From the Psi to Charm: The Experiments of 1975 and 1976

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Exactly 25 months ago the announcement of the ψ/J particle by Professor Ting's and my groups (*1*, *2*) burst on the community of particle physicists. Nothing so strange and completely unexpected had happened in particle physics for many years. Ten days later my group found the second of the ψ's (*3*), and the sense of excitement in the community intensified. The long-awaited discovery of *anything* which would give a clue to the proper direction in which to move in understanding the elementary particles loosed a flood of theoretical papers that washed over the journals in the next year.

The experiments that my colleagues and I carried through in the 2 years after the discovery of the ψ have, I believe, selected from all the competing explanations the one that is probably correct. It is these experiments that I wish to describe. The rapid progress is a consequence of the power of the electron-positron colliding-beam technique, and so I also want to describe this technique and tell something of my involvement in it.

Colliding Beams

I completed my graduate studies at the Massachusetts Institute of Technology in 1956, and in the fall of that year I took a position at the High-Energy Physics Laboratory (HEPL) at Stanford University. My main research interest at that time was in exploring the high-momentum-transfer or short-distance behavior of quantum electrodynamics (QED). My original plan for a QED experiment had been to use the 700-Mev electron linac at HEPL in a study of electron-electron scattering. Within a short time, however, I came to realize that a different experiment would be technically simpler to carry out and would also probe QED more deeply (although somewhat differently). During my first year at HEPL I did this latter experiment, which involved the photoproduction of electron-positron pairs in which one of the members of the pair emerged at a large angle. This experiment succeeded in establishing the validity of QED down to distances of about 10^{-13} centimeter.

The Stanford-Princeton electron-electron storage rings. In 1957 the idea of an electron-electron scattering experiment came alive again, although in a much different form. This happened when G. K. O'Neill of Princeton University informally proposed the construction at HEPL of a figure 8–shaped set of rings capable of storing counterrotating beams of electrons at energies up to 500 Mev for each beam. In this plan the HEPL linac was to act as the injector for the rings, and the circulating electron beams would collide in the common straight section between the two rings. O'Neill's aim was not only to demonstrate the feasibility of colliding electron beams, but also to carry out electron-electron scattering at an energy that could significantly extend the range of validity of QED.

The potential of such an e^-e^- colliding-beam experiment, with its total center-of-mass energy of 1000 Mev, was much greater than the ~ 50 Mev that would have been available to test QED in my original e^-e^- scattering idea. Thus when O'Neill asked me to join in this work, I accepted enthusiastically and became an accelerator builder as well as an experimenter. With two other collaborators, W. C. Barber and B. Gittelman, we set out in 1958 to build the first large storage ring, and we hoped to have our first experimental results in perhaps 3 years. These results were not in fact forthcoming until 7 years later, for there was much to learn about the behavior of beams in storage rings; but what we learned during that long and often frustrating time opened up a new field of particle physics research (*4*).

A moment of realization. Let me digress here for a moment to recount a formative experience. In 1959, as the work on the HEPL rings progressed, I was also trying to learn something about how to calculate cross sections in QED under the tutelage of Stanford theorist J. D. Bjorken. One of the problems Bjorken gave me was to calculate the cross section for the projection of a pair of pointlike particles having zero spin (bosons) in electron-positron annihilation. I carried out this calculation, but I was troubled by the fact that no pointlike bosons were known to exist. The only spin zero bosons I knew about were pions, and the strong interactions to which these particles were subject gave them a finite size. I realized that the structure function of the particle would have to enter into the cross section to account for this finite size. The structure function for the pion could be measured in an experiment in which e^+e^- annihilation resulted in the production of pion pairs. Further, the structures of any of the family of strongly interacting particles (hadrons) could be determined by measuring their production cross sections in e^+e^- annihilation. It is certain that many people had realized all this before, but it came as a revelation to me at that time, and it headed me firmly on the course that eventually led to this platform.

The electron-positron annihilation process. This connection between e^+e^- annihilation and hadrons is worth a brief elaboration here, since it is central to the experimental results I shall describe later. The method by which new particles are created in electron-positron collisions is a particularly simple one that I have always naively pictured in the following way. The unique annihilation process can occur only in the collision between a particle and its antiparticle. The process proceeds in two steps:

1) The particle and antiparticle coalesce, and all the attributes that give them their identities cancel. For a brief instant there is created a tiny electromagnetic fireball of enormous energy density and precisely defined quantum numbers $J^{PC} = 1^{--}$; all others cancel out to zero.

2) The energy within the fireball then rematerializes into *any* combination of newly created particles that satisfies two criteria: (i) the total mass of the created particles is less than or equal to the total energy of the fireball; and (ii) the overall

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quantum numbers of the created particles are the same as those of the fireball. There is no restriction on the individual particles that comprise the final state, only on their sum.

The formation of the fireball or virtual-photon intermediate state in e^+e^- annihilation is described in QED, a theory whose predictions have so far been confirmed by every experimental test. Since we therefore understand step 1, the creation of the fireball, we are in a sense using the known e^+e^- annihilation process to probe the unknown hadrons that are produced in step 2 of the process. Our ignorance is thus limited to the structure of the final-state hadrons and to the final-state interactions that occur when particles are created close together. And while that is a great deal of ignorance, it is much less than that of any other particle-production process. In addition, the quantum numbers of the final state in e^+e^- annihilation are simple enough so that we can hope to calculate them from our theoretical models. This is in sharp contrast, for example, to high-energy hadron-hadron collisions, in which very many different angular momentum states may be involved and thus must be calculated.

The SPEAR electron-positron storage ring. In 1961, while work on the e^-e^- rings at HEPL continued, I began with D. Ritson of Stanford some preliminary design on a larger e^+e^- storage ring. In 1963 I moved from HEPL to the Stanford Linear Accelerator Center (SLAC), and set up a small group to carry out the final design of the e^+e^- ring. The design energy chosen was 3 Gev (each beam). A preliminary proposal for this colliding-beam machine was completed in 1964, and in 1965 a full, formal proposal was submitted to the U.S. Atomic Energy Commission (now the Energy Research and Development Administration).

There followed a period of about 5 years before any funding for this proposed project could be obtained. During this time, other groups became convinced of the research potential of the e^+e^- colliding-beam technique, and several other projects began construction. We watched this other activity enviously, worked at refining our own design, and tried to appropriate any good ideas the others had come up with. Finally, in 1970, funds were made available for a reduced version of our project, now called SPEAR, and we all fell to and managed to get it built in record time—some 21 months from the start of construction to the first beam collisions (5).

The SPEAR storage ring is located in a part of the large experimental area at the end of the 3-kilometer-long SLAC linac. The facility is shown schematically in Fig. 1. Short pulses of positrons, then electrons, are injected from the SLAC accelerator through alternate legs of the Y-shaped magnetic injection channel into the SPEAR ring. The stored beams actually consist of only a single short bunch of each kind of particle, and the bunches collide only at the midpoints of the two straight interaction areas on opposite sides of the machine. Special focusing magnets are used to give the beams a small cross-sectional area at these two interaction points. The time required to fill the ring with electrons and positrons is typically 15 to 30 minutes, while the data-taking periods between

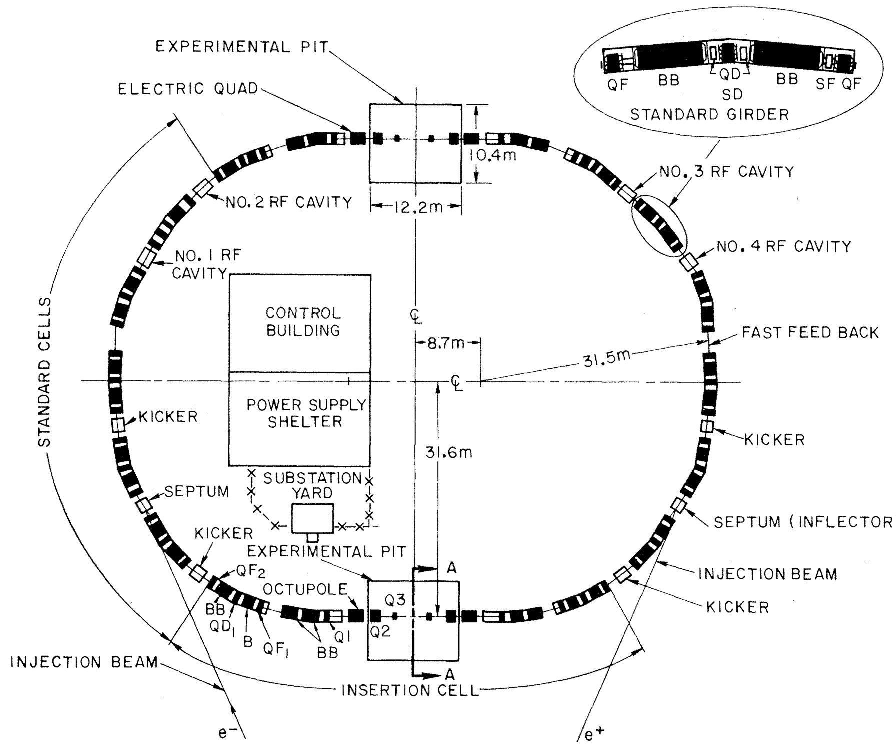


Fig. 1. Schematic of the SPEAR storage ring.

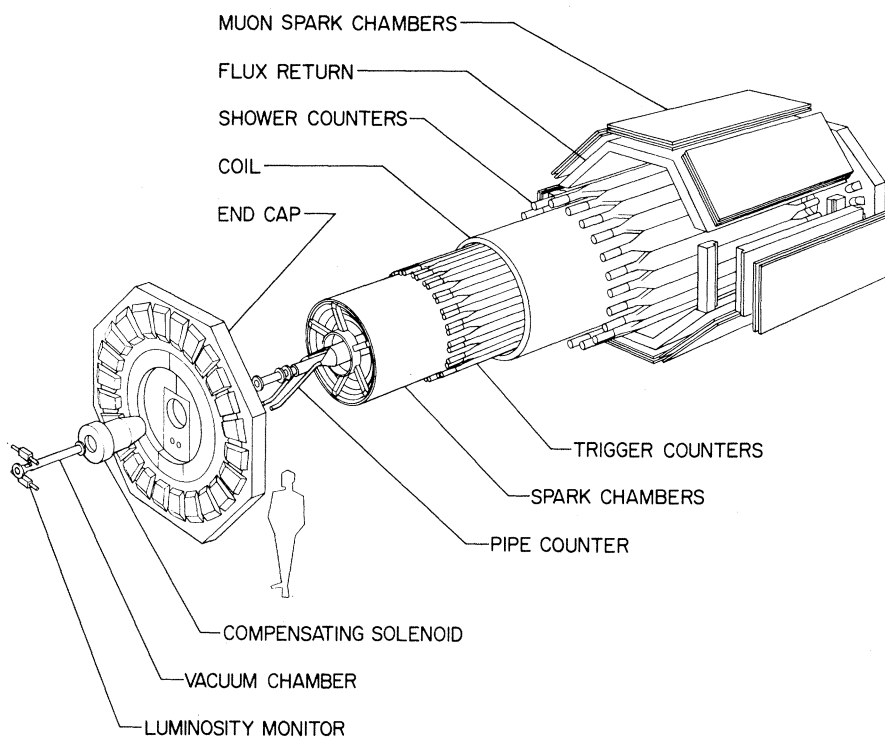


Fig. 2. An exploded view of the SLAC-LBL magnetic detector.

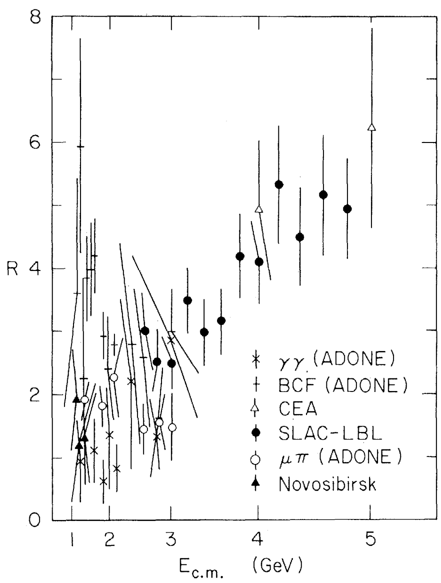


Fig. 3. The ratio R as of July 1974.

successive fillings are about 2 hours. To achieve this long lifetime, it is necessary to hold a pressure of about 5×10^{-9} torr in the vacuum chamber. The center-of-mass (CM) energy of the colliding e^+e^- system can be varied from 2.6 to 8 Gev. The radio-frequency power required to compensate for synchrotron radiation losses rises to 300 kilowatts at the maximum operating energy. The volume within which the e^+e^- collisions occur is small and well defined ($\sigma_x \times \sigma_y \times \sigma_z \simeq 0.1 \times 0.01 \times 5$ cm^3), which is a great convenience for detection.

The Mark I magnetic detector. While SPEAR was being designed, we were also thinking about the kind of experimental apparatus that would be needed to carry out the physics. In the 1965 SPEAR proposal, we had described two different kinds of detectors: the first, a nonmagnetic detector that would have looked only at particle multiplicities and angular distributions, with some rather crude particle-identification capability; the second, a magnetic detector that could add accurate momentum measurement to these other capabilities. When the early results in 1969 from the ADONE storage ring at Frascati, Italy, indicated that hadrons were being produced more copiously than expected, I decided that it would be very important to learn more about the final states than could be done with the nonmagnetic detector.

Confronted thus with the enlarged task of building not only the SPEAR facility itself but also a large and complex magnetic detector, I began to face up to the fact that my group at SLAC had bitten off more than it could reasonably chew, and began to search out possible collaborators. We were soon joined by the groups of M. Perl of SLAC and W. Chinowsky, G. Goldhaber, and G. Trilling of the University of California's Lawrence Berkeley Laboratory (LBL). This added manpower included physicists, graduate students, engineers, programmers, and technicians. My group was responsible for the construction of SPEAR and for the inner core of the magnetic detector, while our collaborators built much of the particle-identification apparatus and also did most of the programming work that was necessary to find tracks and reconstruct events.

This collaborative effort resulted in the Mark I magnetic detector, shown schematically in Fig. 2. The Mark I magnet produces a solenoidal field, coaxial with the beams, of about 4 kilogauss throughout a field volume of about 20 cubic meters. Particles moving radially outward from the beam-interaction point pass successively through the following elements: the beam vacuum pipe, a trigger counter, 16 concentric cylinders of magnetostrictive wire spark chambers that provide track information for momentum measurements, a cylindrical array of 48 scintillators that act as both trigger and time-of-flight counters, the one-radiation-length-thick aluminum magnet coil, a cylindrical array of 24 lead-scintillator shower counters that provide electron identification, the 20-cm-thick iron flux-return plates of the magnet, and finally an additional array of plane spark chambers used to separate muons from hadrons.

The Mark I magnetic detector was ready to begin taking data in February 1973. During the fall of 1977 it will be replaced at SPEAR by a generally similar device, the Mark II, that will incorporate a number of important improvements. During its career, however, the Mark I has produced a remarkable amount of spectacular physics (*6*).

Early Experimental Results

I would like to set the stage for the description of the journey from the ψ's to charm by briefly reviewing here the situation that existed just before the discovery of the new particles. The main international conference in high-energy physics during 1974 was held in July in London. I presented a talk at the London Conference (*7*) in which I tried to summarize what had been learned up until that time about the production of hadrons in e^+e^- annihilation. This information, shown in Fig. 3, will require a little bit of explanation.

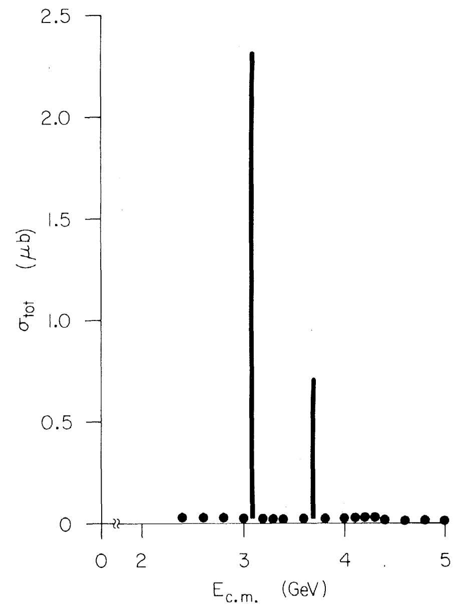


Fig. 4. Total cross section of hadron production plotted against center-of-mass energy.

The hadron/muon-pair ratio. Measurements of the process $e^+e^- \rightarrow$ hadrons can be presented straightforwardly in a graph which plots the hadron-production cross section against the CM energy of the colliding e^+e^- system. For reasons that I shall explain later, it has become common practice to replace the hadron-production cross section in such graphs by the following ratio

$$R = \frac{\text{cross section for } e^+e^- \rightarrow \text{hadrons}}{\text{cross section for } e^+e^- \rightarrow \mu^+\mu^-} \quad (1)$$

It is that ratio R that is plotted against CM energy in Fig. 3. Historically, the earliest measurements of R were made at the ADONE ring at Frascati; these occupy the lower-energy region of the graph, and they indicate values of R ranging from less than 1 to about 6. These were followed by two important measurements of R made at the storage ring that had been created by rebuilding the Cambridge Electron Accelerator (CEA) at Harvard; the CEA measurements gave an R value of about 5 at an E_{CM} of 4 Gev, and $R = 6$ at 5 Gev. The early experimental results from the SLAC-LBL experiment at SPEAR filled in some of the gap between the ADONE and CEA results and between the two CEA points in a consistent manner; that is, the SPEAR data appear to join smoothly onto both the lower- and higher-energy data from ADONE and from CEA. With the exception of the experimental points at the very lowest energies, the general picture conveyed by Fig. 3 is that the value of R seems to rise smoothly from perhaps 2 to 6 as E_{CM} increases from about 2 to 5 Gev.

The theoretical predictions. During the same London Conference in 1974, J. Ellis of CERN (*8*) undertook the complementary task of summarizing the process $e^+e^- \rightarrow$ hadrons from a theoretical point of view. Once again, the predictions of many different theories could most conveniently be expressed in terms of the hadron/muon-pair ratio R rather than directly as hadron-production cross sections. The most widely accepted theory of the hadrons at that time gave the prediction that $R = 2$, but there were many theories. Let me illustrate this by reproducing here, as Table 1, the compilation of R predictions that Ellis included in his London talk. As this table shows, these predictions of the hadron/muon-pair ratio ranged upward from 0.36 to ∞, with many a stop along the way.

I included this table to emphasize the situation that prevailed in the summer of 1974—vast confusion. The cause of the confusion lay in the paucity of e^+e^- data and the lack of experimental clues to the proper direction from elsewhere in particle physics. The clue lay just around the next corner, but that corner itself appeared as a totally unexpected turn in the road.

The Psi Particles

Widths of the psi resonances. Figure 4 shows the cross section for hadron production at SPEAR on a scale where all of the data can be plotted on a single graph. This figure is clearly dominated by the giant resonance peaks of the ψ and the ψ'. The extreme narrowness of the peaks implies that these two states are very long-lived, which is the principal reason why they could not be accounted for by the previously successful model of hadronic structure. In Fig. 5 we show the ψ and ψ' peaks on a greatly expanded energy scale, and also as they are measured for three different decay modes: $\psi, \psi' \rightarrow$ hadrons; $\psi, \psi' \rightarrow \mu^+\mu^-$; and $\psi, \psi' \rightarrow e^+e^-$. In this figure the ψ and ψ' peaks can be seen to have experimental widths of about 2 and 3 Mev, respectively. These observed widths are just about what would be expected from the intrinsic spread in energies that exists within the positron and electron beams *alone*, which means that the true widths of the two states must be very much narrower. The true widths can be determined accurately from the areas that are included under the peaks in Fig. 5 and are given by the following expression

$$\int \sigma_i \, dE = \frac{6\pi^2}{M^2} B_e B_i \Gamma \qquad (2)$$

where σ_i is the cross section to produce final state i, B_i is the branching fraction to that state, B_e is the branching fraction to e^+e^-, M is the mass of the state, and Γ is its total width. The analysis is somewhat complicated by radiative corrections but can be done, with the result that (*9*)

$$\Gamma_{\psi'} = 69 \pm 13 \text{ kev}$$
$$\Gamma_{\psi'} = 225 \pm 56 \text{ kev} \qquad (3)$$

The widths that would be expected if the psi particles were conventional hadrons are about 20 percent of their masses. Thus the new states are several thousand times narrower than those expected on the basis of the conventional model.

Psi quantum numbers. The quantum numbers of the new psi states were expected to be $J^{PC} = 1^{--}$ because of their direct production in e^+e^- annihilation and also because of the equal decay rates

Table 1. Values of R from the talk by J. Ellis at the 1974 London Conference (*8*). (The references are from Ellis's talk.)

Value	Model	Reference
0.36	Bethe-Salpeter bound quarks	Bohm *et al.*, ref. 42
2/3	Gell-Mann and Zweig quarks	
0.69	Generalized vector meson dominance	Renard, ref. 49
~1	Composite quarks	Raitio, ref. 43
10/9	Gell-Mann and Zweig with charm	Glashow *et al.*, ref. 31
2	Colored quarks	
2.5 to 3	Generalized vector meson dominance	Greco, ref. 30
2 to 5	Generalized vector meson dominance	Sakurai and Gounaris, ref. 47
3⅓	Colored charmed quarks	Glashow *et al.*, ref. 31
4	Han-Nambu quarks	Han and Nambu, ref. 32
5.7 ± 0.9	Trace anomaly and ρ dominance	Terazawa, ref. 27
$5.8^{+3.2}_{-3.5}$	Trace anomaly and ϵ dominance	Orito *et al.*, ref. 25
6	Han-Nambu with charm	Han and Nambu, ref. 32
6.69 to 7.77	Broken scale invariance	Choudhury, ref. 18
8	Tati quarks	Han and Nambu, ref. 32
8 ± 2	Trace anomaly and ϵ dominance	Eliezer, ref. 26
9	Gravitational cutoff, universality	Parisi, ref. 40
9	Broken scale invariance	Nachtmann, ref. 39
16	$SU_{12} \times SU_{12}$ } gauge models	Fritzsch and Minkowski, ref. 34
35⅓	$SU_{16} \times SU_{16}$ } gauge models	
~5,000	High-Z quarks	Yock, ref. 73
70,383	Schwinger's quarks	
∞	∞ of partons	Cabibbo and Karl, ref. 9 Matveev and Tolkachev, ref. 35 Rozenblit, ref. 36

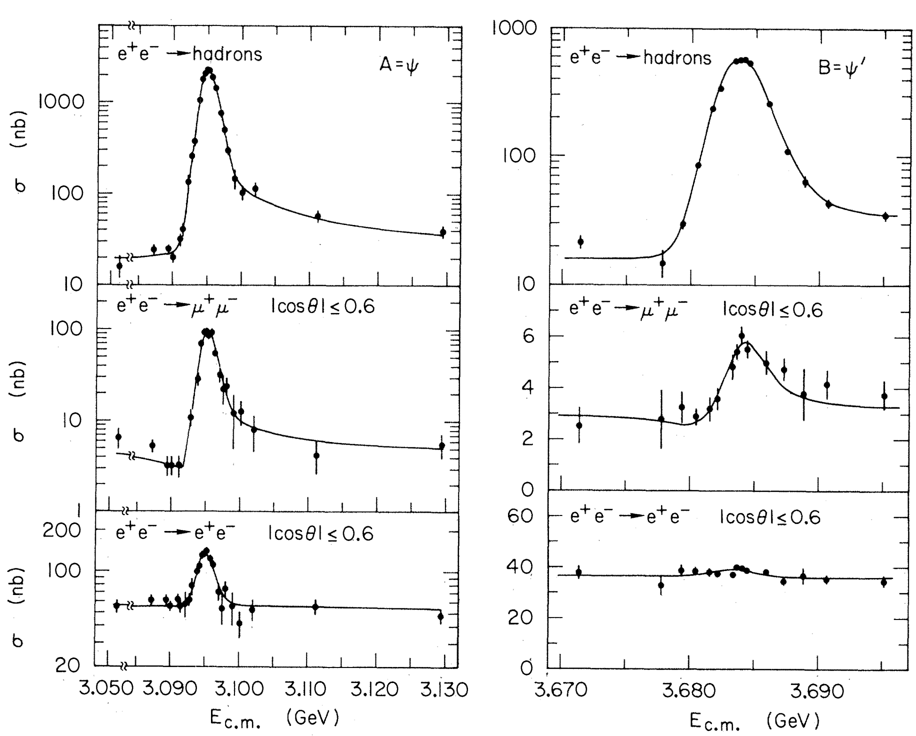


Fig. 5. Hadron, $\mu^+\mu^-$, and e^+e^-e pair production cross section in the regions of the ψ and ψ'. The curves are fits to the data using the energy spread in the colliding beams as the determinants of the widths.

to e^+e^- and $\mu^+\mu^-$. In so new a phenomenon, however, anything can go, and so that assumption needed to be confirmed. In particular, one of the tentative explanations of the psi particles was that they might be related to the hypothetical intermediate vector boson, a particle that had long been posited as the carrier of the weak force. Such an identification would permit the psi's to be a mixture of $J^{PC} = 1^{--}$ and 1^{+-}. These quantum numbers can be studied by looking for an interference effect between on- and off-peak production of muon pairs, since the latter is known to be pure 1^{--}. If the new particles were also 1^{--}, then an interference should occur and produce two recognizable effects: a small dip in the cross section below the peak, and an apparent shift in the position of the peak relative to that observed in the hadron channels. In addition, any admixture of 1^{+-} could be expected to show up as a forward/backward asymmetry in the observed angular distribution.

This analysis was carried out as soon as there were sufficient data available for the purpose. The postulated interference effect was in fact observed, as shown in Fig. 6, while no angular asymmetry was seen (*8, 9*). Thus both of the psi states were firmly established as $J^{PC} = 1^{--}$.

Psi decay modes. We also studied the many decay modes of the ψ and ψ'. In these studies it was important to distinguish between direct and "second-order" decay processes, a point that is illustrated in Fig. 7. This figure shows the following processes.

1) $e^+e^- \rightarrow \gamma \rightarrow \psi \rightarrow$ hadrons (direct decay)

$$\left.\begin{array}{l} 2)\ e^+e^- \rightarrow \gamma \rightarrow \psi \rightarrow \gamma \rightarrow \text{hadrons} \\ 3)\ e^+e^- \rightarrow \gamma \rightarrow \psi \rightarrow \gamma \rightarrow \mu^+\mu^- \end{array}\right\} \quad (4)$$

(second-order electromagnetic decay)

In processes 2 and 3, hadrons and muon pairs are produced by virtual photons in exactly the same way that they are produced at off-resonance energies. If the observed hadrons were produced *only* through second-order electromagnetic decay, then the hadron/muon-pair production ratio, R, would be the same on resonance as off. This is decidedly not the case. Since R is much larger on resonance than off, both ψ and ψ' do have direct hadronic decays.

More branching fractions for specific hadronic channels have been measured for the ψ and ψ' than for any other particles. Most of these are of interest only to the specialist, but a few have told us a good deal about the psi particles. Since the second-order electromagnetic decays

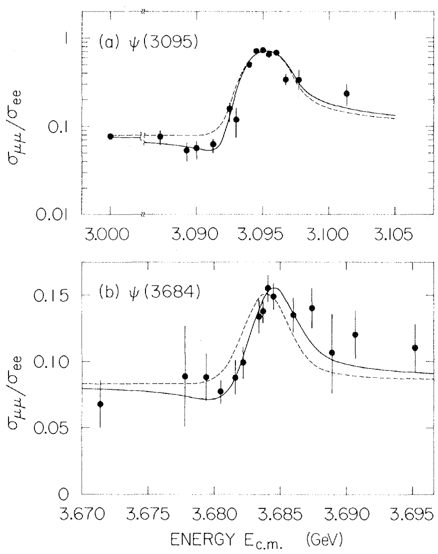


Fig. 6. The $\mu^+\mu^-$ cross sections at the ψ and the ψ'. The solid curves show the results expected if both states are $J^{PC} = 1^{--}$ and hence interfere with the nonresonant $\mu^+\mu^-$ production. The dashed curves assume no interference.

also complicate these analyses, we must again make on- and off-resonance comparisons between muon-pair production and the production of specific hadronic final states. In Fig. 8 we show such a comparison plotted against the number of pions observed in the final state (*10*). Even numbers of pions observed are consistent with what is expected from second-order electromagnetic decays, while the observed odd-pion decays are much enhanced. The ψ decays appear, from these data, to be governed by a certain selection rule (G-parity conservation) that is known to govern only the behavior of hadrons, thus indicating that the ψ itself is a hadron.

There are certain specific decay modes that, if observed, provide definite evidence on the isospin of the psi particles. Such modes are

$$\psi \text{ or } \psi' \rightarrow \pi^+\pi^-\pi^0,\ \Lambda\bar{\Lambda},\ p\bar{p} \qquad (5)$$

Each of these decay modes has, in fact, been seen, thus establishing $I^GJ^{PC} = 0^-1^{--}$ for both particles.

Search for other narrow resonances. By operating the SPEAR storage ring in a "scanning" mode, we have been able to carry out a systematic search for any other very narrow, psi-like resonances that may exist. In this scanning mode, the ring is filled and set to the initial energy for the scan; data are taken for a minute or two, the ring energy is increased by about 1 Mev, data are taken again, and so forth. Figure 9 shows these scan data from CM energies of about 3.2 to 8 Gev (*11, 12*). No statistically significant peaks (other than the ψ' that was found in our first scan) were observed in this search, but this needs two qualifications. The first is that the sensitivity of the search extends down to a limit on possible resonances that have a cross section × width of about 5 to 10 percent of that of the ψ. The second qualification is that the particular method of search is sensitive only to extremely narrow resonances like the ψ and ψ'; other, much broader resonances have been found at SPEAR, and we shall soon see how these apparently much different states fit into the picture.

The Intermediate States

Radiative transitions. There are other new states, related to the ψ and ψ' but not directly produced in e^+e^- annihilation, which are observed among the decay products of the two psi particles. More specifically, these new states are produced when either ψ or ψ' decays through the emission of a gamma ray

$$\psi \text{ or } \psi' \rightarrow \gamma + \text{intermediate state} \qquad (6)$$

At least four (perhaps five) distinct intermediate states produced in this way have been observed experimentally.

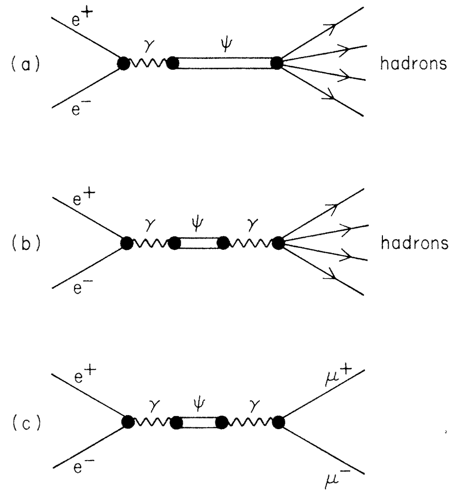
The first such observation was made by an international collaboration working at the DORIS e^+e^- storage ring at the DESY laboratory in Hamburg (*13*). This state was named P_c, and its mass was found to be about 3500 Mev. This same group (*14*) in collaboration with another group working at DESY later found some evidence for another possible state, which they called X, at about 2800 Mev (*15*). At SPEAR, the SLAC-LBL group has identified states with masses of about 3415, 3450, and 3550 Mev, and has also confirmed the existence of the DESY 3500-Mev state. We have used the name χ to distinguish the state intermediate in mass between the ψ(3095) and the ψ'(3684). To summarize these new states

$$\begin{array}{ll} \psi'(3684) \rightarrow \gamma + \chi(3550) & \\ \psi'(3684) \rightarrow \gamma + \chi(3500) \text{ or } P_c & \\ \psi'(3684) \rightarrow \gamma + \chi(3455) & (7) \\ \psi'(3684) \rightarrow \gamma + \chi(3415) & \\ \psi\,(3095) \rightarrow \gamma + X(2800) \text{ (not yet firmly established)} & \end{array}$$

Three methods of search. The three methods we have used at SPEAR to search for these intermediate states are indicated schematically in Fig. 10. To begin with, the storage ring is operated at the center-of-mass energy of 3684 Mev that is required for resonant production of the ψ'. In the first search method, Fig. 10a, ψ' decays to the intermediate state and then decays to the ψ through γ-ray emission, and finally the ψ decays, for example, into $\mu^+\mu^-$. The muon pair is detected along with one or both of the γ-ray photons. This was the method used at DESY to find the 3500-Mev state and also by our group at SLAC to confirm this state (*16*). In our apparatus at SPEAR, it will occasionally happen that one of the two γ-ray photons converts into an e^+e^- pair before entering the tracking region of the detector. This allows the energy of the converting γ-ray to be measured very accurately, and this information can be combined with the measured momenta of the final $\mu^+\mu^-$ pair to make a twofold ambiguous determination of the mass of the intermediate state. The ambiguity arises from the uncertainty in knowing whether the first or the second γ-rays in the decay cascade have been detected. It can be resolved by accumulating enough events to determine which assumption results in the narrower mass peak. (The peak associated with the second γ-rays will be Doppler-broadened because these photons are emitted from moving sources.) Figure 11 shows the alternate low- and high-mass solutions for a sample of our data (*17*). There appears to be clear evidence for states at about 3.45, 3.5, and 3.55 Gev.

The second search method we have used, Fig. 10b, involves measuring the momenta of the final-state hadrons and reconstructing the mass of the intermediate state (*18*). Figure 12 shows two cases in which the effective mass of the final-state hadrons recoils against a missing mass of zero (that is, a γ-ray). In the case where four pions are detected, peaks are seen at about 3.4, 3.5, and 3.55 Gev. In contrast, the two-pion *or* two-kaon case shows only one clear peak at 3.4 Gev, with perhaps a hint of something at 3.55 Gev. The appearance of the two-pion or two-kaon decay modes indicates that the quantum numbers of the states in question must be either 0^{++} or 2^{++}.

In the third method of search, Fig. 10c, only a single γ-ray is detected. The presence of a monoenergetic γ-ray line would signal a radiative transition directly to a specific intermediate state. In our apparatus, this method is difficult to apply because of the severe background problems, but we were able to identify the direct γ-ray transition to the 3.4-Gev state (*17*). A different experimental



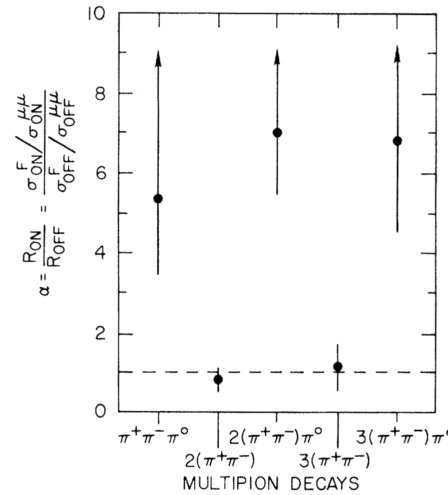


Fig. 7 (left). Feynman diagrams for ψ production and (a) direct decay to hadrons, (b) second-order electromagnetic decay to hadrons, and (c) second-order electromagnetic decay to $\mu^+\mu^-$. Fig. 8 (right). The ratio of the ratios of hadron to $\mu^+\mu^-$ production on and off the ψ resonance plotted against the number of π mesons in the final state.

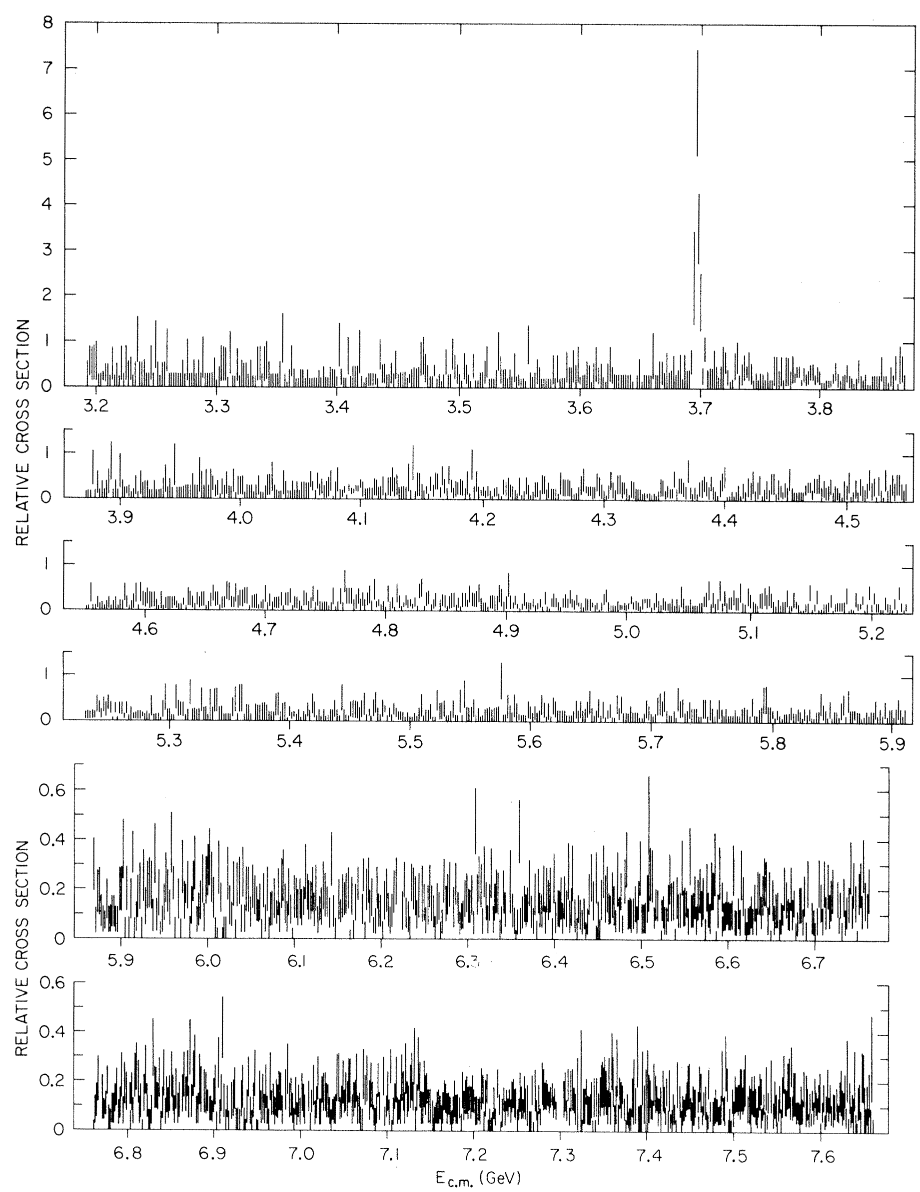


Fig. 9. Fine-scan data from our search for other narrow ψ-like states. The signal near 3.7 Gev is the ψ'.

group working at SPEAR (a collaboration among the universities of Maryland, Princeton, Pavia, Stanford, and California–San Diego) was able to make use of a more refined detection system to observe several of these radiative transitions and to measure the ψ' branching fractions of those states (*19*).

To summarize, these studies have led to the addition of four (the 2800-Mev state is still marginal) new intermediate states, all with charge-conjugation $C = +1$, to the original ψ and ψ' particles.

Table 2. Some of the low-lying bound states of a fermion-antifermion system together with an assignment of the new particle to states with appropriate quantum numbers.

State	L	S	J^{PC}	Particle
1^3S_1	0	1	1^{--}	ψ
2^3S_1	0	1	1^{--}	ψ'
3^3S_1	0	1	1^{--}	ψ'''
1^3D_1	2	1	1^{--}	ψ''
2^3D_1	2	1	1^{--}	ψ''''
1^1S_0	0	0	0^{-+}	X
2^1S_0	0	0	0^{-+}	$\chi(3.45)$
1^3P_0	1	1	0^{++}	$\chi(3.4)$
1^3P_1	1	1	1^{++}	$\chi(3.5)$
1^3P_2	1	1	2^{++}	$\chi(3.55)$

Total Cross Section and Broader States

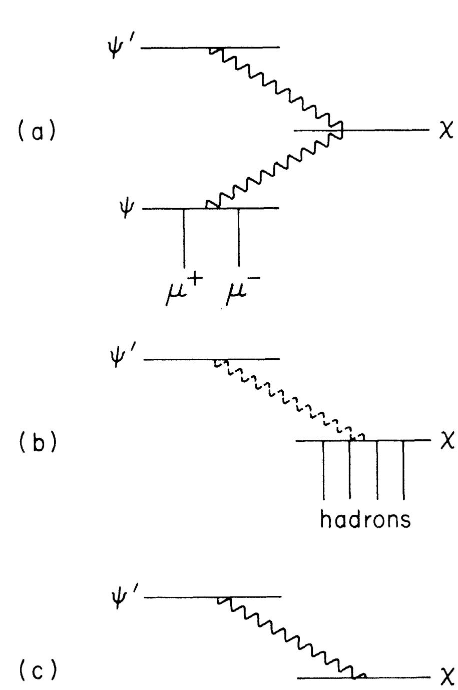
Total cross section. So far our discussion of the process $e^+e^- \rightarrow$ hadrons has been concerned largely with the two psi particles, which are created directly in e^+e^- annihilation, and with the intermediate states, which are not directly created but rather appear only in the decay products of the ψ and ψ'. It is now time to turn our attention to the larger picture of hadron production to see what else can be learned.

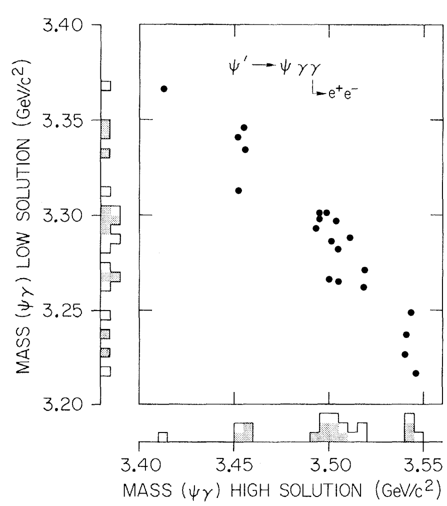
Figure 4 presented the total cross section for $e^+e^- \rightarrow$ hadrons over the full range of CM energies accessible to SPEAR. This figure was dominated by the ψ and ψ' resonance peaks, and very little else about the possible structure of the cross section outside of these peaks was observable. We now remedy this situation in Fig. 13, which shows the hadron/muon-pair ratio R, with the dominating ψ and ψ' resonance peaks removed, including their radiative tails. We can characterize the data in the following way. Below about 3.8 Gev, R lies on a roughly constant plateau at a value of $\simeq 2.5$; there is a complex transition region between about 3.8 and perhaps 5 Gev in which there is considerable structure; and above about 5.5 Gev, R once again lies on a roughly constant plateau at a value of $\simeq 5.2$ Gev.

Broader (psi?) states. The transition region is shown on a much expanded energy scale in Fig. 14. This figure clearly shows that there seem to be several individual resonant states superposed on the rising background curve that connects the lower and upper plateau regions (*20*). One state stands out quite clearly at a mass of 3.95 Gev, and another at about 4.4 Gev. The region near 4.1 Gev is remarkably complex and is probably composed of two or more overlapping states; more data will certainly be required to try to sort this out.

The properties of the several states within the transition region are very difficult to determine with any precision. One obvious problem is that these resonances sit on a rapidly rising background whose exact shape is presently neither clear experimentally nor calculable theoretically. Since these new states are, like the ψ's, produced directly in e^+e^- annihilation, they all have $J^{PC} = 1^{--}$ and can therefore interfere with each other, thus distorting the classical resonance shape that would normally be expected because new particle-production thresholds are almost certainly opening up in the transition region between the lower and upper plateaus. While precise properties cannot be given for the new states, we can get some rough numbers from the data. The 3.95-Gev state (ψ'') has a width of about 40 to 50 Mev. The 4.4-Gev state (ψ'''') seems to be about 30 Mev wide. The 4.1-Gev region (temporarily called ψ''') seems to consist of at least two peaks: one at 4.03 Gev, which is 10 to 20 Mev wide, and a broad enhancement at 4.1 Gev, about 100 Mev wide.

The widths of all of these states are much greater than the intrinsic energy spread in the e^+e^- beams, and very much greater than the widths of the ψ and ψ'. The suspicion remains, however, that they may still be correctly identified as members of the psi sequence, and that the vast apparent differences between their widths and those of the ψ and ψ' may result simply from the fact that the higher-mass states can undergo rapid hadronic decay through new channels





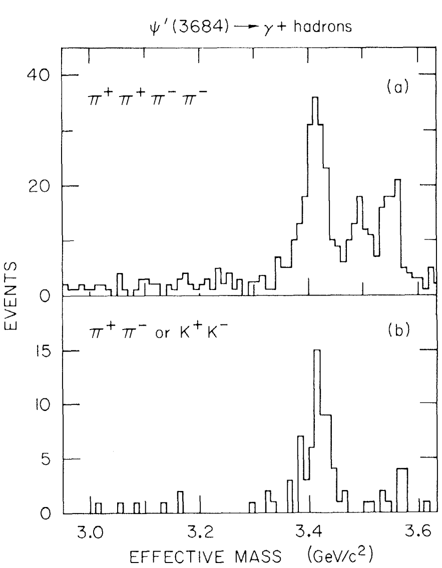


Fig. 10 (left). Schematics of the three methods of searching for narrow intermediate states. Fig. 11 (center). High-resolution ψ-γ mass data. The clustering indicates at least three intermediate states. Fig. 12 (right). Invariant mass of the indicated hadron final states that appear with a γ-ray in ψ' decay. The data show three distinct intermediate states, one of which is not seen in the previous figure.

that have opened up above the 3684-Mev mass of the ψ'. As with most of the questions in the transition region, this matter will require a good deal more experimental study before it is resolved. In the meantime, however, we shall tentatively add the three or four new psi-like states shown above to the growing list of members of the "psion" family.

Table 3. Properties of the three quarks and three antiquarks.

Quarks				Antiquarks			
Symbol	Charge	Baryon number	Strangeness	Symbol	Charge	Baryon number	Strangeness
u	2/3	1/3	0	$\bar{u}$	−2/3	−1/3	0
d	−1/3	1/3	0	$\bar{d}$	1/3	−1/3	0
s	−1/3	1/3	1	$\bar{s}$	1/3	−1/3	−1

An Excursion into Theory

Up to this point, we have been cataloging new particles without much worrying about what it all means. Granting full status to even the several doubtful states, we have a total of 11 new particles. These are grouped together in Fig. 15 in a kind of energy-level diagram, which also includes principal decay modes.

The system shown in Fig. 15, with its radiative transitions, looks remarkably like the energy-level diagram of a simple atom, in fact like the simplest of all "atoms"—positronium, the bound state of an electron and a positron. Although the mass scale for this new positronium is much larger than that of the old, the observed states of the new system can be placed in a one-to-one correspondence with the levels expected for a bound fermion-antifermion system such as e^+e^-. Table 2 shows these predicted levels together with the most probable assignments of the new particles to the appropriate levels. To gain some insight into the origins of the new positronium system, let us now turn to some specific theoretical models.

The three-quark model. Some 25 years ago, when only three kinds of hadrons were known (proton, neutron, and pi-meson), these particles were universally regarded as simple, indivisible, *elementary* objects. In those days the central task in hadron physics was the effort to understand the strong nuclear force between protons and neutrons in terms of pi-meson exchange. But as the family of hadrons grew steadily larger (they are now numbered in the hundreds), it became increasingly difficult to conceive of them *all* as elementary. In 1963, M. Gell-Mann and G. Zweig independently proposed a solution to this dilemma—that *none* of the hadrons was elementary, but rather that all were complex structures in themselves and were built up from different combinations of only three fundamental entities called quarks. These quarks were assumed to carry the familiar ½ unit of spin of fermions, but also to have such unfamiliar properties as fractional electric charge and baryon number. A brief listing of the three quarks and three antiquarks and their properties is given in Table 3.

According to this three-quark model, all mesons were made up of one quark and one antiquark; all baryons, of three quarks; and all antibaryons, of three antiquarks. The quark compositions of some of the better-known hadrons are shown here as examples

$$\pi^+ = u\bar{d},\ K^+ = u\bar{s},\ p = uud,\ \bar{n} = \bar{d}\bar{d}\bar{u} \quad (8)$$

Prior to 1974, all of the known hadrons could be accommodated within this basic scheme. Three of the possible meson combinations of quark-antiquark ($u\bar{u}$, $d\bar{d}$, $s\bar{s}$) could have the same quantum numbers as the photon, and hence could be produced abundantly in e^+e^- annihilation. These three predicted states had all in fact been found; they were the familiar $\rho(760)$, $\omega(780)$, and $\phi(1005)$ vector mesons.

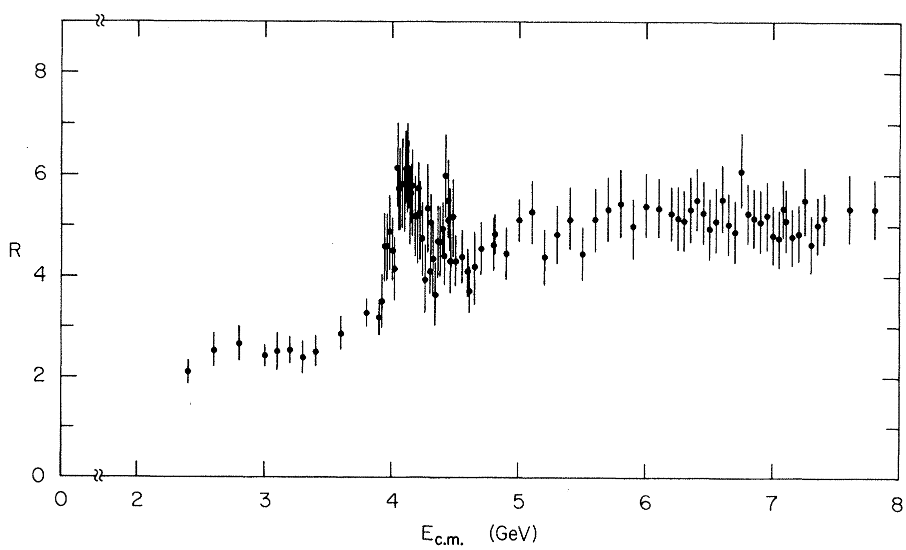
R *in the quark model*. The quark model postulated a somewhat different mechanism for the process $e^+e^- \rightarrow$ hadrons than that previously described. For comparison

Customary view: $e^+e^- \rightarrow \gamma \rightarrow$ hadrons

$$\text{Quark model hypothesis: } e^+e^- \rightarrow \gamma \rightarrow q\bar{q} \rightarrow \text{hadrons} \quad (9)$$

where $q\bar{q}$ means any quark-antiquark pair. The quark model hypothesis is shown schematically in Fig. 16. In this picture the virtual photon intermediate state creates a $q\bar{q}$ pair, which then in turn "clothe" themselves with additional $q\bar{q}$ pairs to form the hadrons that are observed in the final state.

Since the quarks are assumed to be elementary, pointlike fermions and thus similar to electrons and muons in their electromagnetic properties, it was possible to predict the ratio that should exist



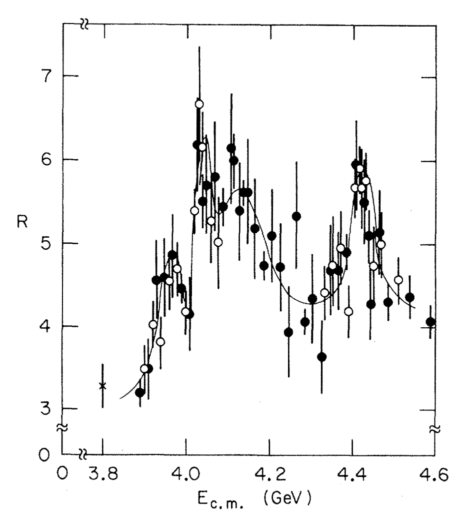
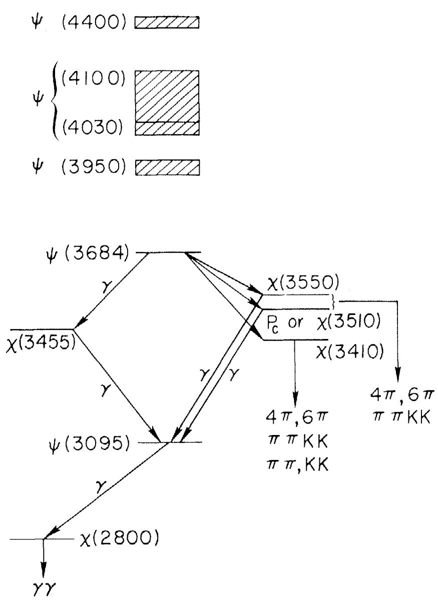
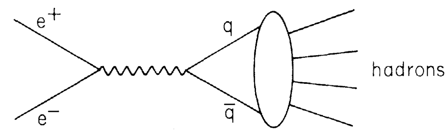


Fig. 13 (left). The ratio R with the ψ and ψ' deleted (including their radiative tails). Fig. 14 (right). Expanded view of R in the transition region around 4 Gev.





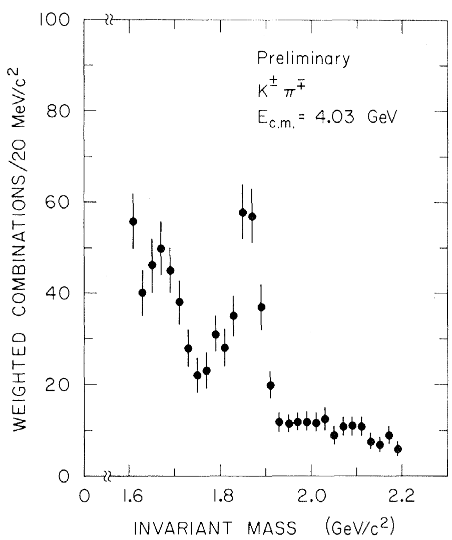


Fig. 15 (left). Energy-level diagram of the new particles. The many observed decay modes of the psi family have been omitted. Fig. 16 (upper right). Hadron production in the quark model. Fig. 17 (bottom right). Invariant mass distribution of the $K^{\pm}\pi^{\mp}$ system in multiparticle final states. The peak at a mass of 1865 Mev is the D^0 meson.

between the production cross sections for quark pairs and muon pairs

$$\frac{\sigma_{q\bar{q}}}{\sigma_{\mu^+\mu^-}} = q_i^2 \qquad (10)$$

where q_i is simply the quark's electric charge. Of course, quarks were supposed to have half-integral spin and fractional charge in the final state, while all hadrons have integral charge and some hadrons have integral spin. In a breathtaking bit of daring it was assumed that the "final-state" interactions between quarks that were necessary to eliminate fractional charge and half-integral spin would have no effect on the basic production cross section. With this assumption the ratio of hadron production to muon-pair production becomes simply

$$R = \sum_{u,d,s} q_i^2 \qquad (11)$$

As developed up to 1974, the quark model actually included three triplets of quarks, rather than simply three quarks, so that with this 3 × 3 model the hadron/muon-pair ratio, R, would be

$$R = \{3[(2/3)^2 + (-1/3)^2 + (-1/3)^2]\} = 2 \qquad (12)$$

This beautiful model had great simplicity and explanatory power, but it could not accommodate the ψ and ψ' particles. Nor could it account for the two plateaus that were observed in the measured values of R. The model allowed for excited states of $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$, but the required widths were typically some 20 percent of the mass of the excited state—more than 1000 times broader than the observed widths of the ψ and ψ'. Before that time there had been a number of suggested modifications or additions to the basic three-quark scheme. I shall not describe these proposed revisions here, except for the one specific model which seems now to best fit the experimental facts.

A fourth quark. The first publications of a theory based on four rather than three basic quarks go all the way back to 1964 (*21*), only a year or so after the original Gell-Mann and Zweig three-quark scheme. The motivation at that time was more esthetic than practical, and these models gradually expired for want of an experimental fact that called for more than a three-quark explanation. In 1970, Glashow *et al.* (*22*) breathed life back into the four-quark model in an elegant paper that dealt with the *weak* rather than the strong interactions. In this work the fourth quark—which had earlier been christened by Glashow the "charmed" quark (c)—was used to explain the nonoccurrence of certain weak decays of strange particles in a very simple and straightforward way. The new c quark was assumed to have a charge of +2/3, like the u quark, and also to carry +1 unit of a previously unknown quantum number called charm, which was conserved in both the strong and electromagnetic interactions but not in the weak interactions. The c and $\bar{c}$ quarks were also required to have masses somewhat larger than the effective mass of the three original quarks, and it was clear that they should be able to combine with the older quarks and antiquarks to form many new kinds of "charmed" hadrons (*23*).

"Charmonium." The four-quark theoretical model became much more compelling with the discovery of the psi particles. This model postulates that the ψ is the lowest-mass $c\bar{c}$ system which has the quantum numbers of the photon. The long life of the ψ is explained by the fact that the decay of the ψ into ordinary hadrons requires the conversion of *both* c and $\bar{c}$ into other quarks and antiquarks. The positronium-like energy-level states of the psions discussed earlier are also well accounted for by the $c\bar{c}$ system; indeed, five specific intermediate states were predicted by Applequist *et al.* (*24*) and by Eichten *et al.* (*25*) before they were actually discovered. It was the close analogy with positronium that led Applequist and Politzer to christen the new $c\bar{c}$ system charmonium, a name that has caught on.

The four-quark model also requires two plateaus on R. Above the threshold for charmed-hadron production, the $R = 2$ calculation made above must be modified by the addition of the fourth quark's charge, which results in a prediction of $R = 10/3$ (not enough, but in the right direction). The broad psi-like states at 3.95, 4.1, and 4.4 Gev are accounted for by postulating that the mass of the lightest charmed particle is less than half the mass of the ψ''(3950) but more than half the mass of the very narrow ψ'(3684), which means that ψ'' can decay strongly to charmed-particle pairs, but ψ' cannot.

To summarize briefly, the four-quark model of the hadrons seemed to account, in at least a qualitative fashion, for all of the main experimental information that had been gathered about the psions, and by the early part of 1976 the consensus for charm had become quite strong. The $c\bar{c}$ system of charmonium had provided indirect but persuasive evidence for a fourth, charmed quark, but there remained one very obvious and critically important open question. The particles formed by the $c\bar{c}$ system are not in themselves charmed particles, since charm and anticharm cancel out to zero. But it is necessary to the theory that particles which exhibit charm exist ($c\bar{u}$, $c\bar{d}$, and so on). What was needed, then, was simply the direct experimental observation of charmed particles, and the question was, Where were they? (*26*).

What are we looking for? By early 1976 a great deal had been learned about the properties that the sought-after charmed particles must have. As an example, it was clear that the mass of the lightest of these particles, the charmed D-meson, had to fall within the range

$$1843 < m_D < 1900 \text{ Mev} \quad (13)$$

The lower limit was arrived at by noting once again that the $\psi'(3684)$ was very narrow and therefore could not decay into charmed particles, and also that the upper limit had to be consistent with the beginning of the rise of R from its lower to its upper plateau. Since the principal decay product of the c quark was assumed for compelling reasons to be the s quark, then the decay products of charmed particles must preferentially contain strange particles such as the K-mesons. The charmed D-mesons, for example, could confidently be expected to have the following identifiable decay modes

$$D^0 \rightarrow K^-\pi^+$$
$$D^0 \rightarrow K^-\pi^+\pi^-\pi^+$$
$$D^+ \rightarrow K^-\pi^+\pi^+ \quad (14)$$

A further point was that, since the charmed quark would decay only through the weak interactions, one might reasonably expect to see evidence of parity violation in the decays of the D-mesons.

At SPEAR our collaboration had looked for such charm signatures in the limited data taken before the psi discoveries, but without success. As the post-psi data accumulated throughout 1975, it was evident that we should have another go at it, with particular emphasis on the results obtained at energies close to the expected charm threshold, where the simplest charmed mesons would be produced without serious masking effects from extraneous background. Since I spent the academic year 1975–1976 on sabbatical leave at CERN, this chapter of the charmed-particle story belongs to my collaborators.

The charmed meson. With the advantages of a much larger data sample and an improvement in the method of distinguishing between pi- and K-mesons in the Mark I detector, a renewed search for charmed particles was begun in 1976. Positive results were not long in coming. The first resonance to turn up in the analysis was one in the mass distribution of the two-particle system $K^{\pm}\pi^{\mp}$ in multiparticle events (*27*). The evidence for this is shown in Fig. 17. This was the first

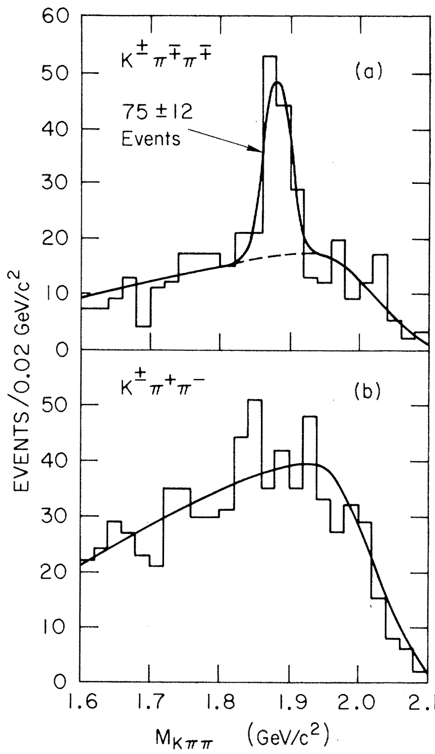


Fig. 18. Invariant mass distribution of the $K\pi\pi$ system. The $D^{\pm}$ appears in (a) with same-sign pions and not in (b) with opposite-sign pions.

direct indication of what might be the D-meson, for the mass of 1865 Mev was in just the right region. If it was the D^0, then presumably the production process was

$$e^+e^- \rightarrow D_0\bar{D}_0 + X \quad (15)$$

where X represents any other particles. The $\bar{D}^0$ or D^0 would subsequently decay into the observed $K^+\pi^-$ or $K^-\pi^+$ some fraction of the time—the data indicated a branching fraction of about 2 percent for this charged two-body mode. The branching fraction was a little low compared to the charm model predictions, but not alarmingly so. The measured width of the resonance was consistent with the resolution of our apparatus, which in this case was determined by the momentum resolution of the detector rather than by the more precise energy resolution of the circulating beams. The measured upper bound on the full width was about 40 Mev; the actual value could well be much smaller, as a weak-interaction decay of the D-meson would require.

Continuing analysis of the data yielded two more persuasive findings. The first was a resonance in $K^+\pi^-\pi^+\pi^-$ or $K^-\pi^+\pi^-\pi^+$, which appears to be an alternate decay mode of the D^0 since the mass is also 1865 Mev. The second was the discovery of the charged companions (*28*) of the D^0, which were observed at the slightly larger mass of 1875 Mev in the following decay channels

$$D^+ \rightarrow K^-\pi^+\pi^+$$
$$D^- \rightarrow K^+\pi^-\pi^- \quad (16)$$

The data for the charged D states are shown in Fig. 18. It is important to note that these states are *not* observed in three-body decay when the pions are oppositely charged

$$D^+ \rightarrow K^+\pi^-\pi^+$$
$$D^- \rightarrow K^-\pi^+\pi^- \quad (17)$$

This is precisely what is required by the charmed-quark model. In addition to the clear identification of both neutral and charged D-mesons, an excited state (*29*) of this meson (D^*) has also turned up and has been seen to decay to the ground state by both strong and electromagnetic interactions

$$D^* \rightarrow D + \pi$$
$$D^* \rightarrow D + \gamma \quad (18)$$

Since we have several times mentioned the possibility that the psi-like states having masses above that of the $\psi'(3684)$ may be much broader than ψ and ψ' because they are able to decay strongly into charmed-particle pairs, it is interesting to note that this speculation has now been confirmed in the case of the $\psi'''(4030)$. It now appears, in fact, that the following are the principal decay modes of this particle

$$\psi'''(4030) \rightarrow D^0\bar{D}$$
$$\rightarrow D^*\bar{D}^0$$
$$\rightarrow D^*\bar{D}^* \quad (19)$$

As a final bit of evidence in support of the charmed-meson interpretation of the experimental data, the predicted parity violation in D decay has also been observed. In the decay process $D^0 \rightarrow K^+\pi^-$, the K and π each have spin 0 and odd intrinsic parity. This means that any spin possessed by the D^0 must show up as orbital angular momentum in the $K\pi$ system, and thus that the parity of the D^0 must be given by

$$P = (-1)^J \quad (20)$$

where J is the spin of the D^0. An analysis of the three-body decay data, $D^{\pm} \rightarrow K^-\pi^+\pi^+$ or $K^+\pi^-\pi^-$, showed that the parity cannot be the same as that given above, and therefore that parity must be violated in D-meson decay (*30*).

The experimental data that have been described here are strikingly consistent with the predictions of the four-quark or charm theory of the hadrons, and there is little doubt that charmed particles have

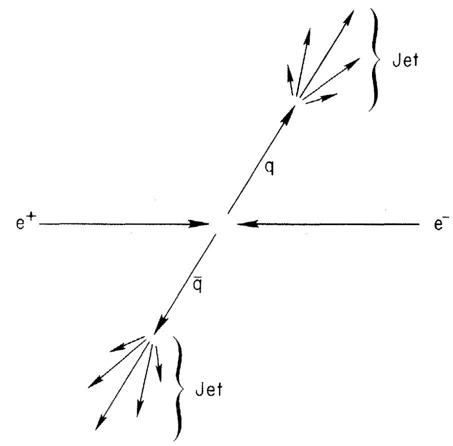
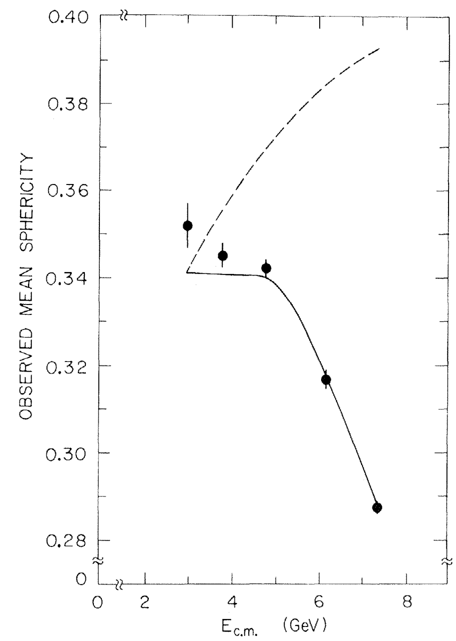


Fig. 19 (left). Jet production in the quark model. Fig. 20 (right). Mean sphericity of multihadron events plotted against center-of-mass energy. The solid curve is that expected of the jet model, while the dashed curve is that expected from an isotopic phase-space model.



now in fact been found. In addition to these charmed mesons uncovered at SPEAR, there has been recent information from Fermilab that a collaborative group working there under Wonyong Lee has now discovered the first of the charmed baryons (*31*)—actually an antibaryon designated $\bar{\Lambda}_c$ to identify it as the charmed counterpart of the $\bar{\Lambda}$.

Observation of Jets

While this topic is not directly connected with the new particles, it does have a direct bearing on the validity of the quark model. As I noted earlier, the picture of e^+e^- annihilation that is derived from the quark model indicates that the final-state hadrons do not come directly from the virtual-photon intermediate state, but rather from the quark-antiquark pair that is first created from the electromagnetic fireball and subsequently forms the final hadrons. These hadrons are produced with low transverse momenta with respect to the $q\bar{q}$ direction and, as illustrated in Fig. 19, if the energy is sufficiently high, form two collimated jets of particles whose axes lie along the original $q\bar{q}$ direction.

At SPEAR we have analyzed our highest-energy data (*32*) by determining for each event the particular axes that minimize the transverse momentum relative to those axes for all of the observed particles. This method of analysis leads to the definition of a quantity we have called "sphericity," which is related to the quadrupole moment of the particle distribution in momentum space. The more jetlike the event, the lower the sphericity. Figure 20 shows the data compared to the jet model and to an "isotropic" model with no jetlike characteristics. As the energy increases, the events do become more jetlike as required. The result was excellent agreement, not only in the general sense but also in the finding that the angular distribution of the jet axes was consistent with the $1 + \cos^2\theta$ distribution that is expected if the jets originate from parent particles of spin ½.

In addition, under certain operating conditions the beams in the SPEAR storage ring become polarized, with the electron spin parallel and the positron spin antiparallel to the ring's magnetic bending field. In this polarized condition an azimuthal asymmetry in particle production can appear with respect to the direction of the beams. Jets measured under these conditions also displayed the azimuthal asymmetry that is expected of spin-½ particles.

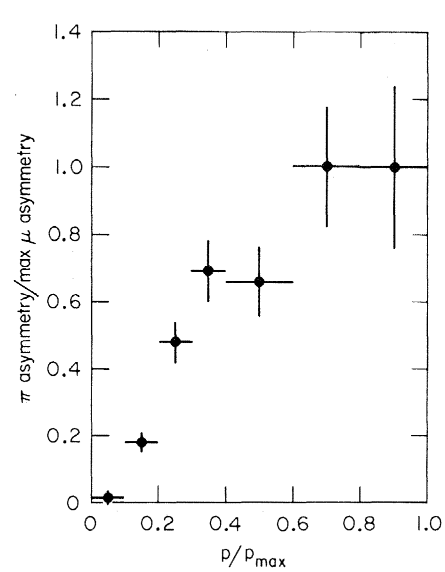


Fig. 21. Azimuthal asymmetry parameter for pions normalized to the asymmetry in μ-pair production plotted against fractional pion momentum.

Further, the individual hadrons within the jets also displayed this asymmetry (*33*). It will be evident that the greater the momentum of a single hadron, the closer that hadron must lie to the original direction defined by the quark. By looking at pion production in detail, we were able to determine that as the pion momentum approached the maximum value possible for the particular machine energy, so did the azimuthal asymmetry approach the maximum possible asymmetry expected for spin-½ particles. This point is illustrated in Fig. 21.

I find it quite remarkable that a collection of hadrons, each of which has integral spin, should display all of the angular-distribution characteristics that are expected for the production of a pair of spin-½ particles. Such behavior is possible without assuming the existence of quarks (the final-state helicity must be one along the direction of the particle or jet), but any other explanation seems difficult and cumbersome. In my view the observations of these jet phenomena in e^+e^- annihilation constitute one of the very strongest pieces of evidence for believing that there really is a substructure to the hadrons.

Conclusions and Questions

The electron-positron colliding-beam experiments of the past 2 years have, I believe, settled the question of the significance of the psi particles. The charmonium family, the two plateaus in R, the wide resonances above charm threshold, the charmed particles themselves, the evidence for the weak decays of the charmed particles, and the existence of jets—all these support most strongly the ideas of the quark model of hadron substructure and the four-quark version of that model. To me, one of the most remarkable features of the quark model is that it correctly explains a great deal of data on strongly interacting particles with the most simpleminded of calculations. The charmonium spectrum, for example, is calculated with the nonrelativistic Schrödinger equation using a simple potential. The two plateaus in R and the jet structure are explained by assuming that the final-state interactions of strongly interacting particles can be ignored. Why it is all so simple, while at the same time the quarks themselves appear confined to hadrons and are never seen in the free state, is one of the central questions of strong-interaction physics.

We already know, however, that the four-quark model cannot be the complete story. The colliding-beam experiments are not entirely consistent with this model. The high-energy plateau value of R is about 5.1 rather than 3⅓ as demanded by the charm model. While $R = 3\frac{1}{3}$ is only reached in the theory at very high energies, the difference between 3⅓ and 5.1 is too large to be explained easily. At the same time, there is evidence in our data for a class of events (the μ-e events) which are not easily explained within the framework of four quarks and four leptons (e^-, ν_e, μ^-, ν_μ) and which may require an expansion of the lepton family and/or the quark family. These inconsistencies immediately bring up the question of how many quarks and leptons there are.

There are two schools of thought on this question. One school says that the quark system is complete or nearly complete—while there may be a few more quarks to be found, there is a small number of indivisible elements, among which are the present four, and all of the strongly interacting particles are built out of these elementary and indivisible components. The other school says that the quarks themselves are probably built from something still smaller, and that we shall go on forever finding smaller and smaller entities each inside the next larger group.

These and other questions on particle structure may be answered by the next generation of e^+e^- colliding-beam machines now being built at DESY and SLAC, which will reach 35 to 40 Gev in the center-of-mass system. Experiments on these machines will begin in 4 to 5 years and should tell us promptly about the existence of new plateaus in R, new "oniums," or new leptons.

An even more fundamental set of questions, which I find more interesting than the number of quarks, will probably not be answered by experiments at any accelerator now in construction. These questions have to do with the possibility of a unified picture of the forces of nature; gravity, the weak interaction, the electromagnetic interaction, and the strong interaction. Weinberg (*34*) and Salam (*35*) have made the first models of a unified weak and electromagnetic interaction theory. Attempts have been made at a unified picture of the weak, electromagnetic, and strong interactions—more primitive than the Weinberg-Salam model, for the problem is more difficult, but still a beginning. The experimental information required to establish these unified pictures will almost certainly require still higher energies: several hundred Gev in the center of mass and again, I believe, in the e^+e^- system. If any of these unified pictures is correct at very high energies, then our only correct field theory, quantum electrodynamics, will necessarily have to break down, and I will have come full circle back to the first experiment I wanted to do as an independent researcher.

References and Notes

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3. G. S. Abrams *et al.*, *ibid.*, p. 1453.
4. The early development of the colliding-beam technique was an international effort. The two groups who, in those early days, suffered with us through the discovery and conquest of what at times seemed to be an endless series of beam instabilities and technological problems were those of F. Amman at Frascati and G. I. Budker at Novosibirsk.
5. The success of the SPEAR project is in large measure due to J. Rees, who was then my deputy, and to M. Allen, A. M. Boyarski, W. Davies-White, N. Dean, G. E. Fischer, J. Harris, J. Jurow, L. Karvonen, M. J. Lee, R. McConnell, R. Melen, P. Morton, A. Sabersky, M. Sands, R. Scholl, and J. Voss.
6. The physicists of the SLAC-LBL group who were responsible for building the detector and for the experiments I will discuss are S. M. Alam, J.-E. Augustin, A. M. Boyarski, M. Breidenbach, F. Bulos, J. M. Dorfan, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, J. A. Jaros, B. Jean-Marie, R. R. Larsen, D. Lüke, V. Lüth, H. L. Lynch, C. C. Morehouse, J. M. Paterson, M. L. Perl, I. Peruzzi, M. Piccolo, T. P. Pun, P. Rapidis, B. Richter, R. H. Schindler, R. F. Schwitters, J. Siegrist, W. Tanenbaum, and F. Vannucci from SLAC; and G. S. Abrams, D. Briggs, W. C. Carithers, W. Chinowsky, R. G. DeVoe, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, A. D. Johnson, J. A. Kadyk, A. Litke, B. Lulu, R. J. Madaras, H. K. Nguyen, F. Pierre, B. Sadoulet, G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse from LBL.
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