San Diego, the University of Pavia, Princeton University and Stanford University. This gamma-ray spectrum is like the line spectrum of an ordinary atom, with one spectacular difference: the energy of a typical photon in an atomic transition is usually a few electron volts, whereas the gamma rays emitted in charmonium transitions have energies of several hundred million electron volts.

The spectrum of charmonium states represents strong evidence that the psi and its relatives consist of a particle bound up with its own antiparticle, but there is no assurance that the quantum number carried by those particles is charm. The property itself is hidden in all the charmonium states. It becomes manifest only in hadrons that include a charmed quark or antiquark in combination with uncharmed quarks.

In electron-positron collisions such charmed hadrons can be created only in pairs. Hence the lowest annihilation energy at which charm could appear is equal to twice the mass of the lightest charmed particle. This threshold energy can be estimated from an examination of the ratio R. A lower bound is the mass of the psi prime: if the threshold were below this mass, then the psi prime itself would decay rapidly to yield a pair of charmed particles and the resonance would be much broader than it is. Just above the psi prime mass a significant increase in R with several broad peaks suggests the creation of highly excited states of charmonium that do decay strongly to particles with nonzero charm. Thus the threshold appears to lie between 3.7 GeV and roughly 4 GeV, implying that the lightest charmed particle has a mass between 1.85 GeV and about 2 GeV.

Like massive strange particles, massive charmed ones could decay strongly while conserving charm by passing on the c quark or c antiquark to a lighter charmed state. The lightest charmed particles, however, should decay only through weak interactions, and they should therefore be comparatively long-lived. The lifetimes might be on the order of 10^{-13} second.

The lightest charmed states were expected to comprise six mesons, three of them made by combining a charmed c quark with a $\bar{u}$, a $\bar{d}$ or an $\bar{s}$ antiquark, the other three by combining a $\bar{c}$ antiquark with a u, a d or an s quark. The mesons containing a charmed quark have been named respectively D^+, D^0 and F^+; the corresponding antiparticles are D^-, $\bar{D}^0$ and F^-.

How could charmed particles be recognized when they were found? Even if long-lived mesons with the appropriate masses were discovered, how could it be established that they are distinguished by charm rather than by some other new property of matter? The answers to these questions lie in the special relation that must exist between the charmed quark and the strange quark if the suppression of strangeness-changing neutral weak currents is to be explained. Because of this relation weakly decaying charmed particles should usually include strange particles among their decay products. K mesons, the strange particles of lowest mass, serve as a distinctive signature of events involving the decay of charmed particles.

These properties of charmed-particle decays suggest an experimental procedure for finding charm. That procedure is to examine electron-positron collisions above the psi prime mass for multiparticle events (which usually contain hadrons) in which there are long-lived particles that include K mesons among their decay products.

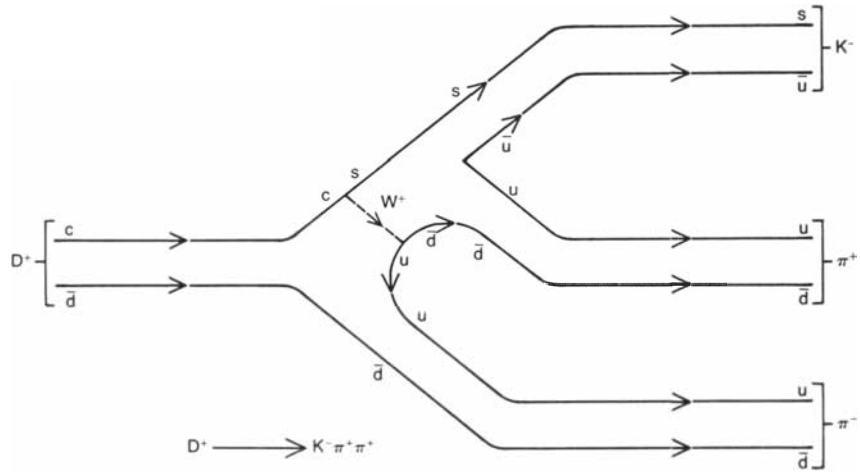
The usual method for conducting such searches is to hypothesize a particular mode of decay, then to select from a large sample of events all those that might be examples of the presumed mode. For example, a reasonable hypothesis is that some charmed particles might sometimes decay into a K meson and two pions, and so all events that included these three particles would be selected. From measurements of the momentum of the decay products in each event the mass of the parent particle can be calculated. If the particles detected are in fact the products of a single mode of decay, then the majority of the computed masses will be clustered at a single value. If the selected particles are present through mere coincidence, on the other hand, then the computed masses will have a broad and featureless distribution. This procedure, which is quite common in high-energy physics, is called "bump hunting."

Our first attempts at bump-hunting at annihilation energies near 4 GeV were unsuccessful. The absence of a perceptible signal was discouraging, but it was not fatal to the charm hypothesis. Charmed mesons might decay through many different modes, so that no one mode is represented by a large number of events.

Meanwhile circumstantial evidence of charmed-particle production began to appear in experiments involving quite different techniques. In these experiments events were initiated by high-energy collisions between neutrinos and nuclear matter; because the neutrino interactions are necessarily mediated by the weak force, charmed particles might be created singly rather than in pairs. At Brookhaven and at the European Organization for Nuclear Research (CERN) a few bubble-chamber photographs showed events that could be interpreted as decays of charmed particles. At the Fermi National Accelerator Laboratory (Fermilab) an array of particle counters registered numerous candidate events distinguished by the presence of two leptons in the final state. The pairs of leptons were strong but nevertheless inconclusive evidence for the decay of a charmed particle with a mass in the vicinity of 2 GeV. With the exception of a single bubble-chamber photograph made at Brookhaven, none of these events provided enough information to precisely determine the mass of the parent particle.

At SPEAR we continued to accumulate data while studying the broad features in R at energies near 4 GeV. In the spring of 1976, with improved techniques for identifying strange particles and with a much larger sample of events, a bump was finally recognized. Gerson Goldhaber and François Pierre of the Lawrence Berkeley Laboratory found small but significant peaks at an energy of 1.863 GeV in two decay modes leading to the emission of K mesons and pions.

One class of events had in the final state a single K meson and a single pion with opposite charges, that is, $K^+\pi^-$ or $K^-\pi^+$. The other class of events had a K meson accompanied by three pions with the charge assignments $K^+\pi^-\pi^+\pi^-$ or $K^-\pi^+\pi^+\pi^-$. All these combinations of particles have a net electric charge of zero, and they all seem to derive from the decay of the same object. The most plausible candidate for that object is the electrically neutral D^0 meson, made up of a c quark and a $\bar{u}$ antiquark.



DECAY OF THE D^+ MESON is mediated by a weak interaction between quarks. Whereas the strong force can only create or annihilate matched pairs of quarks and antiquarks, the weak force can change one kind of quark into another. In the decay of the D^+ the weak force is transmitted by a particle called the W^+. The c quark emits a W^+ and is transformed into an s quark; the W^+ then decomposes into a u quark and a $\bar{d}$ antiquark. Analysis of the interaction shows that neither charm nor strangeness is conserved, although electric charge is conserved.

Additional bumps have since been discovered. The most important of them results from the decay of the charged relative of the D^0, the D^+ meson. The evidence for this state is an enhancement, at an energy 1.868 GeV, in the number of events yielding the combination of particles $K^-\pi^+\pi^+$. Significantly, the decay mode $K^+\pi^-\pi^+$, which has the same net electric charge of $+1$, has no corresponding peak at the same energy. This subtle distinction between charge states has a simple and elegant explanation in the charm theory, and it represents the best available evidence for the existence of charm. The D^+ meson consists of a c quark bound to a $\bar{d}$ antiquark. The relation between charm and strangeness specifies that a c quark can decay through the weak interaction to yield a strange s quark, but it cannot be converted into an $\bar{s}$ antiquark. The K^- meson contains an s quark, and so it can be produced in the decay of the D^+; the K^+ meson, on the other hand, contains an $\bar{s}$ antiquark, and as theory requires it is not observed in D^+ decays. No competing model of the new particles offers such definitive predictions, and none is so consistently in agreement with experimental findings.

In electron-positron annihilations charmed particles are invariably created in pairs, but the bumps by which they are identified represent the decay products of only one member of the pair. It is possible, however, to deduce some of the properties of the missing partner. Because the detected particle is recoiling from the one that escapes detection, both states must have the same momentum. From the known momentum and the known total energy of the system of particles (which is equal to the annihilation energy of the electron and positron) the rest mass of the escaping particle can be determined.

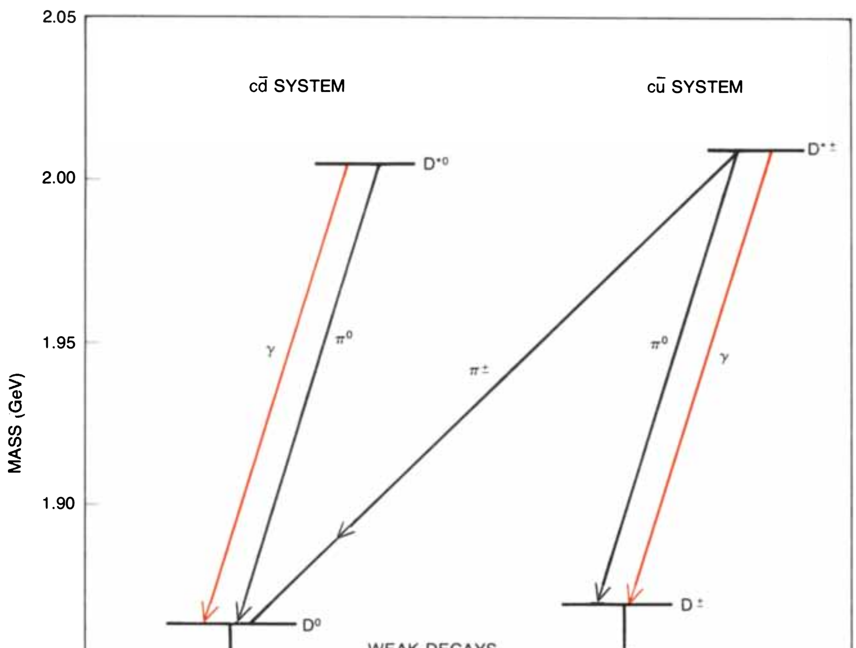
When the events involving D^0 and D^+ mesons were analyzed in this way, we found that in some cases the recoiling objects were simple antiparticles, $\bar{D}^0$ and D^-, with masses identical to those of the detected particles, about 1.87 GeV. A more prominent peak in the recoiling-mass spectrum was observed near 2.01 GeV. The peak is interpreted as evidence for excited states of the mesons, labeled D^{*0} and D^{*+}. If this interpretation is correct, the lowest-energy states (D^0 and D^+) are made up of quarks with their spins oriented antiparallel, so that the meson itself has zero angular momentum, whereas in the excited states parallel quark spins give the mesons one unit of angular momentum. Various angular correlations between the particles and their decay products depend on the spins, so that this hypothesis can be tested. Preliminary measurements of those correlations are in agreement with the model.

Once the mass of the psi had been established, psi particles could be produced at will and in large numbers. The more recent experimental successes have not been won as easily. States of matter with overt charm have proved remarkably difficult to observe. Even after three years of intensive searching only a few hundred events have been recorded in which all the decay products of a charmed particle are identified. All but a handful of those events are decays of charmed mesons. There must also be an extensive family of charmed baryons, made up of three quarks. A few events offering glimpses of charmed baryons have been recorded at Fermilab, but most properties of the particles remain to be determined.

The most elusive charmed particle is another meson, the F^+. It is made up of a c quark and an $\bar{s}$ antiquark, and so it is both charmed and strange. Several searches for the F^+ are under way. Although there is no conclusive evidence for its existence neither is there much doubt it will eventually be discovered.

Even if all the evidence in the case for charm has not yet been presented, there can no longer be any doubt about the verdict. The charmed quark began with an abstract symmetry principle relating quarks and leptons, a principle that can almost be reduced to a longing for tidiness. At the outset the hypothesis was proposed without the support of a single experimental observation; today a great many experiments point to a conclusion that is all but incontestable. An entire spectrum of particles testifies to the existence of the charmed quark: the psi and the other states of charmonium and the charmed mesons D^0 and D^+. The most compelling evidence is also the subtlest: it is the special relation between strangeness and charm manifested in the decay of the D^+ to the three mesons $K^-\pi^+\pi^+$ but not to $K^+\pi^-\pi^+$. If this is not charm, it is a superlative counterfeit.

Perhaps the most significant result of the discovery of charm is an improved understanding of ordinary matter. It has often been said that high-energy physics needs an equivalent of the hydrogen atom, the comparatively simple system of bound particles that served as a constant point of reference for the development of quantum mechanics 50 years ago. In a sense, of course, the quark model makes simple atomlike systems of all hadrons, but that structure was never very obvious in experiments until the discovery of the psi particle. Now the sharp transitions between charmonium states, with the emission of photons, provide an exact analogy to atomic spectroscopy, but at energies a million times greater. The discovery of charm marks the beginning of quark chemistry.



SPECTRUM OF CHARMED MESONS that have been observed in electron-positron collisions includes four states and their antiparticles. The states of lowest mass have antiparallel quark spins and a total spin of zero; the excited D^* states are made up of the same quarks but have the quark spins parallel, giving the mesons a total spin of 1. The one missing charmed meson, which would also have excited states, is the F^+. This meson is made up of a c quark and an $\bar{s}$ antiquark and thus is simultaneously charmed and strange. There is some evidence that the F^+ may have been seen in a European experiment but the evidence is not conclusive.

The case for charmed quarks may by now have been proved, but it would be entirely misleading to suggest that it ought to be closed. One conspicuous problem is the value of the ratio R. The most plausible quark model predicts a value of 3.3, but the observed ratio is nearer 5.5. Once again R seems to be much too large. Furthermore, there is a growing number of anomalous events, observed both at SPEAR and at DORIS, that are not readily explained by present versions of the quark model, even with the inclusion of charm. The events are characterized by the presence of two charged particles, often leptons, and undetected neutral particles, which may be neutrinos.

At the moment the hypothesis that seems best able to account for the anomalous events and for most of the excess in R is that a fifth member of the lepton family is appearing. It would have a mass of roughly 2 GeV (or 4,000 times the electron mass) and might be accompanied by still another new lepton, a neutrino. Of course, if there are additional leptons, the appealing symmetry between leptons and quarks would be destroyed. The obvious solution is to postulate more quarks, and preliminary evidence for particles containing a fifth kind of quark has now been reported in high-energy neutrino interactions at Fermilab. Further experiments will be needed to confirm that discovery, but it appears that the future of elementary-particle physics is at least as bright as the recent past.