Electron-Positron Annihilation and the New Particles

Energetic collisions between electrons and positrons give rise to the unexpected particles discovered last November. They may help to elucidate the structure of more familiar particles

by Sidney D. Drell

When matter and antimatter are brought together, they can annihilate each other to form a state of pure energy. A fundamental principle of physics demands that the reverse of that process also be possible: A state of pure energy can (quite literally) materialize to form particles of ponderable mass. When the matter and antimatter are an electron and a positron, the state formed by their annihilation consists of electromagnetic energy. It is a particularly simple state, since electromagnetism is described by a well-tested theory and is believed to be understood. For some time physicists have been eager to learn just what kinds of particles are created when an electron and a positron collide at high energy. During the past two years several experiments have provided a preliminary view of the annihilation process; the results have annihilated expectations. It is as the British poet Gerald Bullett described the arrival of spring:

Like a lovely woman late for her
appointment
She's suddenly here, taking us
unawares,
So beautifully annihilating
expectation.

The discoveries are the most startling and exciting to emerge from high-energy physics in a decade or more.

One reason for the great interest in these experiments is that they provide a means of testing a central concept of modern particle physics: the notion that the "herd" of supposedly elementary particles discovered during the past 25 years may actually be assemblages of only a few structureless entities that are truly fundamental. These constituent particles have been named quarks. Different versions of the quark theory make different predictions about what is to be expected in the aftermath of an electron-positron annihilation, and it was hoped that the experiments would help to determine which version is the correct one.

As it turned out, the results of an initial series of experiments in 1973 and early 1974 were not in accord with any of the predictions. Then, last November, as the measurements were being repeated and refined, two very massive particles were unexpectedly discovered. By coincidence the discovery of the first of the particles was announced simultaneously by physicists at two laboratories studying quite different reactions.

Four Forces

The existence of the new particles is in itself a surprise, but even more remarkable is their extraordinary stability. Although they decay to more familiar, less massive particles in a period that by conventional standards is very brief, their lifetime is about 1,000 times longer than that of other particles of comparable mass. This exceptional stability suggests that the new particles are fundamentally different from other kinds of matter. As yet their nature has not been satisfactorily explained, and their significance remains a subject of lively speculation. Theories abound and physics is in a state of great ferment, but we cannot be sure where the particles fit into the scheme of things.

Subatomic particles can be classified in broad families according to the kinds of interactions they participate in, or, as it is often put, according to the kinds of forces they "feel." The forces considered are the four fundamental ones that are believed to account for all observed interactions of matter: gravitation, electromagnetism, the strong force and the weak force.

In the everyday world gravitation is the most obvious of the four forces; it influences all matter, and the range over which it acts extends to infinity. For the infinitesimal masses involved in subatomic events, however, its effects are vanishingly small and can be ignored.

The electromagnetic force also has infinite range, but it acts only on matter that carries an electric charge or current. The photon is the quantum, or carrier, of the electromagnetic force, and when two particles interact electromagnetically, they can be considered to exchange a photon or photons. In the classification of particles the photon is in a category by itself: it has no mass and no charge and it does not participate in either strong or weak interactions.

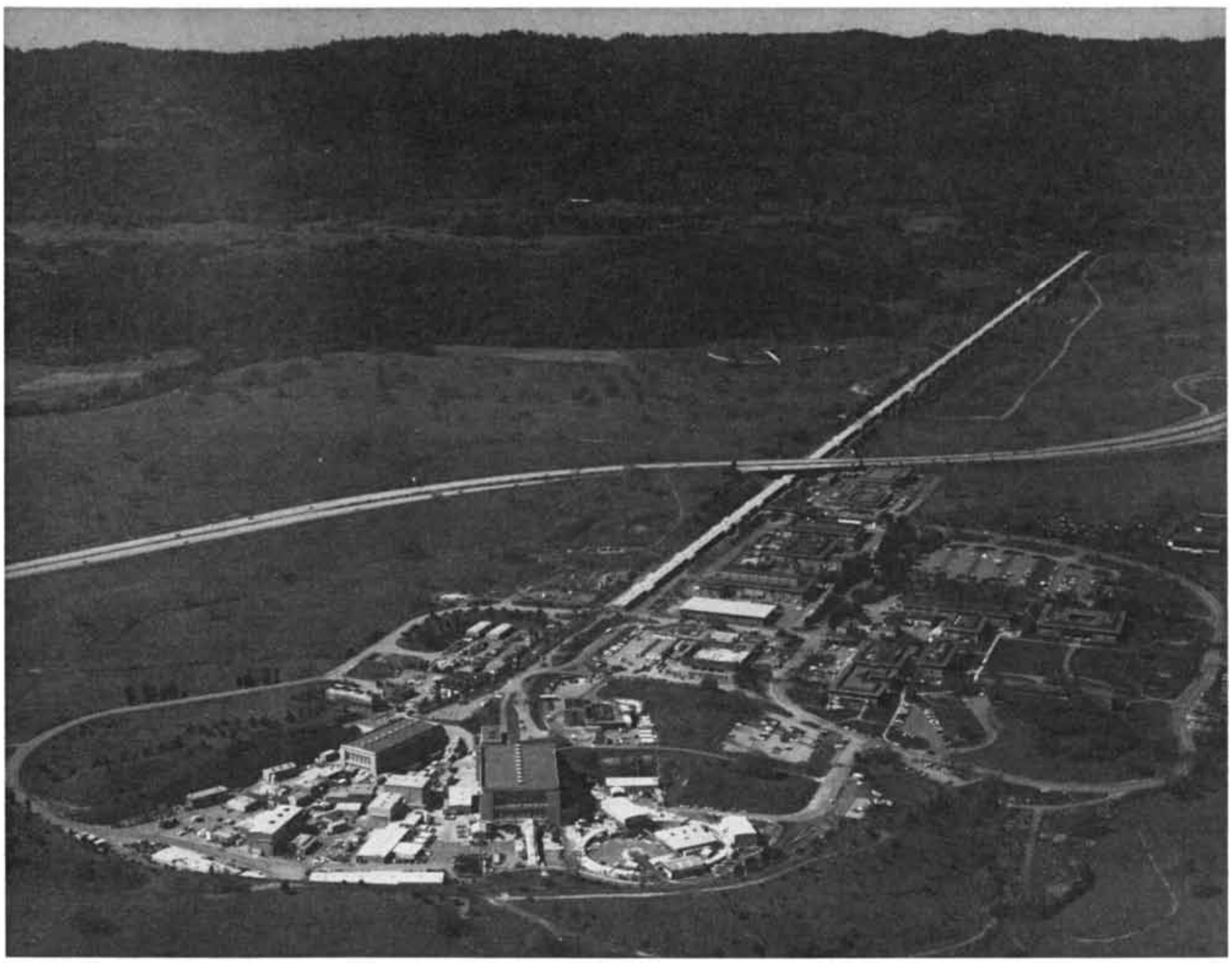
The strength referred to in the names of the strong and the weak interactions is related to the rate at which the interactions take place. The strong force has a short range: its effects extend only about 10^{-13} centimeter, or approximately the diameter of a subatomic particle such as a proton. When two particles that feel the strong force approach to within this distance, the probability is very high that they will interact, that is, they will either be deflected or they will produce other particles. In contrast, particles that interact electromagnetically are 10,000 times less likely to interact under the same circumstances. If the strongly interacting particles pass each other at nearly the speed of light (3×10^{10} centimeters per second), then they must interact during the 10^{-23} second they are within range of each other. That is the characteristic time scale of the strong interactions.

Compared with the strong force, the weak force is feeble indeed: for collisions at low energy it is weaker by a factor of about 10^{13}. At higher collision energies the strength of the weak force increases, but even at the highest energies yet studied experimentally it is weaker than the strong force by a factor of about 10^{10}. Moreover, the range of the weak force is at most a hundredth that of the strong force. Two particles must approach to within 10^{-15} centimeter in order to feel the weak force, and even at that range the probability that they will interact is less than one in 10^{10}.

All particles except the photon are classified according to their response to these two forces. Those that feel the strong force are called hadrons; those that do not feel the strong force but do respond to the weak force are called leptons. Particles belonging to these two families have quite different properties.

The hadrons are subdivided into two classes called baryons and mesons. The baryons include the familiar proton and neutron (and it is the strong force that binds these particles together in atomic nuclei). The mesons include such particles as the pion and the kaon; they are generally less massive than the baryons, but they are all more massive than the leptons.

As a result of discoveries made over the past two decades the baryons and the mesons have become very large families of particles; there are in all more than 100 known hadrons, most of them massive and unstable. It was in an effort to explain this great proliferation of particles that the quark hypothesis was introduced independently in 1963 by Murray Gell-Mann and by George Zweig, both of the California Institute of Technology. The quark model posits that the unstable particles are excited states of the stable ones. Baryons are thought to consist of three quarks bound together and mesons to consist of a quark and an antiquark. Just as an atom can enter an



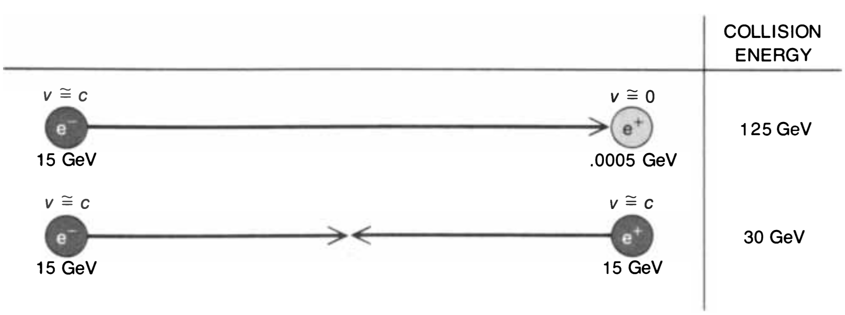
TWO-MILE-LONG ACCELERATOR at the Stanford Linear Accelerator Center (SLAC) was employed to generate high-energy electrons and positrons in the experiments that led to the discovery of the new particles. The main beam of the accelerator (extending under the highway) propels electrons into a target of tungsten, a third of the way down the accelerator. Some of the electrons collide with tungsten nuclei, creating electron-positron pairs. The positrons and the remaining electrons in the main beam are then further accelerated and injected into a storage ring, where the particles and antiparticles interact. The ring, called SPEAR, is to the right of the largest buildings. In it beams of electrons and positrons are confined in a single evacuated chamber. The beams circulate in opposite directions, guided by a magnetic field, and pass through each other twice each revolution. The two buildings straddling the ring enclose detectors that surround the regions where particle-antiparticle annihilations take place. The ring is about 250 feet in diameter.

GROUP	PARTICLE	SYMBOL	MASS	CHARGE	SPIN	LEPTON NUMBER	MU-NESS	BARYON NUMBER	LIFETIME
	PHOTON	γ	0	0	1	0	0	0	STABLE
LEPTONS	ELECTRON	e^-	.5	−1	$\frac{1}{2}$	+1	0	0	STABLE
LEPTONS	POSITRON	e^+	.5	+1	$\frac{1}{2}$	−1	0	0	STABLE
LEPTONS	ELECTRON NEUTRINO	ν_e	0	0	$\frac{1}{2}$	+1	0	0	STABLE
LEPTONS	ELECTRON ANTINEUTRINO	$\bar{\nu}_e$	0	0	$\frac{1}{2}$	−1	0	0	STABLE
LEPTONS	MUON	μ^-	106	−1	$\frac{1}{2}$	+1	+1	0	10^{-6}
LEPTONS	ANTIMUON	μ^+	106	+1	$\frac{1}{2}$	−1	−1	0	10^{-6}
LEPTONS	MUON NEUTRINO	ν_μ	0	0	$\frac{1}{2}$	+1	+1	0	STABLE
LEPTONS	MUON ANTINEUTRINO	$\bar{\nu}_\mu$	0	0	$\frac{1}{2}$	−1	−1	0	STABLE
HADRONS / BARYONS	PROTON	p	939	+1	$\frac{1}{2}$	0	0	+1	STABLE
HADRONS / BARYONS	ANTIPROTON	$\bar{p}$	939	−1	$\frac{1}{2}$	0	0	−1	STABLE
HADRONS / BARYONS	NEUTRON	n	939	0	$\frac{1}{2}$	0	0	+1	10^3
HADRONS / BARYONS	ANTINEUTRON	$\bar{n}$	939	0	$\frac{1}{2}$	0	0	−1	10^3
HADRONS / MESONS	PION	π^+	137	+1	0	0	0	0	10^{-8}
HADRONS / MESONS	PION	π^-	137	−1	0	0	0	0	10^{-8}
HADRONS / MESONS	PION	π^0	137	0	0	0	0	0	10^{-15}
HADRONS / MESONS	RHO MESON	ρ^+	750	+1	1	0	0	0	10^{-23}
HADRONS / MESONS	RHO MESON	ρ^-	750	−1	1	0	0	0	10^{-23}
HADRONS / MESONS	RHO MESON	ρ^0	750	0	1	0	0	0	10^{-23}
HADRONS / MESONS	PSI (3095)	ψ	3095	0	1	0	0	0	10^{-20}
HADRONS / MESONS	PSI (3684)	ψ	3684	0	1	0	0	0	10^{-20}

SUBATOMIC PARTICLES are classified according to the kinds of interactions in which they participate. The hadrons take part in "strong" interactions; the leptons do not; the photon interacts only electromagnetically. The hadrons are divided into mesons and baryons, which differ in their spin angular momentum and in other properties. The classification is reflected in quantum numbers such as lepton number, mu-ness and baryon number. The newly discovered particles, psi(3095) and psi(3684), are mesons. Their most perplexing property is their lifetime, which is 1,000 times longer than that of other particles of comparable mass, such as the rho meson.

excited state when the orbital configuration of its electrons is changed, so a hadron, by analogy, enters an excited state of higher energy (or mass) when the configuration of its constituent quarks is altered.

A further insight into the nature of hadrons was provided in the late 1960's by experiments in which high-energy electrons were scattered by protons and neutrons. The experiments were performed at the Stanford Linear Accelerator Center (SLAC) by a group of investigators from the Massachusetts Institute of Technology and SLAC under the direction of Jerome I. Friedman, Henry W. Kendall and Richard E. Taylor. Once again the results inspired an analogy with events on the atomic scale. In 1911 Ernest Rutherford investigated the scattering of alpha particles by atoms and was led to predict the existence of a massive nucleus within the atom. Similarly, the SLAC experiments revealed an internal structure within the individual hadron; the pattern of electron scattering suggested the existence of pointlike substructures, which were named partons. Partons and quarks are believed to be equivalent [see "The Structure of the Proton and the Neutron," by Henry W. Kendall and Wolfgang K. H. Panofsky; SCIENTIFIC AMERICAN, June, 1971].



COLLISION ENERGY in electron-positron annihilations depends on the initial energy and momentum of both particles. When one particle is stationary and the other has a velocity near *c* (the speed of light in vacuum), the collision energy is only a small fraction of the energy expended in accelerating the moving particle. When two particles collide with equal and opposite velocity, all their energy is made available for the creation of new particles.

The leptons are a much smaller class of particles than the hadrons. There are just four: the electron and its neutrino and the muon and its neutrino (and their four antiparticles). The electron has a mass of about .5 MeV (million electron volts) and an electric charge of −1 unit. The muon has the same charge, but it is 207 times as massive as the electron. Both kinds of neutrino are without mass and charge. Because the electron and the muon are charged they can interact electromagnetically as well as by the weak force; the neutrinos feel only the weak force.

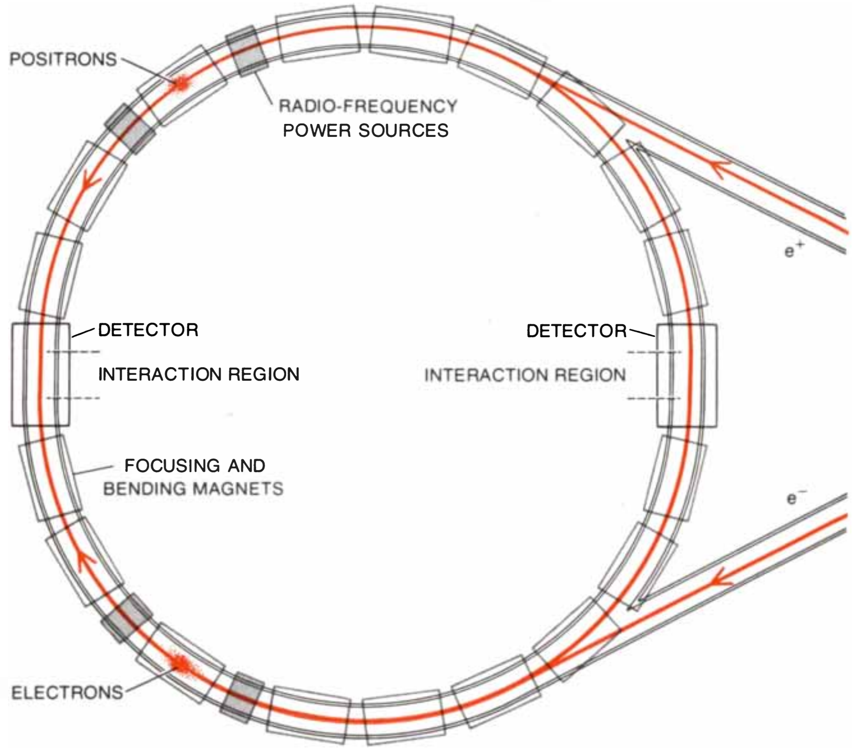
Among the leptons no spectrum of excited states comparable to that of the hadrons has been discovered. Nor have scattering experiments yielded any suggestion of an internal structure. The leptons are thus fundamentally different from the hadrons. They are not composed of quarks or partons but are themselves apparently pointlike. It is possible they are analogues of the pointlike constituents of hadrons.

Quantum Numbers

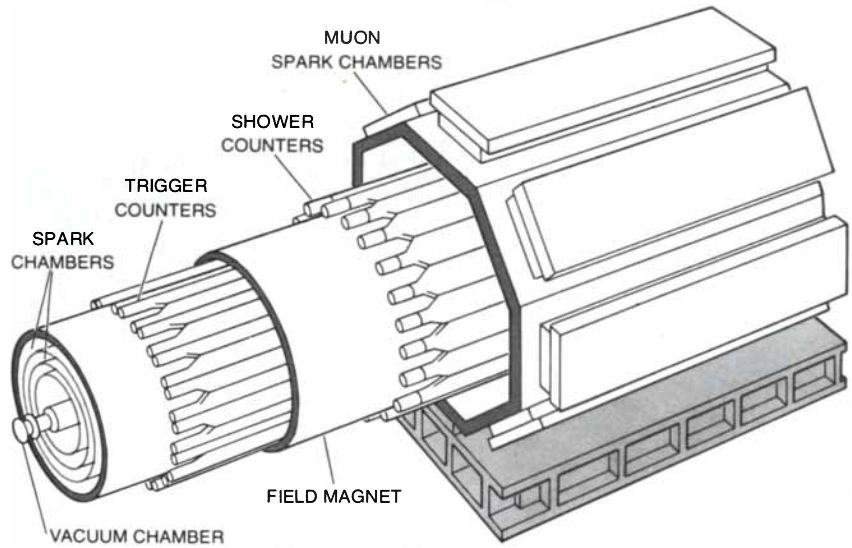
Physicists identify and describe subatomic particles by assigning them quantum numbers. Each number designates a property that is conserved, or left unchanged, when particles interact. Some quantum numbers, such as electric charge and spin angular momentum, refer to physical, measurable attributes of the particle. Others are more abstract; they denote family resemblances among particles and provide a valuable bookkeeping system for classifying particles and their interactions in algebraic form. Baryons and mesons, for example, are distinguished by a property called baryon number. Baryons are assigned a value of +1, antibaryons −1 and mesons 0; to say that baryon number is conserved is merely to say that baryons never turn into mesons. The least massive baryon, the proton, cannot decay into the less massive mesons or leptons because in such a process baryon number would be changed. The proton is therefore stable.

There are also conserved properties, or quantum numbers, of the leptons that ensure the stability of those particles. Lepton number is a quantity handled in the same way as baryon number. Its conservation prohibits the transformation of individual leptons into pure energy or into hadrons, just as hadrons are forbidden to become leptons. For instance, a positron has the same charge as a proton, and it can be accelerated until its mass is equal to that of a proton, but no positron has ever been observed to change into a proton.

In the same way a quantum number named mu-ness divides the leptons into two groups. The muon and the muon neutrino have mu-ness of +1, their anti-



COUNTERROTATING BEAMS of electrons and positrons in the SPEAR storage ring are each confined to a small "bunch" a few centimeters long. Their trajectories are determined by the magnetic field and their energy is maintained by the input of radio-frequency power; a single field guides both electrons and positrons, since the oppositely charged particles respond oppositely to it. Moving at nearly the speed of light, the beams pass through each other several hundred thousand times per second. Each beam can have an energy of up to 4 GeV (billion electron volts), so that total collision energies of up to 8 GeV can be achieved.



MAGNETIC DETECTOR completely surrounds one of the interaction regions at SPEAR. It consists of several layers of scintillation counters and spark chambers, which are here extended along their axis for clarity. Both kinds of detector produce an electrical impulse when a charged particle passes through them. Neutral particles cannot be detected. Information from the detectors is recorded electronically and employed to identify the particles, to reconstruct their trajectories and to determine which events are the result of an electron-positron annihilation and which are derived from other, extraneous sources. The momentum of a particle is determined by measuring its deflection in magnetic field of detector.

particles have mu-ness of −1 and the electron, the positron, the electron neutrino and the electron antineutrino all have zero mu-ness. An electron can transfer its mass and charge to more massive particles and become an electron neutrino, but because mu-ness is conserved it can never change simply into a muon or a muon neutrino.

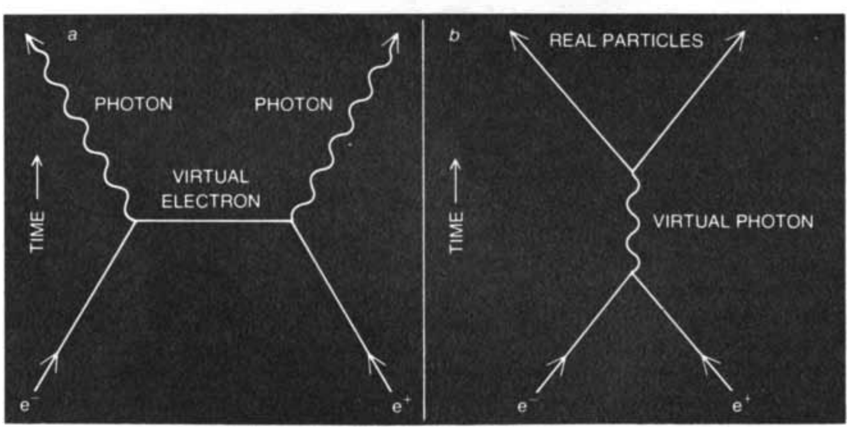
Baryon number, lepton number and mu-ness are always conserved; certain other quantum numbers, however, are conserved only in some interactions. They are said to describe "approximate" conservation laws. Several properties, for example, are conserved in strong interactions but not in weak or electromagnetic ones.

In addition to the several conserved quantum numbers, energy and momentum are always conserved. Energy and momentum can be transferred from one particle to another, but the sum of the energies and momenta before an interaction must be exactly equal to the sum afterward.

In the annihilation of matter and antimatter the arithmetic of quantum numbers is particularly simple. The concept of antimatter was introduced in 1928 by P. A. M. Dirac, and it is now a firmly established principle that for every particle there exists an antiparticle. All the quantum numbers of an antiparticle are "opposite" those of the corresponding particle, that is, the sum of the quantum numbers of the particle and antiparticle is zero. The electron has lepton number +1, mu-ness 0 and charge −1; for the positron the corresponding values are −1, 0 and +1. For each quantum number the sum is zero.

When matter and antimatter meet, their quantum numbers, being opposite, simply cancel. Properties such as charge and lepton number are conserved, but they are also eliminated! Furthermore, from the state of energy thus created, particles having virtually any combination of quantum numbers can, at least in principle, be formed, as long as the sum of the quantum numbers of the products remains zero. In particular, a pair or more than one pair of particles and antiparticles can be created. There is only one constraint on the process: the energies of a colliding particle and antiparticle do not cancel, and in the annihilation energy must be conserved just as it would be in any other interaction. Momentum must also be conserved.

From these considerations it can be seen that some processes that are forbidden in interactions of ordinary particles are permissible in the annihilation of particle-antiparticle pairs. For example, although an electron is prohibited by the conservation of mu-ness from becoming a muon (except with the emission of an electron neutrino and a muon antineutrino, a rare process), it is entirely possible for an electron and a positron to annihilate each other and for a muon and an antimuon to materialize from the energy state formed. It is necessary only that momentum be conserved and that the initial particles have sufficient energy to account for the rest mass of the muon-antimuon pair [see "Electron-Positron Collisions," by Alan M. Litke and Richard Wilson; Scientific American, October, 1973].



ANNIHILATION of an electron and a positron produces electromagnetic energy, or photons. The diagram depicting the event is called a Feynman graph (after Richard P. Feynman); distance is represented on one axis and time on the other. If momentum is to be conserved, two photons must be emitted (*a*); the photons, like the initial particles, have equal and opposite momentum and thus net momentum of zero. When only one photon is created (*b*), it must have large energy but zero momentum, a condition that is impossible for a real photon. The particle formed is called a virtual photon; it can never be detected and it quickly decays into real particles with zero total momentum. The production of two photons is said to take place through the exchange of another virtual particle: a virtual electron.

It is also possible for the annihilation of an electron-positron pair to give rise to hadrons. The reaction is written $e^-e^+ \rightarrow$ hadrons, where e^-e^+ represents the annihilating pair. It was during an investigation of this process at SLAC that the new particles were discovered.

The particles were found by a group of 35 physicists from the Lawrence Berkeley Laboratory and SLAC, led by Burton Richter, William Chinowsky, Gerson Goldhaber, Martin L. Perl and George H. Trilling. The less massive of the two particles was discovered simultaneously at the Brookhaven National Laboratory in experiments investigating a process that is the inverse of the reaction studied at SLAC. The Brookhaven experiments were performed by Samuel C. C. Ting and his colleagues from M.I.T. and Brookhaven; they studied the production of electron-positron pairs in collisions of hadrons. The detection of the particle by Ting's group was a technical tour de force: it is produced by their technique only once in 10^8 events.

Particle Storage Rings

Because hadrons are much more massive than electrons, hadrons can be created only in annihilations at high energy. In order to achieve the required collision energies it has been necessary to build machines known as particle storage rings. In these rings particles and antiparticles are made to circulate and then to collide head on [see "Particle Storage Rings," by Gerard K. O'Neill; Scientific American, November, 1966].

Ordinary particle accelerators can produce electrons or positrons of very high energy, but when such a particle strikes an electron in a stationary target, little of that energy is liberated in the collision. This effect is a consequence of the special theory of relativity, which states that when a particle acquires a large total energy, it also acquires a large total mass (according to the equation $E = mc^2$, where c is the speed of light in vacuum). Once an electron or a positron has been accelerated to about 1 GeV (billion electron volts) its velocity is within a few centimeters per second of the speed of light. Any additional energy imparted to it has negligible effect on its velocity and goes almost entirely toward increasing its mass. The two-mile linear accelerator at SLAC can produce positrons with an energy, or mass, of 15 GeV. The collision of such a particle with an electron at rest (which therefore has a mass of about .0005 GeV, 30,000 times smaller than the mass of the positron) is like the collision of a charging elephant with a mouse. The mouse may bounce back or it may be crushed, but in either case the elephant's kinetic energy will be little changed by the collision. In the case of the stationary electron and the 15-GeV positron only about .125 GeV would be made available to create new particles. That is less than 1 percent of the energy supplied to the accelerated particle, and it is too little to produce even a single pion, the least massive hadron.

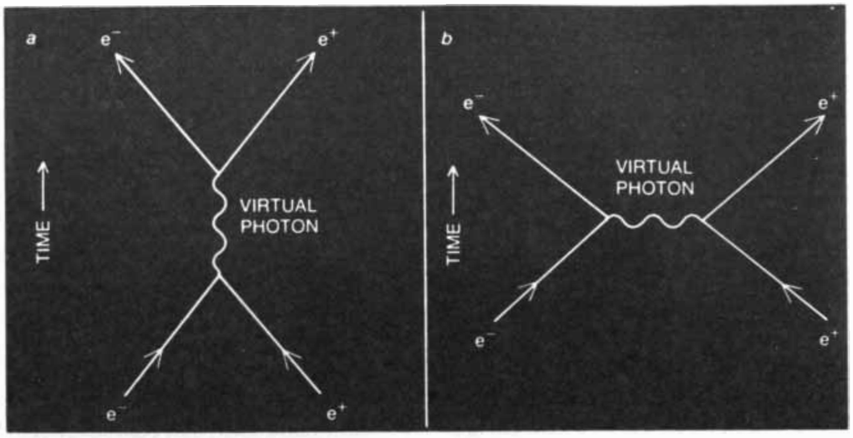
The result is quite different when an electron and a positron moving with equal velocity in opposite directions collide head on. In this case the sum of the momenta of the two particles is zero, and all their energy appears in the products of the annihilation. The collision is analogous to the head-on encounter of two charging elephants. In the storage-ring facility at SLAC, which is called SPEAR, electrons and positrons can be made to collide with energies of up to about 4 GeV each, for a total energy of 8 GeV, enough to generate a rich spectrum of hadrons. To produce such collision energies with stationary targets would call for a particle beam having an energy of 64,000 GeV; the accelerator required would be some 6,000 miles long.

The SPEAR storage ring was built under the direction of John R. Rees and Richter. In it "bunches" of electrons and positrons circulate in opposite directions in a single toroidal chamber about 250 feet in diameter. They are confined by a magnetic field, and their energy is maintained by the input of radio-frequency energy. The same magnetic field sustains both counterrotating bunches; because the particles are oppositely charged they react oppositely to it [*see top illustration on page 53*].

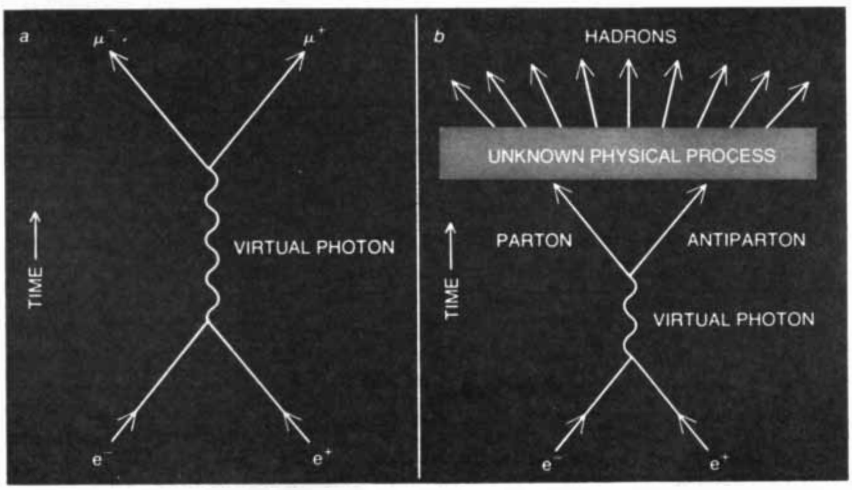
The beams collide at two regions on the perimeter of the ring, where detectors have been installed to record and analyze the products of interactions. The probability of even a single e^-e^+ annihilation in any one pass-through of the bunches is quite low, but because the particles' velocity is nearly that of light they pass through one another several hundred thousand times per second, so that an acceptable reaction rate is achieved. The beams of particles can be stored in the ring for minutes at a time.

Virtual Particles

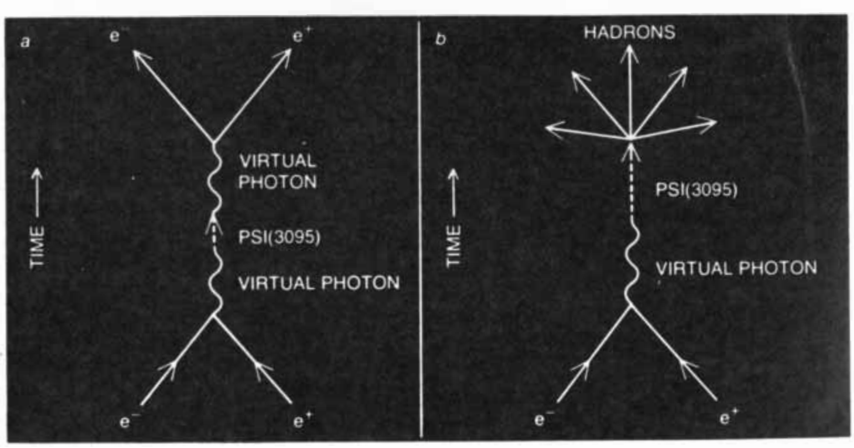
What happens when an electron and a positron meet and annihilate each other with a combined energy of a few billion electron volts? Because the particles



TWO INTERPRETATIONS are possible when the product of an encounter between an electron and a positron is another electron-positron pair. The initial pair may have annihilated (*a*), producing a virtual photon that materialized into an electron and a positron. Or the particles may have passed nearby and been scattered by the exchange of a photon (*b*).



MUONS AND HADRONS can be produced in electron-positron encounters only by the annihilation of the particles, not by scattering. The creation of muons (*a*) requires that the quantum number mu-ness be changed for each of the particles, although the total mu-ness of the pair remains zero. Hadrons are thought to be formed (*b*) through the creation of a parton and an antiparton (or a quark and an antiquark). The partons interact to form hadrons.



NEW PARTICLES, psi(3095) and psi(3684), materialize from the virtual photon when it has exactly the right energy (3.095 GeV and 3.684 GeV respectively). They can decay through a virtual photon into leptons (*a*), such as an electron and a positron, or into hadrons (*b*). The hadrons most commonly produced by psi particles are pions, the least massive of the hadrons.

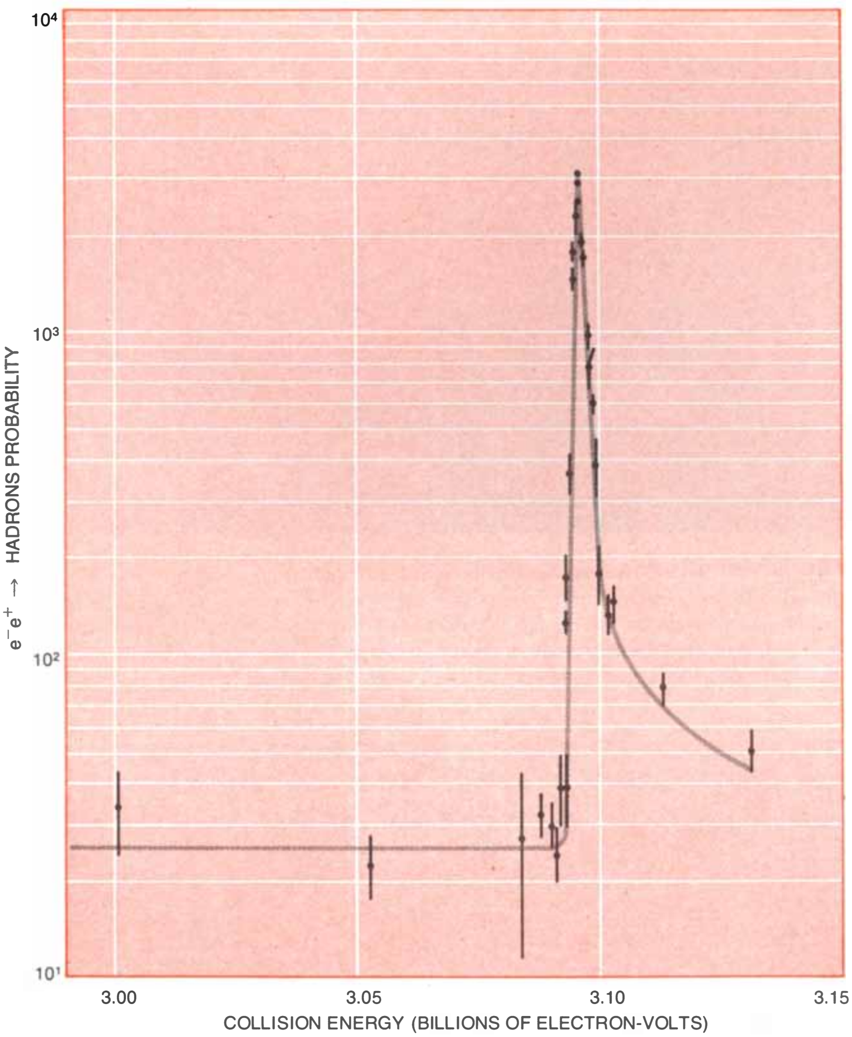
are leptons they do not feel the strong force, and at the energies studied so far the weak interactions are feeble enough to be neglected. The particles are electrically charged, however, so that they do feel the electromagnetic force, and the energy produced by their annihilation is (to a very good approximation) entirely electromagnetic. In other words, the electron and the positron annihilate each other, canceling their electric charges and lepton numbers, to produce a very energetic photon (a gamma ray).

The photon emitted is not, however, a "real" photon such as those that are observed in nature as the quanta of electromagnetic energy. It cannot be real because it has the wrong proportions of energy and momentum, quantities that must be conserved in all interactions. For the photon, which has no mass and which travels at the speed of light, the relation of momentum to energy is constant: the momentum is a fixed fraction of the energy, equal to the energy divided by c. This energy-momentum relation cannot be reconciled with the energy and momentum of the colliding particles. In the storage ring the electron and positron move with equal energy but opposite momentum, and the state formed by their annihilation must therefore have large energy but zero momentum. A photon cannot have that combination of properties.

One possible resolution of this dilemma is for the annihilation to produce two photons that have equal but opposite momenta, thereby satisfying the condition that the sum of the momenta of the products be zero. This reaction does in fact take place, and measurement of it is of major interest. Generally, however, the annihilation process generates as few photons as it possibly can. The probability that an electron or a positron will interact with or produce a single photon is measured by a dimensionless number called the fine-structure constant, equal to about 1/137. For each additional photon the probability is reduced by a higher power of the same factor.

The most likely outcome of the annihilation is therefore the creation of a single photon. As we have seen, however, it cannot be a real particle; it is called a virtual photon, and its most important characteristic is that it can never be observed; it can never emerge from the reaction as radiation. The virtual photon serves merely as a coupling between the initial electron-positron pair having zero total momentum and some subsequent ensemble of particles that must also have zero total momentum.

The virtual photon cannot be observed because it decays before it can be detected. According to the uncertainty principle formulated by Werner Heisenberg, the lifetime of a virtual particle is necessarily too brief for the particle to be observed. In the case of the recent electron-positron annihilation experiments the virtual photon materializes in less than 10^{-25} second into particles with the correct combination of energy and momentum.



RESONANCE detected in electron-positron annihilations at SPEAR signifies the presence of a new particle, psi(3095). It was discovered last November by a group of physicists under the direction of Burton Richter, William Chinowsky, Gerson Goldhaber, Martin L. Perl and George H. Trilling. The resonance represents a greatly increased probability of interaction between the colliding particles at the resonance energy. In this case the electrons and positrons are about 150 times as likely to annihilate each other and yield hadrons when their combined energy is 3.095 GeV as they are at adjacent, "background" energies. The psi(3095) resonance is exceptionally narrow, which indicates that the lifetime of the particle is long.

Particle Production

When the virtual photon decays, several kinds of particles can be created. At the energies investigated so far pairs of electrons and positrons, pairs of muons and antimuons, and hadrons have all been observed.

If the collision yields an electron-positron pair, the annihilation and rebirth of such a pair is phenomenologically indistinguishable from the mere elastic scattering of the incident electron and positron. In the first case the pair disappears in forming a virtual photon and then reappears; in the second the two particles are said to exchange a photon and are deflected, so that their direction is changed but the magnitudes of their energy and momentum are not [*see top illustration on preceding page*].

The creation of a muon-antimuon pair is not complicated by this ambiguity.

Because mu-ness must be conserved the pair can be created only through the annihilation of the electron and the positron. It is also necessary, of course, that the e^-e^+ pair have enough energy to account for the mass of the muons. These reactions are of great interest because they provide a method of testing the validity of present theories of electromagnetism at high energy. In addition there is enormous interest in studying the reactions that lead to the production of hadrons.

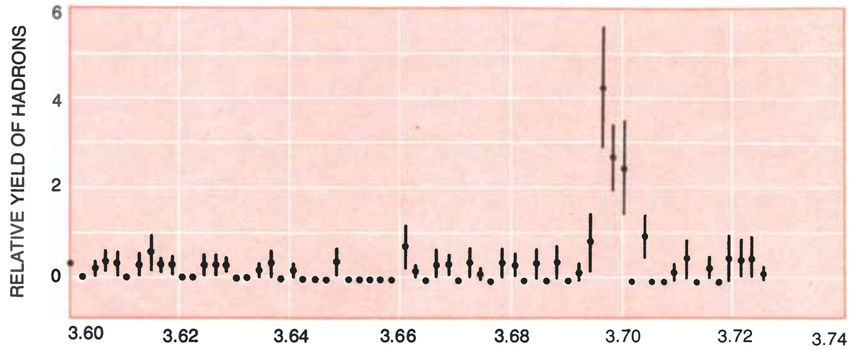
Processes that involve only leptons and photons can be described entirely in terms of the electromagnetic interaction. To predict hadron production, however, one must have a theory of the structure of hadrons; as yet there is no completely satisfactory theory. Most ideas of hadron structure that are under consideration today rely on the concept of partons or quarks as constituents of the hadron. They predict that at high energy a virtual photon can decay into a parton and an antiparton (or a quark and an antiquark). The parton-antiparton pair is then transformed by the strong interaction into hadrons that emerge in the aftermath of the collision.

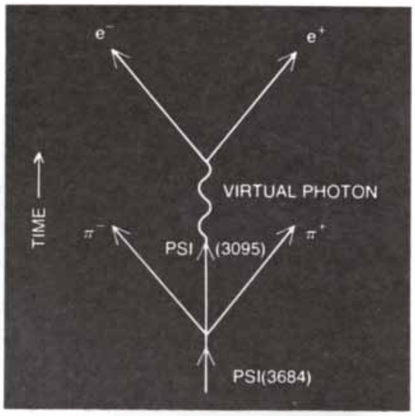
Even though partons and quarks have not been observed in isolation, many of their properties are described in detail by theory; they are *required* to have certain properties in order to explain the properties of the families of hadrons that have been observed. In addition the interpretation of the scattering experiments performed at SLAC (which originally led to the parton hypothesis) indicates that at high energy quarks or partons behave as independent, pointlike entities, just as the leptons do. For this reason it was expected that once the total energy of the colliding particles exceeded a threshold value, suggested by the scattering experiments to be about 2 GeV, the production of leptons and partons would obey similar rules. In particular it was predicted that above 2 GeV the probability of producing hadrons would vary with the collision energy in the same way that the probability of producing a pair of muons varies. This relation was expressed mathematically by stating that the ratio of hadrons to muon-antimuon pairs would be constant and independent of the collision energy. Before the experiments were performed there was argument over what the numercial value of this ratio would be, but there was little doubt that the ratio would in fact be constant at all energies within reach of experiment.

The disagreement arose because several versions of the quark theory predict different values for the hadron/muon ratio. In each case the value is calculated simply by adding the squares of the charges of all the quarks postulated by the model [*see lower illustration on page 62*]. The original formulation of the quark hypothesis, for example, predicts a value of 2/3. Three of the more prominent variations on the theory give values of 2, 10/3 and 4.

Initial measurements of the ratio were made in 1973 at Frascati in Italy and at the Cambridge Electron Accelerator in Cambridge, Mass.; they were soon followed by the first round of measurements with the SPEAR storage ring. To the surprise of most particle physicists, none of the predictions was confirmed; the experiments indicated that the hadron/muon ratio is not constant at all. At 2 GeV the value appeared to be about 2, and it increased gradually to about 5 at 5 GeV. In other words, collisions at 2 GeV were twice as likely to produce hadrons as to produce muon pairs, and at 5 GeV hadrons were about five times as likely. This disturbing development had not yet been accommodated by theory (and it still has not been) when the unexpected massive particles were encountered last November.

At the SPEAR storage ring the first of the new particles was discovered during a second round of measurements of the hadron/muon ratio made at many (and more closely spaced) values of the collision energy. The mass of the particle has now been determined accurately as being 3.095 GeV, and the particle has been named by the SPEAR group psi(3095). (The particle was given another name, *J*, at Brookhaven, but here I am adopting the SPEAR nomenclature.) A second, heavier particle was subsequently found at SPEAR, and it was designated psi(3684), to denote its mass of 3.684 GeV. The heavier particle can decay to form the lighter one, along with two pions. The Brookhaven workers have searched for the 3.684-GeV resonance, but they have found that it cannot be detected by their methods, a fact that may provide a clue to the properties of the particle.

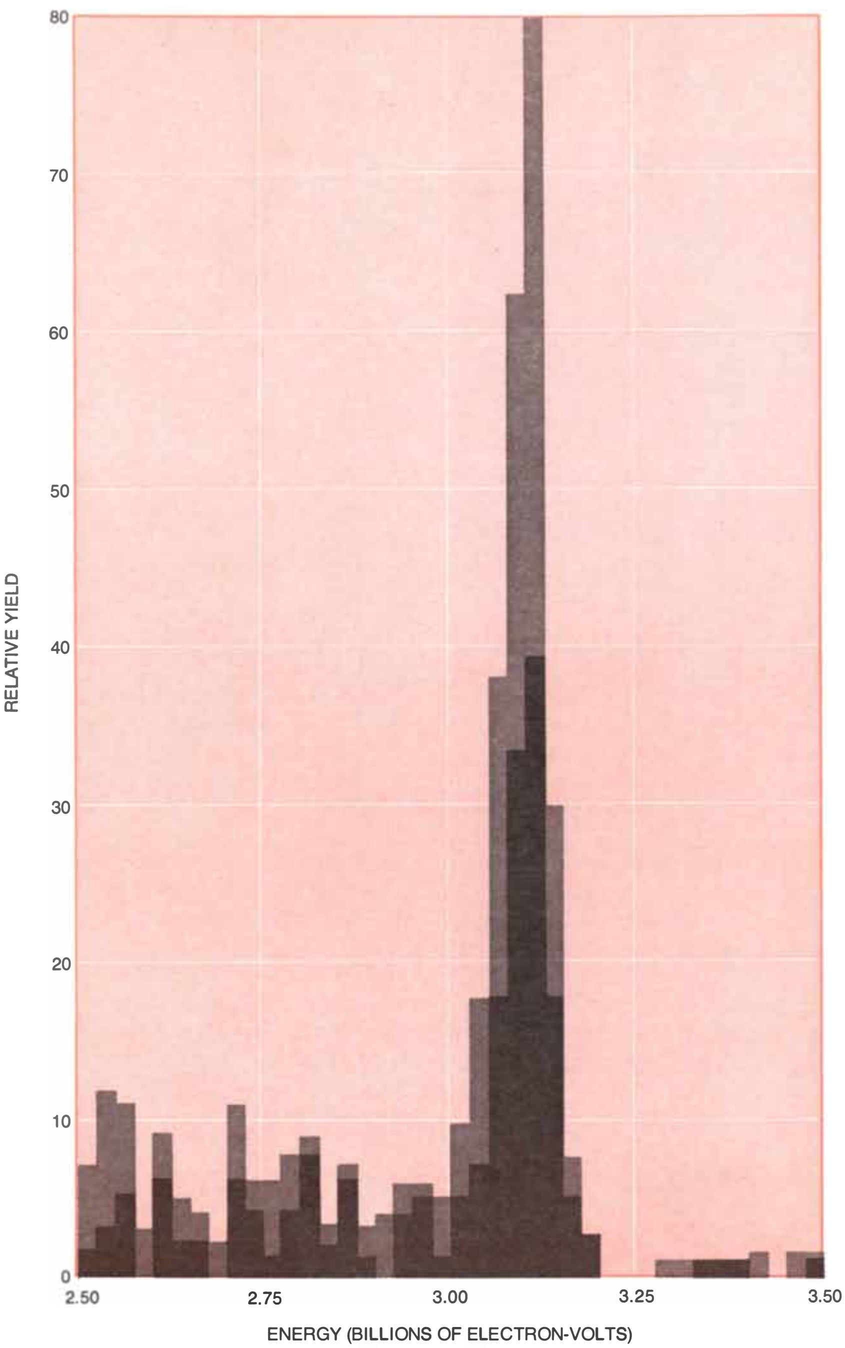




PSI(3684) RESONANCE is neither as tall nor as narrow as that of the psi(3095) particle. The graph (*above*) is at lower resolution than the one on the opposite page, that is, the yield of the electron-positron collisions was measured at fewer energies. The yield is expressed in relative numbers of hadrons produced at each energy. Psi(3684) decays spontaneously into psi(3095) with the emission of a pair of charged pions (*left*). Psi(3095) can then decay in turn, producing other particles, such as an electron-positron pair or hadrons. Because psi(3684) can produce psi(3095) by decay, it has been suggested that the more massive particle is an excited state of the less massive one.

The New Particles

The new particles are unstable, and like all other very massive and short-lived particles they are detected as "resonances," or enhancements of the probability of an interaction [see "Resonance Particles," by R. D. Hill; SCIENTIFIC AMERICAN, January, 1963]. As the energy of the colliding beams is increased in small steps a sudden peak in the production of particles is observed at the resonance energy; when the beam energy is increased further, the production drops off again. Such a pattern indicates that a particle exists with a mass equal to the combined masses of the colliding particles; when the colliding particles have exactly the required energy, they are more likely to interact than they are at other energies. In the case of psi(3095) the probability that the electron and the positron will interact was observed to increase by a factor of about 150 at the resonance energy compared with its value at adjacent energies.



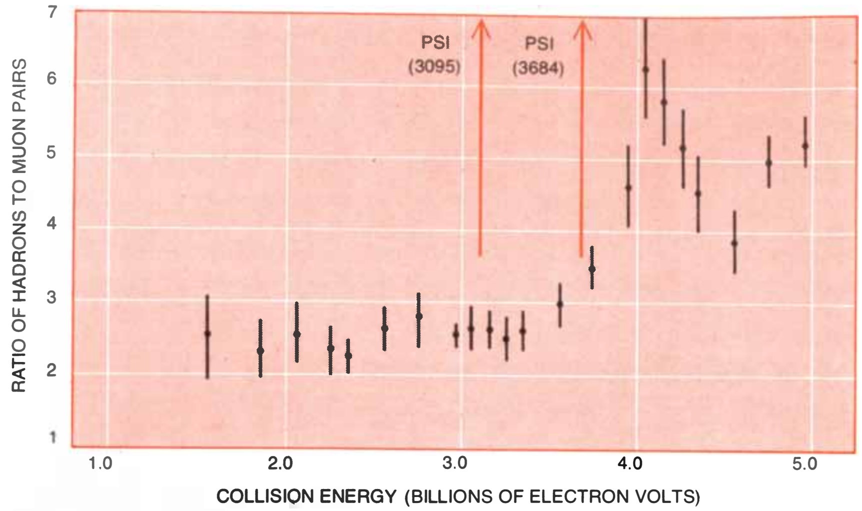
HADRON COLLISIONS also result in the production of one of the new particles. The resonance is detected as an increased probability of the production of electron-positron pairs in the collision of protons with beryllium nuclei; this process is the inverse of an electron-positron annihilation. The production of the new particle in hadron collisions was observed by a group of physicists, directed by Samuel C. C. Ting, working at the Brookhaven National Laboratory. They discovered it simultaneously with the SPEAR group and named it *J*. The psi(3684) particle has proved to be undetectable in the reaction studied at Brookhaven. The 3.095-GeV resonance is measured by the number of electron-positron pairs detected. Measurements at two calibrations of the detector are superposed (*gray and black*).

The height of the resonance peaks is related to their most remarkable feature—their narrowness. The width of a resonance represents the uncertainty in the determination of the energy at which the resonance occurs. This uncertainty in the energy is in turn related to the lifetime of the particle by Heisenberg's uncertainty principle. The equation that gives the lifetime is $\Delta E \Delta t = h/2\pi$, where ΔE is a measure of the uncertainty in the determination of the energy, Δt is a measure of the lifetime and h is Planck's constant (approximately 6.6×10^{-27}). Only for a stable particle—one that has an indefinitely long lifetime, as the proton apparently does—can the energy or mass be precisely defined. In that case Δt is large and ΔE is correspondingly small; the lifetime is unlimited and the resonance width is vanishingly small, so that the energy of the particle can be known with arbitrarily great precision.

The width of the psi(3095) resonance has been determined to be about 77 KeV (thousand electron volts), which represents a very sharp peak. Substituting this value in the equation above yields a lifetime of about 10^{-20} second. The psi(3684) resonance is somewhat broader, and that particle therefore decays faster, with a lifetime of about 10^{-21} second.

Although 10^{-20} second is an almost unimaginably brief interval, far too brief to be measured directly, it is 1,000 times longer than the expected lifetime of such a particle. All other heavy resonances are far broader (their width is typically measured in millions of electron volts rather than thousands), and the particles they represent decay in the characteristic time of the strong interaction: about 10^{-23} second. We are immediately compelled to ask what properties of psi(3095) hold it together so long. Does it exhibit a new kind of structure? Is there a previously unknown quantum number that nature wants to conserve but that must be changed when psi(3095) decays? Questions of this kind are among the most fundamental that can be asked in the physics of elementary particles.

Although the psi particles are themselves mystifying, their discovery has to some extent simplified, if not clarified, the earlier measurements of the hadron/muon ratio. It now appears that for energies between 2 GeV and 3.8 GeV the ratio is roughly constant at about 2.5; the only significant deviations are those associated with the two psi resonances. At higher energy the ratio increases, reaches a broad peak at about 4.1 GeV, then stabilizes at a value of about 5 [*see illustration at right*]. Recent experiments at SPEAR have confirmed that the hadron/muon ratio remains approximately constant up to 6 GeV. The causes of the observed peculiarities near 4.1 GeV are not yet understood. The broad peak may or may not represent an additional resonance or perhaps several resonances.



RATIO of hadrons to muon-antimuon pairs produced in electron-positron annihilations was predicted to be constant at collision energies above 2 GeV. The SPEAR experiments demonstrated that the ratio is roughly constant up to about 3.8 GeV if the effects introduced by the two psi particles are ignored. It rises to a peak at about 4.1 GeV, then declines again to a nearly constant value of approximately 5. Various versions of the quark model predict different constant values for the ratio, but none of them explains the observed fluctuations.

Quantum Electrodynamics

The interpretation of the puzzling events revealed by electron-positron collisions is made substantially easier by the fact that the initial state emerging from the annihilation—the virtual photon—is simple and well understood. Because it is formed in a purely electromagnetic process it is described by the theory of quantum electrodynamics, one of the most successful theories in physics.

Quantum electrodynamics is the theory constructed by imposing the laws of quantum mechanics on the classical theory of electromagnetism. It is a basic tenet of quantum electrodynamics that electrons, when they interact with electromagnetic radiation, act as point charges. This assumption, however, may be only an idealization that, although useful at large distances, fails to describe events at subnuclear dimensions.

Physicists are eager to test the theory of quantum electrodynamics at ever higher energy and with greater precision in order to probe it in finer detail. It is particularly important to know whether or not quantum electrodynamics is valid for the very-high-energy collisions studied at SPEAR, since the theory is central to the interpretation of hadron structure.

Quantum electrodynamics has been tested at distances ranging from more than 250,000 miles (in measurements of the earth's magnetic field) to subatomic dimensions much smaller than 10^{-8} centimeter (in describing the detailed spectrum of the hydrogen atom). The atomic measurements have been made so precisely that theory and experiment agree to roughly four parts in 10^9.

In interactions of electrons and positrons whose final products are either electron-positron pairs, muon-antimuon pairs or two or more real photons only the electromagnetic interaction makes a significant contribution. The entire process, therefore, should be comprehended by quantum electrodynamics and can be employed to test the theory. Another application of the uncertainty principle demonstrates that at the energies available with existing storage rings such events probe distances as small as 10^{-15} centimeter, or roughly 1 percent of the diameter of a hadron. Even at that small scale experiment has so far revealed no flaws in the theory.

The quantitative verification of quantum electrodynamics is the 20th-century parallel to the exciting voyage of Isaac Newton 300 years ago. The elegant simplicity of nature was first comprehended when Newton realized that the same law of gravity that governs the apple's fall to the ground also describes the motion of the planets, hundreds of millions of miles apart. We have now also learned that nature applies the same laws of electrodynamics both on a large scale, extending to about 80 earth radii, and in a realm less than a millionth the size of an atom. Quantum electrodynamics has been verified for distances encompassing more than 25 orders of magnitude.

If a colliding electron-positron pair can create a psi(3095) resonance, then of necessity the resonance particle, by the reverse process, must be able to decay into an electron-positron pair. (Indeed, that is how the particle was discovered by Ting and his colleagues at Brookhaven.) Psi(3095) decays in this way about 7 percent of the time, and muon pairs are produced in another 7 percent of the decay events. The remaining 86 percent of the time the resonance decays to yield hadrons. Since both muon pairs and electron pairs are created through purely electromagnetic forces, quantum electrodynamics should describe these processes, and it is possible to determine to what extent the two mechanisms interfere with each other.

In practice the interference is detected by measuring the ratio of muon pairs to electron pairs produced at energies near the psi(3095) resonance. Of particular importance is the observed decline in the ratio just below the peak energy of the psi(3095) resonance. On fundamental theoretical grounds such an "interference dip" is expected only when the electron-positron annihilation has two possible final states and the two states are, with regard to the electromagnetic interactions, interchangeable. In this instance the two final states can only be the photon and psi(3095), and the experiment has the important implication that psi(3095) has the same quantum numbers as the photon.

This discovery enables us to specify some of the characteristics of the new particles. For example, psi(3095), like the photon, must have a spin angular momentum of 1. Thus our detailed understanding of quantum electrodynamics provides us with information on the new particles.

Color and Charm

There is more to the psi particles, however, than their quantum numbers alone. In particular we want to know what kind of quarks they are made up of. For now all attempts to deduce their quark constitution must be considered speculations only, because experiment has not provided the evidence to discriminate conclusively among a welter of competing theories; nevertheless, two proposals that have been given considerable attention deserve discussion. Both were proposed to explain unrelated phenomena long before the psi particles were discovered.

Quarks, like the particles they compose, are assigned quantum numbers. All of them have spin angular momentum of 1/2, for example, and baryon number of 1/3. Of the original triplet of quarks proposed by Gell-Mann and Zweig, the *u* quark has a charge of 2/3 and the *d* and *s* quarks have a charge of −1/3. Antiquarks, of course, have the opposite quantum numbers. According to these assignments, the baryons, being made up of three quarks, must have a half-integral spin, a baryon number of +1 and a charge of +2, +1, 0 or −1. The mesons, as aggregates of a quark and an antiquark, must have an integral spin, a baryon number of 0 and a charge of +1, 0 or −1.

This ingenious scheme neatly accounted for all the particles and resonances that had been observed when it was proposed, and it soon proved its predictive power by postulating an unknown resonance that was promptly discovered. It contains a deeply disturbing peculiarity, however: the quarks are required to be particles with a half-integral spin but they do not behave as such particles are expected to.

All observed particles with a spin of 1/2 obey Wolfgang Pauli's exclusion principle, which demands that no two be in an identical state. The electrons of an atom, for example, always differ in at least one quantum number; if they have the same orbital configuration, they have opposite spin. Our understanding of atomic structure and of the periodic table of the elements is based on this concept. Particles with integral spin (such as the mesons and the photon) are not affected by the exclusion principle; arbitrarily large numbers of them can be assembled in the same state. (The half-integral-spin particles are said to obey Fermi-Dirac statistics, and they are called fermions; the integral-spin particles obey Bose-Einstein statistics and are called bosons.)

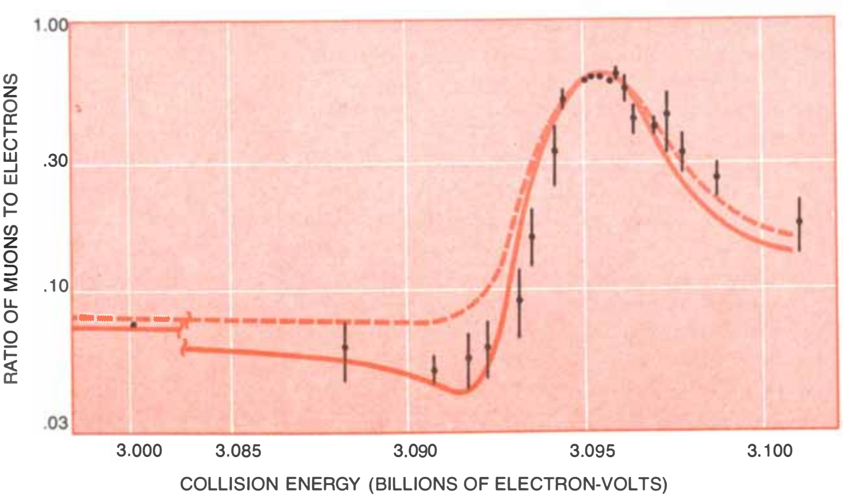
Quarks seem to violate these rules. They must have spin of 1/2, but on the other hand in constructing the baryons it is necessary to assume that two or more are bound together in the same state. The paradox threatens to do violence to some basic and cherished theoretical principles. It can be resolved, however, simply by insisting that quarks do obey the exclusion principle. All that is necessary to make them conform to the rule is to endow them with a new quantum number having three possible values, so that the quarks bound together in a baryon, although identical in all other properties, can differ in this new one. The new property, first suggested in 1964 by Oscar W. Greenberg of the University of Maryland, is called color, although it has nothing to do with vision or the color of objects in the macroscopic world; in this context color is merely a label for a property that expands the original ensemble of three quarks to nine. Each quark of the original triplet can appear in any of three colors—say red, yellow or blue.

An incidental feature of the color hypothesis is that the addition of six more quarks to the original three enables us to reformulate the quark theory with integral charges rather than fractional ones. A model of this kind was constructed by Moo-Young Han of Duke University and Yoichiro Nambu of the University of Chicago in 1965.

All versions of the color theory assume that in the known baryons the three colors of quarks are equally represented; as a result the particle exhibits no net color. Similarly, the mesons are made up of equal proportions of red, yellow and blue quark-antiquark pairs and are also colorless. Indeed, some physicists have speculated that in nature all particles may be colorless. One of a class of proposed interpretations of the psi particles suggests that they may be the first observed states of colored matter.

The second important theory that has been invoked to explain the psi particles is called the charm hypothesis. It was proposed by a number of theorists in 1964 simply for the sake of symmetry. (In particle physics that is not a trivial motive, since every symmetry has an associated conservation law.) In order to construct a parallel to the four known leptons, the theory adds to the three original quarks a fourth, designated *c* for charm. The *c* quark has a charge of 2/3, and it has +1 unit of the new quantum number charm; all the other quarks have zero charm.

In 1970 the new quark and its quantum number were given an important role in physics through the work of Sheldon L. Glashow, John Iliopoulos and Luciano Maiani of Harvard University. They invoked the charm quark in order to explain the suppression of certain particle decays that in the three-quark model should have proceeded normally.



INTERFERENCE between entirely electromagnetic events and events that involve the strong interaction is detected by measuring the ratio of muon pairs to electron pairs produced in annihilation experiments. The presence of interference is an indication that psi-(3095) has the same quantum numbers as the photon. If the quantum numbers are the same, theory predicts that the muon/electron ratio will be depressed at energies just below the resonance energy (*solid colored line*); if the numbers are different, there will be no interference (*broken colored line*). Experimental results (*black dots and bars*) show interference.

Significance of the Particles

If the *c* quark exists, of course, one would expect to observe charmed states of matter, such as a baryon made up of a *c* quark and two other quarks. No charmed particles have been observed, and hence it is believed that charmed quarks are much more massive than uncharmed ones. The psi particles are not believed to be charmed either, since they are produced electromagnetically and the electromagnetic interactions conserve charm, but it has been suggested that they could be mesons consisting of a *c* quark and an anti-*c*-quark. That combination would not exhibit charm, because the charm quantum numbers of the two quarks would cancel.

The first requirement of any theory of the new particles is that it explain their anomalously long lifetime. At the moment neither color nor charm seems to offer an entirely satisfactory explanation.

If psi(3095) and psi(3684) are considered to be colored particles, then it is assumed that they live long because there are no other particles of lower mass to which they can transfer their color when they decay. In the strong interactions color is conserved, so that a colored particle could not decay by the strong force. A particle might well be able to change color, however, in the electromagnetic interactions; the unit of color would be carried off by a photon, leaving decay products of colorless hadrons. As we have seen, the emission of a photon is suppressed by a factor of 1/137, and so the requirement that psi(3095) decay electromagnetically offers a partial explanation of its stability. The actual suppression of the decay involves a factor of about 1,000 instead of 137, but the discrepancy might be accounted for.

The hypothesis that the psi particles are colored is subject to experimental test by at least two methods. First, the gamma rays needed to carry off color in the electromagnetic decay should be detected among the decay products of the particles. Second, if the psi particles do represent colored particles, they cannot be the only ones; all versions of the color theory predict families of associated colored mesons, some of which would be electrically charged.

The charmed-quark theory is simpler and therefore more appealing, but it offers no compelling explanation for the psi lifetime. There is no known mechanism that would prevent a meson made of a charmed quark and antiquark from simply transforming itself into an ordinary quark and antiquark. In this process there are no quantum numbers to be conserved, since in the particle-antiparticle pair charm and all other properties cancel. The only apparent solution is to postulate a new law of nature, to declare arbitrarily that the decay of mesons made of a charmed quark and antiquark is inhibited by a factor of 1,000. There is precedent for such a rule in the theoretical treatment of other meson decays, but psi(3095) involves a larger inhibition factor. Moreover, it is a mystery why such rules should be required at all.

In spite of this weakness the charm hypothesis has attractive elements. The existence of resonances corresponding to a charmed quark and antiquark meson was predicted before the psi particles were discovered. The existence of the particle was discussed by Thomas W. Appelquist and H. David Politzer of Harvard, who named the hypothetical entity charmonium. They also suggested that it could be formed in electron-positron annihilations.

The charm hypothesis is also susceptible to experimental test. Theorists have already suggested mass regions where it might be profitable to look for excited states of charmonium. Psi(3684) could be one of those states, but there would have to be more. The transition between psi(3684) and psi(3095) with the emission of two pions conforms to theoretical expectations. The energy transitions between other states have also been calculated, and if they exist, it should be possible to detect them. Finally, particles incorporating just one charmed quark and therefore exhibiting charm should exist; the discovery of a charmed meson would provide strong evidence for the theory.

In experiments completed so far none of the phenomena that would confirm the color or charm hypotheses have been detected. Indeed, the failure to find this supporting evidence has become an embarrassment to both theories.

The new particles are not the only challenges to theory issuing from the recent discoveries. Some explanation is also required for the broad enhancement of hadron production in the vicinity of 4.1 GeV, and the questions raised by the odd behavior of the hadron/muon ratio throughout the energy range have not been resolved. The search for bumps and lines in the mass spectrum goes on not only at SPEAR but also at the DORIS storage ring at the German Electron Synchrotron in Hamburg and the ADONE storage ring at Frascati. Other investigators are studying the production of the psi particles through the interaction of photons and hadrons and through hadron-hadron collisions. (The last is the method employed by Ting and his colleagues at Brookhaven.)

In the experimental and theoretical investigations now under way many current concepts are being challenged; one, however, is not in question: that of quarks themselves. The discovery of the psi particles has confirmed again the central importance of quarks as the constituent particles of hadrons. Whether or not we shall ever see free quarks in the laboratory is another question; it is possible that they will always remain unobserved, exhibiting their physical reality only through their success in explaining the structure of hadrons and the forces that act on them.

Furthermore, we have no assurance that the quarks, whether there are three or nine or 12 or more of them, are the fundamental particles of matter. In the 20th century physics has probed the atom to discover the nucleus within, and has broken up the nucleus into its constituent particles. Those particles are now interpreted as being composites of more basic entities, the quarks. It is not unreasonable to imagine that we shall someday penetrate the quark and find an internal structure there as well. Only the experiments of the future can reveal whether quarks are the indivisible building blocks of all matter, the "atoms" of Democritus, or whether they too have a structure, as part of the endless series of seeds within seeds envisioned by Anaxagoras.

QUARK		CHARGE	BARYON NUMBER	CHARM	COLOR
u	u_r	+2/3	+1/3	0	RED
	u_y				YELLOW
	u_b				BLUE
d	d_r	−1/3	+1/3	0	RED
	d_y				YELLOW
	d_b				BLUE
s	s_r	−1/3	+1/3	0	RED
	s_y				YELLOW
	s_b				BLUE
c	c_r	+2/3	+1/3	+1	RED
	c_y				YELLOW
	c_b				BLUE

QUARK HYPOTHESIS states that hadrons are not elementary particles but composites of more fundamental entities called quarks. The original formulation of the theory, proposed independently by Murray Gell-Mann and George Zweig, postulated three quarks, *u*, *d* and *s*. Charge and baryon number (and other quantities not shown) are assigned to them according to the principle that baryons are made up of three quarks and mesons of a quark and an antiquark. Modifications of the theory add a fourth quark, *c*, which exhibits a property arbitrarily called charm, and propose that each quark exists in three states, distinguished by another property, called color. Thus there could be three, four, nine, 12 or more quarks.

MODEL OF HADRON STRUCTURE	PREDICTED VALUE OF HADRON-MUON PAIR RATIO
GELL-MANN-ZWEIG MODEL THREE QUARKS FRACTIONAL CHARGE	$(\frac{2}{3})^2 + (-\frac{1}{3})^2 + (-\frac{1}{3})^2 = \frac{2}{3}$
COLOR HYPOTHESIS THREE TRIPLETS OF QUARKS FRACTIONAL CHARGE	$3\left[(\frac{2}{3})^2 + (-\frac{1}{3})^2 + (-\frac{1}{3})^2\right] = 2$
COLOR HYPOTHESIS AND CHARM HYPOTHESIS THREE QUARTETS OF QUARKS FRACTIONAL CHARGE	$3\left[(\frac{2}{3})^2 + (-\frac{1}{3})^2 + (-\frac{1}{3})^2 + (\frac{2}{3})^2\right] = \frac{10}{3}$
HAN-NAMBU MODEL THREE QUARTETS OF QUARKS INTEGRAL CHARGE	$(1)^2 + (1)^2 + (-1)^2 + (-1)^2 = 4$

VARIANTS OF THE QUARK THEORY predict different values for the ratio of hadrons to muon pairs produced in electron-positron annihilations. In each case the predicted value is equal to the sum of the squares of the charges of the quarks included in the theory. The Gell-Mann–Zweig model gives a value of 2/3; the color hypothesis would increase the ratio to 2; assuming that both color and charm exist would yield a value of 10/3. The scheme devised by Moo-Young Han and Yoichiro Nambu eliminates the fractional charges common to other quark theories and predicts a value of 4 for the ratio. So far experimental findings at SPEAR and other laboratories cannot be reconciled with any of the predictions.

People all over the world talk the same language about the DC-10: "I like it."

Chicago...
"I like it."

Rome...
"Veramente fantastico."

Copenhagen...
"Den er skøn."

Frankfurt...
"Ein phantastisches Flugzeug."

Dakar...
"J'adore."

New York...
"I like it."

Tokyo...
好きですね

Paris...
"J'aime beaucoup."

Hong Kong...
我中意

Caracas...
"Me gusta."

If you've already enjoyed flying on a DC-10, you've shared a pleasant experience with millions of other people. Each day, more than 75,000 travelers fly a DC-10 to more than 120 cities in 67 countries. In many languages, they say they like the spacious, quiet comfort of the DC-10. So, ask your favorite airline or travel agent to book you aboard the DC-10.

DC-10 the choice of 34 airlines

MCDONNELL DOUGLAS

Now: Beautiful Bacteria, Stunni

Polaroid presents Polacolor 2. A new instant film that can literally saturate your pictures with color.

The next time you call a germ a beauty, the world will understand.

Polacolor 2 will be there to back you up.

It's a totally new 60-second color print film with brilliant dyes, high acutance, and precise separation of color.

Polacolor 2 gives you fiery reds, electric blues, and chlorine greens.

Maybe you like beauty, but you still need accuracy.

g Steroids and Dazzling Diodes.

The same development process hat makes color saturation deeper, gives Polacolor 2 prints clear, crisply-lefined images.

So subtle details, wherein many roofs and discoveries lie, won't fade nto the background.

Neither will your picture. The echnology we pioneered for our SX-70 film has produced a 3¼ x 4¼ nch print that is exceptionally fade-esistant.

Metallized dyes, coupled with a new color negative and positive sheet, make Polacolor 2 prints more stable than almost any other color prints.

So your instant photograph will still be true long after your streptococcus dies.

Polacolor 2 Land film can be used in any Polaroid Land camera, medium format camera or recording instrument that now uses our regular Type 108 film. Plus most 4 x 5 cameras and instruments using our Model 405 adapter.

We've given you beauty. And truth. We also give you convenience: New Polacolor 2 has an anti-curl base. So without a special mount, you'll have flat prints for your permanent records.

Even in the laboratory, a thing of beauty can be a joy—forever.

Polaroid Corporation