SLAC BEAM LINE

"There are therefore Agents in Nature able to make the Particles of Bodies stick together by very strong Attractions. And it is the Business of experimental Philosophy to find them out." -- Isaac Newton, Opticks (1704)

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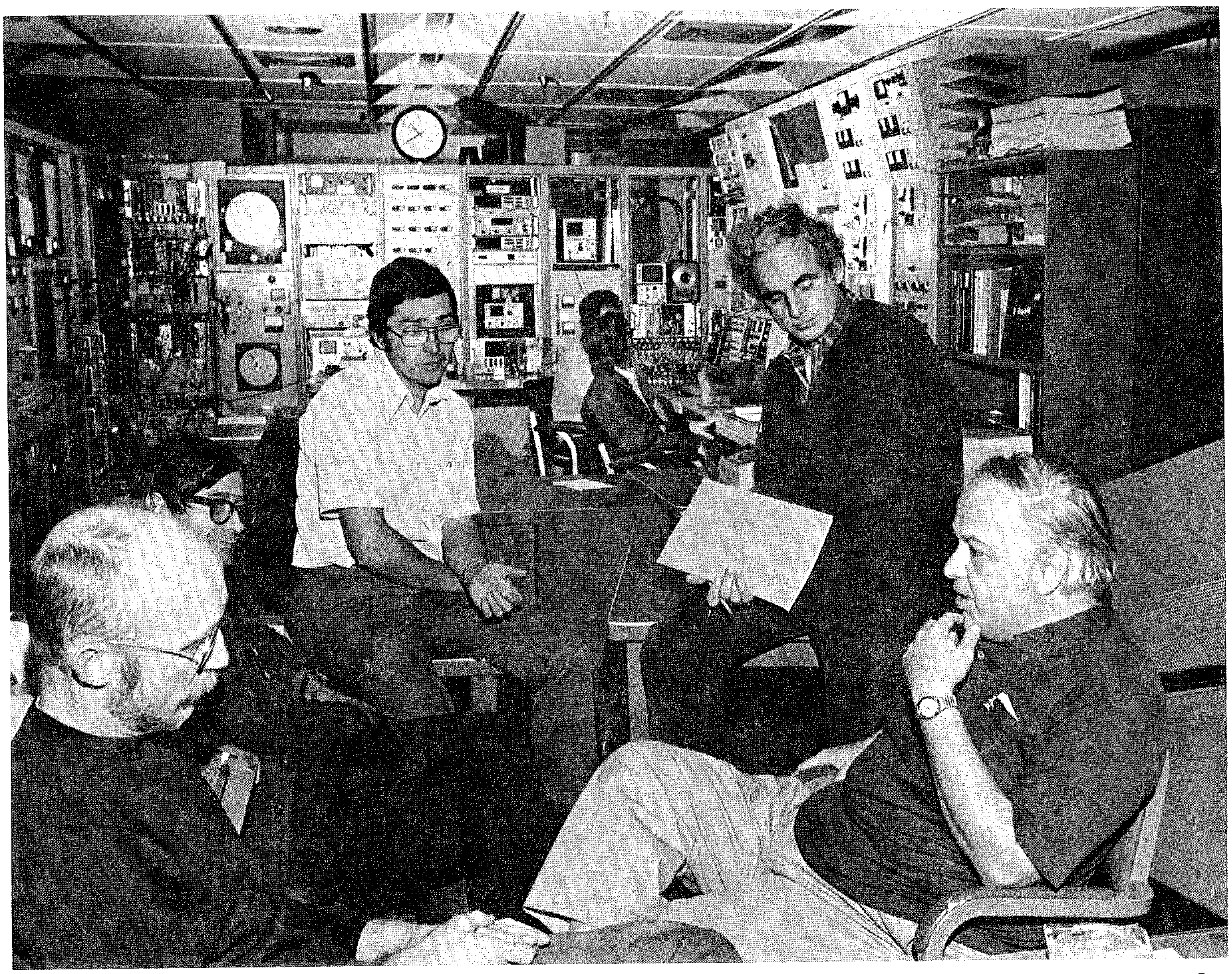
IN THIS ISSUE

Editor's Note: We're so late with this issue of the *Beam Line* that we've decided to have it cover both November and December. We've been getting quite a bit of technical input recently, but not much in the way of people news. Contributions or ideas are still very much welcome. Got any?

--BK



Second from the left in this photo is George Trilling of UC-Berkeley, one of the leaders of the Berkeley physics group that has been collaborating with SLAC Experimental Groups C and E in the remarkably productive SPEAR studies of hadron production. The others, left to right, are SLAC physicists Rudy Larsen, Ewan Paterson, Dave Fryberger and Burt Richter. SPEAR and its sister storage ring, DORIS, at the DESY laboratory in Hamburg, Germany, have been the scene of several recent discoveries of new particles. This issue of the *Beam Line* contains Part II of an article which describes these recent very important results.

DESY: PETRA CONSTRUCTION TO BEGIN

Reprinted from the CERN COURIER, October 1975

As part of the measures taken to stimulate the economy in the Federal Republic of Germany, the Ministry for Research and Technology has allocated money for the buildings of the proposed 19 GeV electron-positron storage ring, PETRA. Additional funds totalling 14.85 million DM [about $5-6 million] have been granted for 1975/76 to the DESY Laboratory for this purpose.

The funds include money specifically assigned to the building of extra experimental halls. In the PETRA proposal, money is requested for the construction of four experimental halls. The machine design, however, has eight beam intersection regions and the possibility of four other halls, being built in the context of international collaboration in the use of the machine, was left open. The money that has been allocated is to cover the construction of six halls, two of them to ensure accomodation for experimental teams from other countries.

The additional budget allocation has passed through all of the relevant Committees. Since construction plans are already complete, building will go ahead immediately when the formal notification is received from the Ministry.

Improvements at the synchrotron

In the midst of the excitement concerning the PETRA decision, the Laboratory continues to tackle its immediate tasks. A shutdown of the 7.5 GeV synchrotron and the DORIS electron-positron storage rings extended from 18 August to 30 September while a series of improvements were implemented. Normal operation has now resumed.

The ejection system from the synchrotron for DORIS was rebuilt and the transfer channels between the machines were modified to raise the DORIS injection energy from 2 to 4.3 GeV. It is now possible to fill DORIS at all operation energies, eliminating the necessity of 'energy ramping' in the storage ring itself. This will improve operation at high energies.

The 400 MeV linac II injector has been modified to yield higher positron currents. The linac used to have 12 accelerator sections with the electron-positron converter positioned behind section 5. The converter has now been moved downstream by two sections leading to a 40% increase in the energy of the bombarding electrons and to a higher positron yield. At the same time, two accelerator sections were added at the end of the linac to keep the emerging positron energy unchanged.

The linac I injector was also modified for higher energy. In the usual DORIS injection scheme, positrons and electrons can be fed in on a pulse-to-pulse basis. This necessitates simultaneous operation of linac II as a positron injector and linac I as an electron injector into the synchrotron. The energy of linac I was raised from 40 to 60 MeV by doubling the klystron power.

In readiness for proton injection into the synchrotron (to take a first look at electron-proton colliding beam problems), a Van de Graaff proton injector was received in August after successful testing at the manufacturers. Its installation in the inner experimental area of the symchrotron began in September and the proton injection channel was installed. The r.f. acceleration unit for proton acceleration in the synchrotron has been operated during the summer, but technical difficulties in the control systems have caused some delay. The accelerating unit was not, therefore, installed during the shutdown and will probably be moved in in November.

The storage rings, DORIS, are looking in progressively better shape. During recent months they have mainly operated at energies of 1.5 and 1.84 GeV at currents of about 2 × 250 mA and a beam lifetime greater than 10 hours. The average luminosity, over a period of several weeks, was about 4×10^{29} per cm^2 per s.

CERN COURIER COMES TO THE U.S.

As of January 1976 the monthly journal CERN COURIER will extend its coverage so that it becomes more fully representative of the world-wide activities in accelerator development and in high energy physics research. All U.S. copies will be printed and distributed from Fermilab. Copies for people at Stanford will be distributed by internal mail. If you are not presently on the distribution list for the COURIER, and feel that you should receive it, please forward your request to Doug Dupen, Public Information, Bin 11.

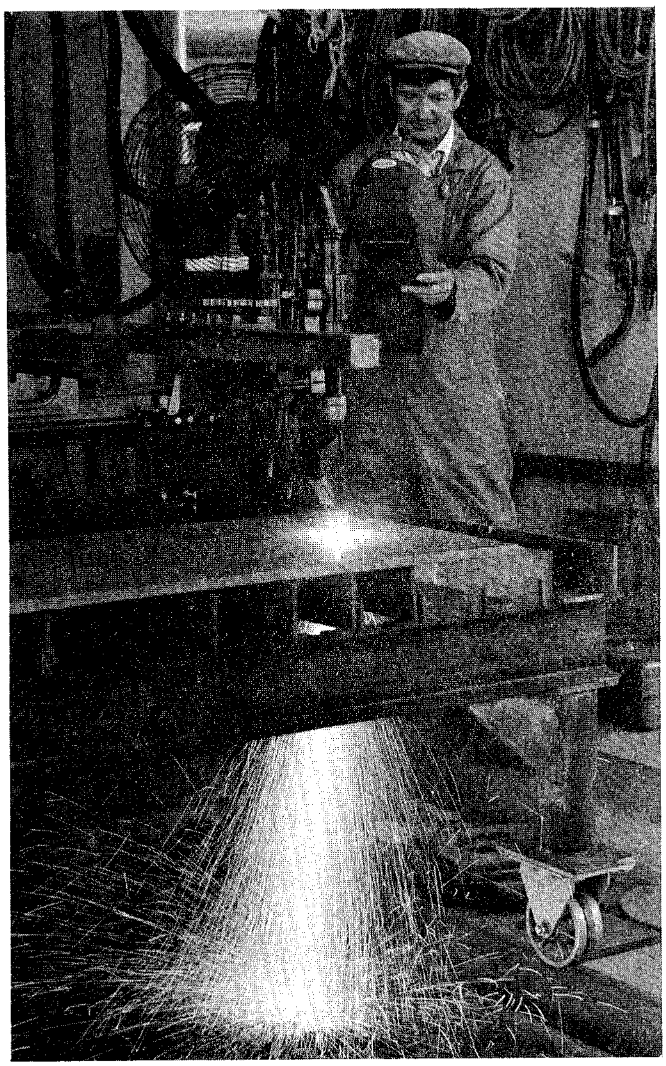
A machine of liberal proportions has been constructed in New York for the purpose of being worked by a steam engine to generate a magneto-electric current by the revolution of permanent magnets in proximity to insulated coils. It has been suggested that this would be the best way to operate the Atlantic telegraph, instead of using immense batteries to generate sufficient galvanism. Since electric apparatus of all kinds is attracting much public attention at present, we hope that this, as well as every other new electric machine, will receive a fair test of its qualities. This is the only true way to progress and improve.

--*Scientific American*
June, 1857

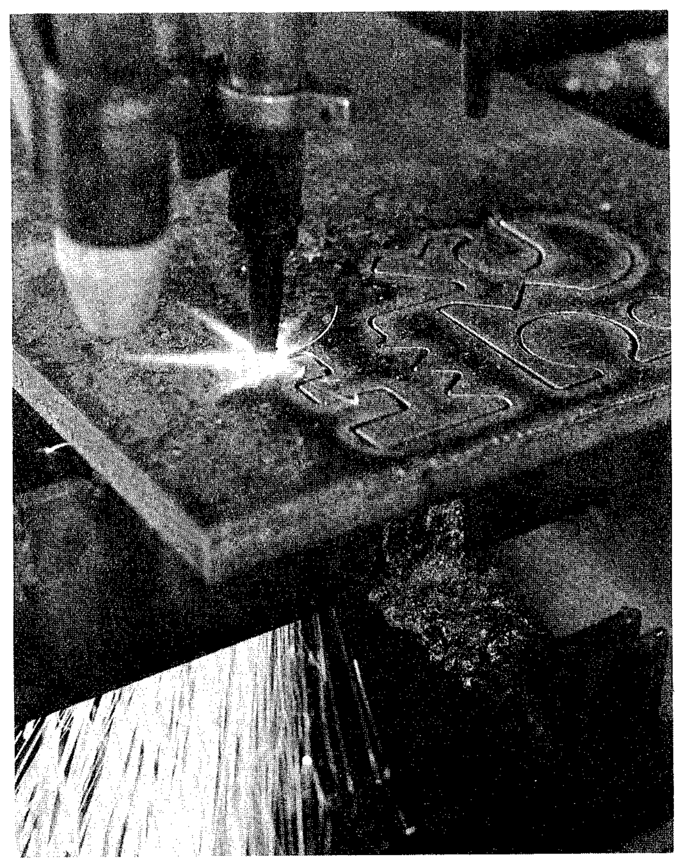
The pattern-following control head of the torch-cutting facility.

TORCH-CUTTING FACILITY

The photographs on this page, all taken by Joe Faust, show the automatic torch-cutting facility that is set up in the MFS Weld Shop and is used for cutting both ferrous and non-ferrous metals. Walt Broers of MFS is shown operating the facility. An optical device attached to the facility controls the motion of the torch by following the dark outline of a pattern. The machine is capable of cutting at speeds up to 40 lineal inches per minute, and it has a capacity of 8-inch-thick carbon steel or two-inch-thick stainless steel.



In this photo the torch is cutting end flanges for SLED from 3/4-inch stainless.



This is a cut being made in 3/4-inch carbon steel following the pattern shown in the other photo.

SLAC'S CHRISTMAS GIFT TO TEXAS

During December, Jean Paist Bohannon will take early retirement from Stanford University and move to McAllen, Texas.

Prior to joining SLAC, Jean worked for the Trojan Construction Company of Sunnyvale, a company that builds homes. She started at SLAC when our Purchasing Department was located in a trailer adjacent to the M-1 Building on the Stanford campus, back in 1962. Jean quickly proved her value to SLAC back in those early pre-construction and construction days.

When your calculator needed repairing, or when you needed supplies and services, or when you were processing a rush-emergency walk-through requisition--at times like that many people at SLAC have been helped out by Jean's friendly and willing attitude and by her expertise. She has been so deeply involved in our Purchasing operation that when Vince Morales left SLAC, a few years ago, he nominated Jean as SLAC's "Number One Vice President."

Jean has been active in bowling, and she has always enjoyed a friendly bridge session during the lunch hour. She obviously enjoys most anything she is doing, and likes to work with people. She has even been known to take a flyer in Reno or at Tahoe upon occasion.

"What's this simple declarative sentence doing on page 39 of your report?"

Jean hails from Perry, Iowa. Her two sons and their families still live there. She frequently visits friends and family, and during this past year she attended her high school reunion. It seems that a certain Charles Bohannon, another former resident of Perry, also heard about the reunion, and what with one thing and another pretty soon there was a correspondence started, and phone calls and visits. And in late September of this year Jean and Charles were married.

We shall miss Jean's cheerful efforts in SLAC's behalf, and we shall decidely miss the good friend we have known for years. We all join together to wish Jean and Charlie the best in life in McAllen, Texas, amid the grapefruit of the lower Rio Grande Valley. Please, Jean and Charlie, don't slice your golf shots into the grapefruit trees or the River. Their address will be 3501 Hackberry Street, McAllen, Texas 78501.

--Ralph Hashagen

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More New Particles - Part II

(CONTINUED FROM LAST MONTH)

E. The New(er) Particles

Last month, in Part I of this article, we concentrated mostly on what has been learned about the two psi particles, $\psi(3.1)$ and $\psi(3.7)$, since their discovery just about a year ago.* This month we'll turn our attention to the more recent discoveries that have been made at SPEAR and at the German storage ring DORIS (similar to SPEAR) at the DESY laboratory in Hamburg. This recent work can be divided into three classes:

1. Two higher energy resonances, at 4.1 and 4.4 GeV, that are probably related to the psi particles. We'll call them $\psi''(4.1)$ and $\psi'''(4.4)$.

2. Four (perhaps more) resonant states that the $\psi(3.1)$ or $\psi'(3.7)$ decay into through "radiative transitions." The names are P_c, X, χ (chi) and χ'.

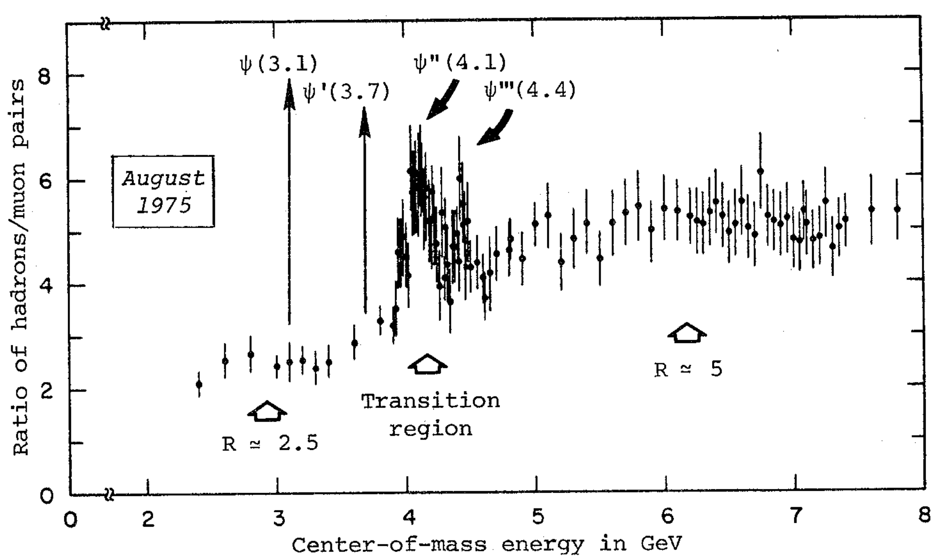
3. One rather mysterious new particle that may or may not have some connection with the psi particles. The name is U (for "unknown").

We'll describe each of these three classes in turn, then in the next section move on to a discussion of their possible significance.

*We were remiss last month is failing to remind our readers that the original discovery, in November 1974, was made both by the SLAC-LBL group working at SPEAR (who called it the "ψ" particle) and by a group from Massachusetts Institute of Technology and Brookhaven National Laboratory working at the BNL 33-GeV proton synchrotron (who called it the "J" particle).

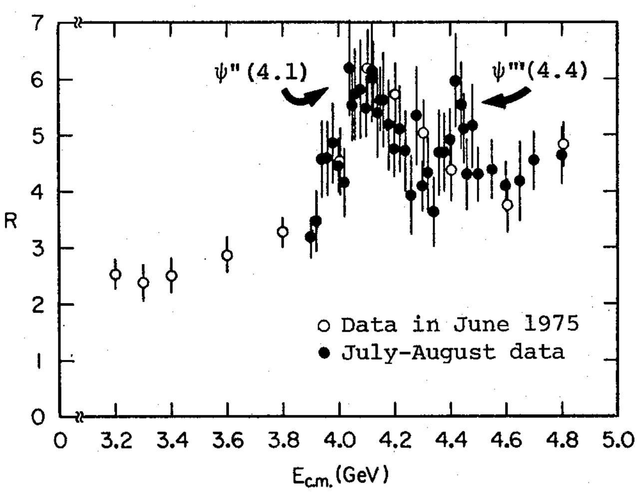
1. THE 4.1 GeV BUMP IN MORE DETAIL

On pages S-5 and S-6 last month we showed two small graphs of the famous ratio, R, of hadron production to muon-pair production at SPEAR as a function of energy. This method of presenting the data probably gives the best general overview of hadron production by e^+e^- colliding beams at SPEAR. We now update the previous two graphs with the figure shown on this page, which represents all the data that the SLAC-LBL group had taken in the large magnetic detector at SPEAR through the end of last August. The figure caption gives a general description of these data; for our purposes the thing we'll want to



This figure summarizes much of the SPEAR data on hadron production as of August 1975. As we noted earlier, there appear to be three distinct regions in the data: (1) Below about 3.8 GeV the hadron/muon-pair ratio R is roughly constant at a value of about 2.5. (2) From 3.8 to perhaps 5 GeV there is a richly structured region in which R scrambles all over the place. (3) Above 5 GeV R again becomes roughly constant, but this time at a value of about 5 or 5.5. Note that the region around 4.1 GeV, previously an unresolved broad enhancement or bump, has emerged from last summer's more detailed study as at least two separate peaks, and very possibly more. Although the connection between the 4.1-4.4 double peak and the $\psi(3.1)$ and $\psi(3.7)$ particles is not yet clear, it has become common to describe the four resonances as a psi sequence: ψ, ψ', ψ'', ψ'''. There is much speculation about the fact that the transition region marks the onset of "new physics"--perhaps the region where "charmed" particles begin to be produced, or where the annihilation process is energetic enough to create pairs of the massive electron-like particles called "heavy leptons" that have often been predicted but never observed. So complex a region will take many months and even years to explore thoroughly, but the more closely it is studied the more it appears to resemble a Mother Lode gold mine.

focus on is the transition region where all the tugging and hauling seems to be going on. In order to see this region a little more clearly, the next figure presents the transition region with an expanded horizontal scale. This is exactly the same experimental data as we had in the previous figure, but spread out a bit and covering a smaller energy span.



An expanded view of the hadron/muon-pair ratio R in the transition region around 4 GeV. The older data (open circles) traced out an enhancement or bump at 4.1 GeV that was about 250 MeV wide. The results of last summer's more detailed study of this region have now resolved the broad structure into two distinct peaks. The resonance at 4.4 GeV has a width of some 30 to 50 MeV. The 4.1 GeV resonance looks wider than that, but there are some hints that it may actually be two or more separate states superposed.

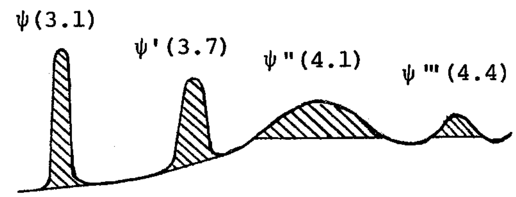
Having seen, then, that last summer's more detailed exploration of the transition region from about 3.8 to 5.0 GeV has turned up a more complex structure than was previously observed, what are we supposed to conclude from that? Well, the one-line answer to that question is something like, "We don't know yet." It may still serve some purpose, however, to talk about a few of the possibilities and plans.

Are The 4.1 And 4.4 Resonances Psi Particles?

The present consensus appears to be "Probably," for the following several reasons:

(a) Each of the resonances ψ(3.1), ψ'(3.7), ψ"(4.1) and ψ'''(4.4) is directly produced in the same e^+e^- annihilation process.

(b) The ψ(3.1) and ψ'(3.7) resonances are very sharp--that is, tall and narrow--whereas the ψ"(4.1) and ψ'''(4.4) are short and wide. As we noted earlier (page *S*-7), however, the total "strength" of a resonance is a combination of height and width. In simplified, schematic form we might sketch the four resonances like this:



Since height and width both count, the total strength is essentially the *area* under the resonance curve; and within a factor of about 3 or so the areas of the ψ, ψ' and ψ" curves are all the same. (The ψ''' is significantly smaller; it may in fact not fit into the psi sequence.)

(c) The most commonly accepted theory of the psi particles postulates that they are composed of a new kind of ("charmed") quark, c, bound together with its corresponding antiquark, $\bar{c}$. In analogy with other bound systems of particles of this kind,* there should be a sequence of $c\bar{c}$ states of increasing mass which result from the different patterns of relative motion that the c and $\bar{c}$ quarks can have with respect to each other in their bound configuration.

But Why The Great Difference In Widths?

First let's compare some of the properties of the four resonances we're talking about.

Resonance	Mass (MeV)	Total Decay Width	Width To e^+e^-
ψ	3095	70 keV	4.8 keV
ψ'	3684	220 keV	2.2 keV
ψ"	∿ 4100	∿ 150 MeV	∿ 2.5 keV
ψ'''	∿ 4400	∿ 50 MeV	∿ 0.6 keV

Although the leptonic decay widths (width to e^+e^-, same as width to $\mu^+\mu^-$) for the four states are comparable and reasonably consistent with a sequence of vector mesons, the total decay widths for ψ" and ψ''' are about 1000 times as large as those for ψ and ψ'. Recalling from our earlier discussion that a broad width goes with a short lifetime, we can see that the ψ" and ψ''' appear simply to be typical hadronic (short-lived) resonances, and thus completely lack the anomalously long lifetime that was identified as the psi particles' most striking characteristic. How come?

The explanation for this very large difference between ψ, ψ' and ψ", ψ''' is a little lengthy but perhaps worth trying. We begin by considering two well-known vector-meson decay processes:

rho: $\rho(770) \rightarrow \pi(137) + \pi(137)$ Width: 150 MeV

phi: $\phi(1019) \rightarrow K(492) + K(492)$ Width: 4 MeV

*See the discussion in *Detour 4: Charmonium*.

The figures in parentheses are the masses of the particles involved in MeV. Note that in the first reaction the 770 MeV mass of the ρ meson is much larger than the combined pion-pair mass of 274 MeV. This large mass difference makes it "easy" for the decay to occur, so it happens very rapidly (large width = fast). In the second reaction the ϕ meson decays much more slowly into the K-meson-pair because there isn't very much "room" between the ϕ mass of 1019 MeV and the combined K-pair mass of 992 MeV. In fact, if nature had been just a little more heavy-handed in designing K mesons (giving them a mass, say, of 510 MeV), then the decay process $\phi \to KK$ simply would not happen because 1020 MeV cannot be squeezed out of 1019 MeV no matter how you slice it.

A second part of the explanation is related to a different decay process in which ϕ mesons are involved:

phi: $\phi(1019) \to \pi(137) + \pi(137) + \pi(137)$ Width: 0.6 MeV

The combined mass of the three pions is 401 MeV, which is much less than the K-pair mass of 992 MeV, but nevertheless the process $\phi \to KK$ is about 6 times as likely to occur as the process $\phi \to \pi\pi\pi$. This is because the ϕ meson consists of the quark-antiquark pair $s\bar{s}$, and these are the quarks that carry the intrinsic property or quantum number called strangeness. (Never mind what strangeness actually *is*; no one knows.) And when it comes time for the ϕ meson to decay, it displays a decided preference for decaying into particles that also contain either an s or an $\bar{s}$ quark. That is, the ϕ meson "wants" to pass on its $s\bar{s}$ quarks unchanged, and for this purpose K mesons are dandy because they are made of such quark-antiquark combinations as $d\bar{s}$, $s\bar{u}$ and $u\bar{s}$, whereas pions consist of $u\bar{d}$, $d\bar{u}$ and $d\bar{d}$. As a result of this preference,* the decay process

$\phi \to KK$ proceeds normally

while

$\phi \to \pi\pi\pi$ is suppressed.

The answer, finally. The question we set out to try to answer was, *But why the great difference in widths?* The answer that is being given these days by many physicists is based on an analogy with the phi meson decays we've just been discussing. The psi particles are assumed to consist of the quark-antiquark pair $c\bar{c}$, and as with the ϕ they have a preference for decaying into particles that also contain c or $\bar{c}$ quarks, with all other decay modes being suppressed (i.e., much reduced, not eliminated). Mesons built from one new c or $\bar{c}$ quark and one ordinary quark would have the composition $c\bar{u}$, $u\bar{c}$, $d\bar{c}$, $c\bar{s}$, etc. We assign to this new class of mesons the generic names $D\bar{D}$. The preferred strong-interaction decay mode of the psi particles, analagous to $\phi \to K\bar{K}$, would then be

$$\psi \to D\bar{D}$$

But there's a problem: the *lightest* of the hypothetical new D mesons is estimated to have a mass of about 1.9 or 2.0 GeV, in which case a $D\bar{D}$ pair has a mass of about 3.8 to 4.0 GeV. If those masses are correct, then

$$\left.\begin{array}{l}\psi(3095) \not\to D\bar{D} \\ \psi'(3684) \not\to D\bar{D}\end{array}\right\} \text{doesn't happen}$$

$$\left.\begin{array}{l}\psi''(4100) \longrightarrow D\bar{D} \\ \psi'''(4400) \longrightarrow D\bar{D}\end{array}\right\} \text{proceeds normally}$$

So it is this chain of reasoning that purports to explain why the decay widths of the $\psi''(4100)$ and $\psi'''(4400)$ are so large--and also why the decay widths of the $\psi(3095)$ and $\psi'(3684)$ are so small. It is worth noting that the whole explanation may be dead wrong. As it stands now, however, it does provide a way of tentatively grouping the four resonances within the same psi family even with such a large difference in decay widths between the upper and lower pairs.

When Will The ψ'' And ψ''' Questions Be Settled?

Probably many months from now; maybe more than a year. Although the initial broad bump at 4.1 GeV has been known about for at least the

. . . Some typical reaction rates for 6 GeV in the center-of-mass system are:

$e^+ + e^-$	52/hour
$\mu^+ + \mu^-$	26/hour
$\pi^+ + \pi^-$	6/hour
$p + \bar{p}$	.00003 to 200/hour

. . . the magnitude for [$p\bar{p}$] is quite uncertain. The upper limit was calculated using . . . point-like form factors.

The cross sections for those processes that do not involve strongly interacting final states are much less uncertain and much larger than [those which do]. . . Our estimates of the yield of strong interaction processes may be pessimistic, in which case it would be desirable to extend our measurements to higher energy.

--*Proposal for a High Energy Electron-Positron Colliding Beam Storage Ring at SLAC*, June 1965

*The whole "preference" discussion given here is a much oversimplified version of an empirical rule ("Zweig's rule") which states, roughly, that a quark and antiquark cannot both disappear in a single interaction. ("Cannot" means "happens rarely.") A more general formulation of the same idea (the "Levin-Frankfurt" rule) postulates that only one quark in a hadron is active in any single interaction; all others are simply spectators and are unaffected. This rule appears to work remarkably well in a variety of cases, although no one has been able to explain why. For more on this rule, see S. Glashow, "Quarks with color and flavor," *Scientific American*, October 1975.

last 15 months, there were certain experimental jobs that had a higher priority for much of the intervening time. The first job was a general survey to map the energy region covered by SPEAR I (2.4 to 4.8 GeV). Then after the $\psi(3.1)$ and $\psi'(3.7)$ were discovered, there was extensive "resonance running" at those energies to study the properties of the new particles, and also a systematic fine-toothed search through the full energy region to search for other possible narrow resonances. Then much of this work was repeated at the higher energies (presently up to about 7.8 GeV) that the SPEAR II improvement program made possible.

The problem at SPEAR has not been that of trying to find something interesting to do. So far it has been more nearly trying to find time to investigate what has been an embarrassment of riches. When the opportunity finally presented itself, last July, to begin exploring the region around 4.1 GeV, just a few weeks of running turned up the complicated structure that we saw in an earlier figure. At present these studies are continuing, and the most recent tentative results appear to be even craggier looking than anything we've previously seen. More hills and valleys means lots more *physics*, but it also means that it will take a long time to chart every landmark in enough detail to understand what is happening. For the time being, then, all we can say is that the transition region from 3.8 to 4.6 Gev looks like superb high country, and if the yeti's don't git 'em, the climbers ought to bring back some pretty tall tales.

2. RADIATIVE TRANSITIONS

Having just come from a place where there was plenty of action but not many facts, we now turn to several specific recent discoveries. By studying in detail the decays of the $\psi(3.1)$ and $\psi'(3.7)$ resonances into other, lighter particles, four new resonant states have been observed during the past few months. These new particles and the decay processes from which they come are as follows:

$$\psi'(3.7) \rightarrow P_c(3.5 \text{ or } 3.3) + \gamma$$

$$\psi'(3.7) \rightarrow \chi'(3.5) + \gamma$$

$$\psi'(3.7) \rightarrow \chi(3.4) + \gamma$$

$$\psi(3.1) \rightarrow X(2.8) + \gamma$$

[We're not too happy with these names, but we vent our spleen about names separately, there, and get back to business.]

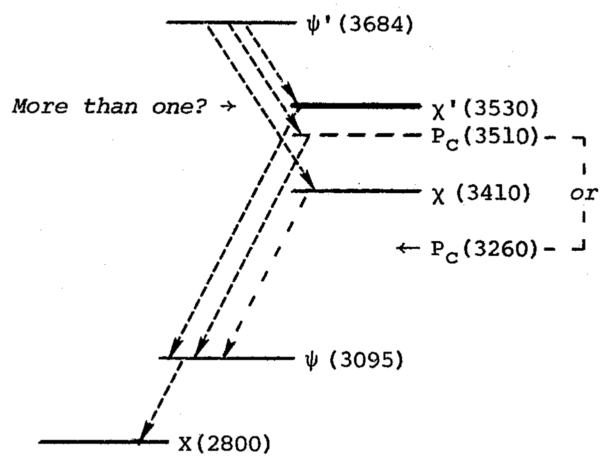
The first of these new states, the P_c, was discovered at the DORIS e^+e^- storage ring at the DESY laboratory in Hamburg, Germany, back in about June of this year. Then soon afterward the SLAC-LBL group at SPEAR observed the two chi states, $\chi(3.4)$ and $\chi'(3.5)$; and at the August *Lepton-Photon Symposium* held at Stanford the DORIS group presented the first evidence for the $X(2.8)$ resonance.

None of these four new states is created directly in the e^+e^- annihilation process that produces the psi particles. All appear, rather, as a result of particular kinds of decay processes that are called *radiative transitions*. These are simply processes in which the change from one state to another is accompanied by the emission of a unit of electromagnetic radiation. In the process $\psi'(3.7) \rightarrow \chi(3.4) + \gamma$, for example, γ is an emitted gamma ray which carries away the difference in energy between the ψ' and χ states (3.7 minus 3.4 GeV = 0.3 GeV).

The subject of radiative transitions in general, and of the transitions between the psi states and the newly discovered states in particular, is covered in some detail in the last part of this article (*Detour 4: Charmonium*). In this section we plan to give a brief description of the new particles and of their relationships to the psi resonances, and then to turn the bulk of our attention to a rundown of the experimental procedures that were used at SPEAR to track down the two new chi states.

ψ, ψ' And The New Particles

Let's begin with a modified version of the energy-level sketch that appeared on page *S-1* at the beginning of this article:



In this sketch we've omitted all decay modes except for the radiative transitions, so each arrow shows a pathway for one state to decay into another with the emission of a gamma ray. In the case of the $\chi(3410) \rightarrow \psi(3095)$, the gapped

In high energy physics, newly discovered particles are often named before enough is known about them to help guide the choice of names. Understandable, perhaps, but to the innocent bystander the results appear to be chaotic. Here, for example, are the names, from lowest to highest mass, of the particles in the class of unstable mesons:

$$\pi\eta\epsilon\rho\omega\eta'\delta S^*\phi A_1 B f D A_2 E f' F_1 \rho' A_3 \omega' g$$

Beautiful.

line (- - -) indicates that this particular transition has been only tentatively identified. The $\chi'(3530)$ level has been drawn thicker than the others because it is the broadest of these resonances and may in fact be two or more resonances jammed together.

The P_c ambiguity. Two alternate positions for the P_c resonance are shown for the following reason. The decay process in which the P_c is created goes like this:

$$\psi' \rightarrow P_c + \gamma$$
$$\quad\quad \hookrightarrow \psi + \gamma$$

But this happens so rapidly that what is actually observed in the experiment is simply $\psi' \rightarrow \psi + \gamma + \gamma$. The energies of the two gamma rays are measured to be about 170 MeV and 420 MeV, and the ambiguity results from the fact that it has not yet been possible to determine which gamma ray is emitted first. The two possibilities are

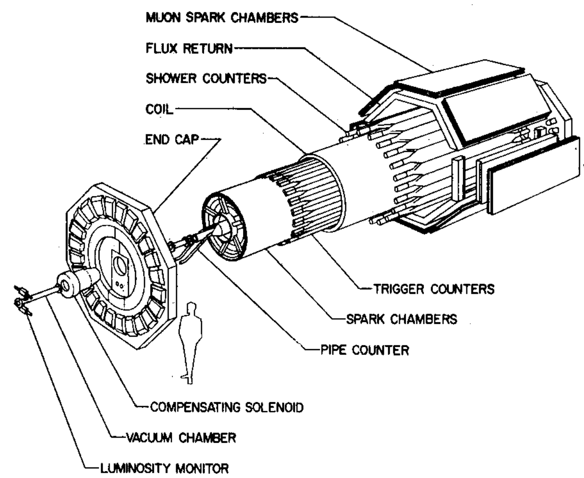
$$\psi'(3684) \rightarrow P_c(3510) + \gamma(170 \text{ MeV})$$
$$\psi'(3684) \rightarrow P_c(3260) + \gamma(420 \text{ MeV})$$

The correct choice can in principle be made by measuring what is called the "Doppler broadening." (Most people are familiar with the way the sound of a train horn sounds lower in pitch as the train goes past; this is the Doppler effect.) A difference between the two gamma rays emitted in the $\psi' \rightarrow P_c \rightarrow \psi$ process above is that the first γ comes from a stationary source, the ψ', so its "pitch" or energy will seem the same to all observers. But after the first part of the decay the P_c and γ go flying off in opposite directions, and thus the second gamma ray will be emitted by a moving source, the P_c. Since the direction of the P_c's motion is random, the experimental detector will record the second gamma ray as sometimes higher and sometimes lower than its actual energy. Thus it should be possible, after enough measurements, to spot the difference between the narrow and broadened gamma ray spectra and therefore to decide whether the 170 or 420 MeV gamma ray is emitted first.

Name	*Mass (MeV)*	*Width*	*Decay Modes*
ψ	3095	70 keV	e^+e^-, $\mu^+\mu^-$ many hadronic modes $X(2800)\gamma$
ψ'	3684	220 keV	e^+e^-, $\mu^+\mu^-$ $\psi\pi\pi$, $\psi\eta$ $P_c(3510)$, $\chi(3410)$
X	2800	?	$\gamma\gamma$, $p\bar{p}$
χ	3410	narrow	$2,4,6\pi$, $K\bar{K}$, $\pi\pi K\bar{K}$ $\psi\gamma$?
P_c	3510	narrow	$\psi\gamma$
χ'	3530	wide or 2 narrow	$4,6\pi$, $\pi\pi K\bar{K}$ $\psi\gamma$

Tracking Down The Chi Particles

We turn now to an attempt to describe how the $\chi(3410)$ and $\chi'(3530)$ particles were discovered at SPEAR. As a starting point, here is a reminder of what the large magnetic detector at SPEAR looks like in a telescoped view:

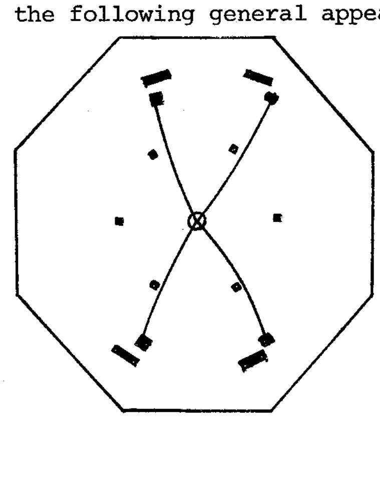


In brief, this detector consists of a number of concentric arrays of various kinds of counters and wire chambers which respond to the passage of an electrically charged particle. These detection devices are located within and around a large solenoidal magnet which deflects the paths of the particles into curved tracks. These elements can provide several kinds of information, but here we'll concentrate on just two: (1) The detectors can measure the time required for a particle to traverse a certain distance and thus establish its *velocity*. (2) The degree of curvature of the track of a particle moving within the magnetic field can also be measured and thus establish its *momentum*. From these two measured quantities a third can be deduced:

$$\text{momentum} = \text{mass} \times \text{velocity}$$

That's all we'll need for the following discussion.

We begin our search for new states that the ψ or ψ' might decay into by collecting from the SPEAR data a large sample of recorded events that have the following general appearance:

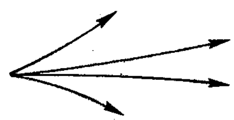


This is a "four-prong" event, with each of the curved tracks representing the path of a charged particle. This particular event might be a picture of either of these two processes (or others)

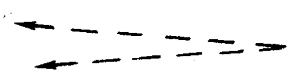
$$e^+e^- \to \psi \to \pi^+\pi^-\pi^+\pi^-$$

$$e^+e^- \to \psi \to \pi^+\pi^-\pi^+\pi^-\pi^o$$

It is not always possible to choose correctly between possible alternative explanations, but when it is possible the method used is to do a detailed bookkeeping job on the quantities of momentum, energy, mass and others to see if everything can be accounted for. Suppose, for example that a different four-prong event from SPEAR looked like this:

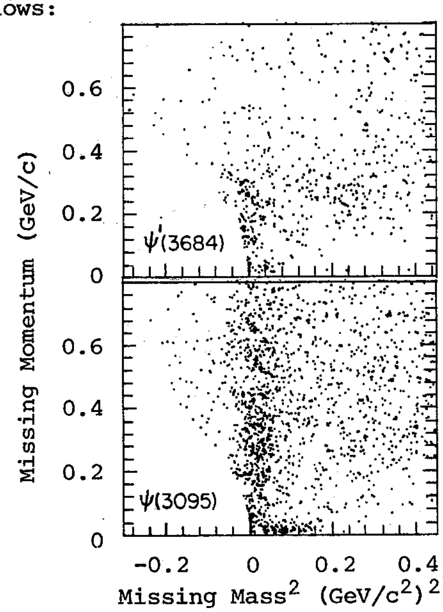


In this case it's perfectly obvious that there must be more than the four visible particles involved, and by a little vector addition we could figure out that the unseen particles would have to have acted something like this

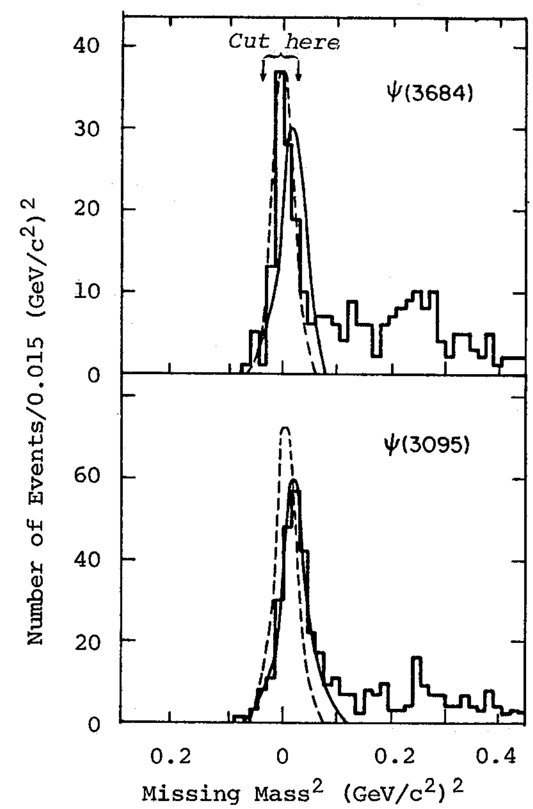


to balance things out. So figuring out the "missing mass" or "missing momentum," etc., can often provide a lot of information about the unobserved particle(s) that carried off what is missing.

OK, then, back to SPEAR. We gather together a nice big sample of four-prong events, add up what we can see in the visible tracks, and then calculate what is missing--specifically for our purposes missing mass and missing momentum. We then make a "scatter plot" of all these events as follows:



A notable feature of this plot is the dense band of events extending upward, at (missing mass)^2 = 0, through the ψ(3095) graph--like a geyser. This band represents the 5-pion decay mode of the ψ, one of its favorites. When we look for a similar fountain in the upper graph, we see that there is indeed a little squirt there, concentrated between 0.1 and 0.3 GeV/c in missing momentum. Since we can't identify that particular decay mode of the ψ'(3684), our next step is take a horizontal slice through the ψ' graph (the band indicated by *"Cut here"*) and pull it out for more detailed attention. For comparison, we also take a similar slice out of the ψ(3095) data, and we show the events from both of these sliced-out strips in the next figure.



Four-prong events with missing momentum between 0.1 and 0.3 GeV/c plotted against missing mass squared for the ψ and ψ' decays. The solid curve is the predicted distribution for a missing π^o; the dashed curve, for a missing gamma ray (γ).

[We forgot to mention that the scatter plot for the ψ'(3684) excludes its most common decay, $\psi' \to \psi\pi\pi$; we threw out all of those events to start with because they weren't what we were looking for.]

Let's recall that what we're studying here is

$$\psi \text{ or } \psi' \to 4 \text{ prongs} + \text{"missing"}$$

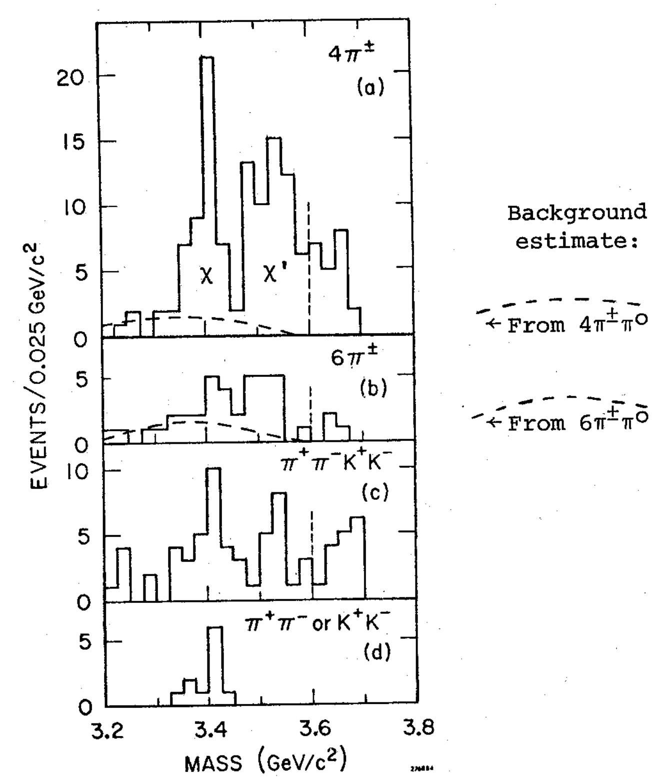
We assume that the 4 prongs are 4 pions (mostly they will be, but the assumption is not critical), and we search for what, if anything, the "missing" is. In the figure we've just seen the "missing" turned out to be two different things: (1) for the $\psi(3095)$ the distribution of events fits the prediction for a missing π^o, which is not too startling since we already knew about $\psi \to 4\pi + \pi^o$; (2) but for the $\psi'(3684)$ the event distribution fits the prediction for a missing photon or gamma ray, $\psi' \to 4\pi + \gamma$, and that begins to sound like one of the radiative transitions we've been looking for.

The next step in the procedure is to cut another slice out of the data, this time a very skinny vertical cut down on either side of the tall peak in the ψ' data from the last figure (*"Cut here"*). This cut selects out the hundred or so events that are centered on a missing mass squared of zero in preparation for the next figure--which we're not quite ready for.

Before we go to the next figure, imagine that we had gone through the whole rigamarole procedure we just carried out not only for $\psi' \to 4\pi$ + missing but also for

$\psi' \to 6\pi$ + missing
$\psi' \to \pi\pi K\bar{K}$ + missing
$\psi' \to \pi\pi$ or $K\bar{K}$ + missing

OK, the final result for all of these ψ' decay modes is shown in the next figure.

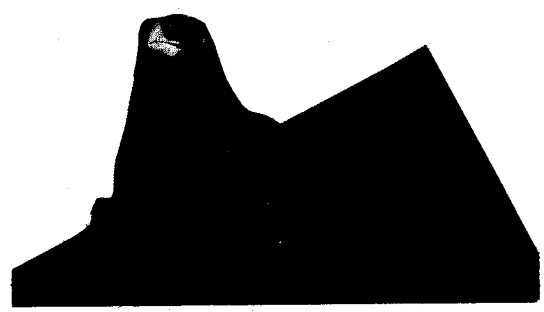


Invariant mass distributions with the missing mass squared constrained to be 0. The narrow $\chi(3410)$ shows up clearly in all modes; the broader (perhaps multiple) $\chi'(3530)$ in the first three. Events above 3.6 GeV don't count.

So after all this cutting and slashing, up like magic from the decimated data leaps the New York City skyline. In the 4π data two structures are very obvious (ignore everything to the right of the vertical dashed lines; most of the events above 3.6 GeV do not fit with what we're talking about here). The first is the sharp, 21-storey skyscraper which is centered at an energy just above 3.4 GeV: this is the $\chi(3410)$ resonance, which appears prominently in all four of the decay-mode graphs. The second apparent structure is the broader, perhaps double-peaked bump that is centered at an energy somewhat above 3.5 GeV: this is the $\chi'(3530)$ resonance, which appears in 4π, 6π, and $\pi\pi K\bar{K}$, but not in $\pi\pi$ or $K\bar{K}$. The fact that the $\chi(3410)$ *does* appear in the bottom graph tells us some important information about this new state, namely that it has the quantum numbers (characteristic properties) J^{PC} = (even)$^{++}$.

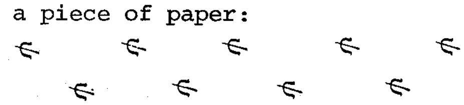
We end this section with our periodic reminder about believing everything you read in the newspapers, this time quoting Mr. Einstein:

If it is certain, it is not physics;
if it is physics, it is not certain.



Shrewd Theorist Predicts Psi Spectroscopy!

Shown above is Professor C. C. Raven, distinguished theorist, who paid a brief visit to SLAC last January, shortly after the discoveries of the original two psi particles. In our interview with Professor Raven, which appeared in the January 1975 *Beam Line*, we asked if he had any predictions to make about the new particles. His first response was to hop onto an ink pad and then slue-foot it across a piece of paper:



Since we're a little slow getting the message, we then asked if any more new particles beides the first two would be discovered.

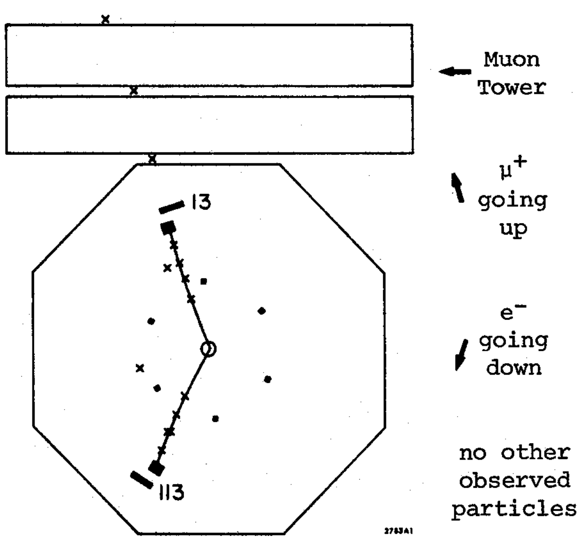
Then quoth the Raven: *"Seven more!"*

Sure makes you kinda wonder, don't it?

3. THE U PARTICLE

We will say less about the U particle than we did about the chi's because there is less to say. The whole plot in brief is this: at SPEAR a number of peculiar events have been observed that do not seem to have a conventional explanation. These events are devilishly tricky to analyze correctly. But if the present analysis is correct (and we think it is), then the events appear to be coming from any of three possible unconventional sources: a new charged meson, "charmed" mesons, or an electron-like "heavy lepton." If any of these possibilities proves to be correct, discovery of the U particle will considerably outweigh in importance the chi and other radiative transition states we've just been discussing. So hang in there, Charlie, we've got another kettle cookin'.

Every so often at SPEAR the magnetic detector turns up an event that looks like this:



In this computer reconstruction of the event the up-going track is a μ^+ that penetrates all the way through the concrete-and-detector sandwich of the muon tower to the far-outside spark chamber. The down-going track is an electron that signals its presence by "showering" a cascade of x-rays and e^+e^- pairs in a shower counter. Both muon and electron behave in a way that is quite distinctive (penetration and showering), and for this reason they are generally not confused with other kinds of particles.

Although no other particles, either charged or neutral, are observed in events of this kind, the reaction being detected must include more than just the $e^-\mu^+$ (or $e^+\mu^-$):

$e^+ + e^- \rightarrow$	e^- +	μ^+ +	something else
6.6 GeV in	1.0 GeV out	1.6 GeV out	4.0 GeV out (?)

The "something else," whatever it is, typically carries off about 1/2 of the total energy (in this case about 2/3) brought into the interaction by the colliding e^+e^- beams at SPEAR.

Some Possibilities

We consider briefly three hypothetical new processes that could give rise to the observed events.

1. New charged meson. If the U particles are a new kind of charged meson, especially a vector meson (something like $\psi^{\pm}$), then they would probably have a pretty frequent two-body decay of the sort

$$e^+e^- \rightarrow U^+U^- \rightarrow e^-\bar{\nu}, \quad U^+ \rightarrow \mu^+\nu$$

This produces a final state of $e^-\mu^+$ and two neutrinos (ν). The neutrinos would certainly escape with a lot of the energy without being detected (they interact far less than any other known particle). However, as we'll soon see, the data favor three-body decay processes over two-body decays such as those noted above. Tentative verdict: *Doesn't seem very likely.*

2. Charmed mesons. Suppose, for example, that the $\psi''(4100)$ decays into two charmed mesons (with quarks $c\bar{u}$ and $u\bar{c}$, say), which in turn decay like this:

$$U^- \rightarrow e^-\bar{\nu}K^0 \qquad U^0 \rightarrow e^-\bar{\nu}K^+$$
$$U^+ \rightarrow \mu^+\nu\bar{K}^0 \qquad \bar{U}^0 \rightarrow \mu^+\nu K^-$$

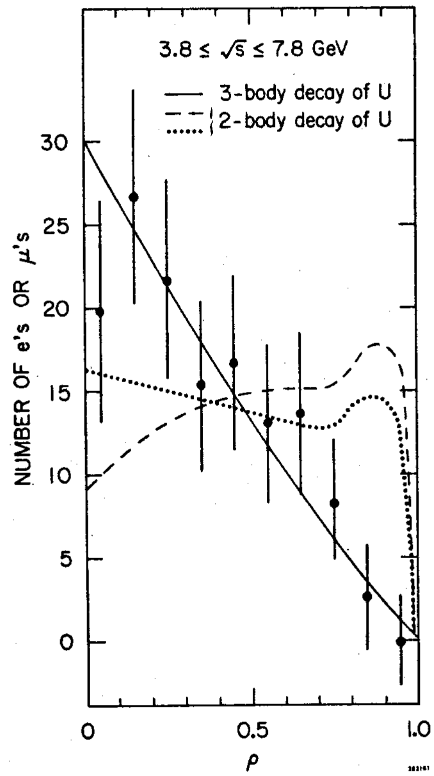
These are examples of the experimentally favored three-body decays, but the trouble is that they are also what are called "semileptonic" decays--a mixture of leptons and hadrons. This means that many mixed lepton-hadron decays should have been observed by now, but this hasn't happened. Tentative verdict: *Also not too likely.*

3. Heavy leptons. The muon is often referred to as a "heavy electron," and there has been endless speculation about the possibility of a sequence of electron-like particles that includes a third, fourth . . . heavy lepton. The decay modes of such hypothetical particles would likely be dominated by the following decays:

$$U^- \rightarrow e^-\bar{\nu}\nu \qquad U^+ \rightarrow \mu^+\nu\bar{\nu}$$

(The neutrinos shown in all these conjectured processes are not all the same, but we've ignored the differences here.) These decays would produce an $e^-\mu^+$ in the final state, the neutrinos would carry off a large fraction of the energy without being detected, and the decays are all of the favored three-body type. Tentative verdict: *Most likely of these three hypotheses. A really first class discovery if heavy leptons prove to be the answer.*

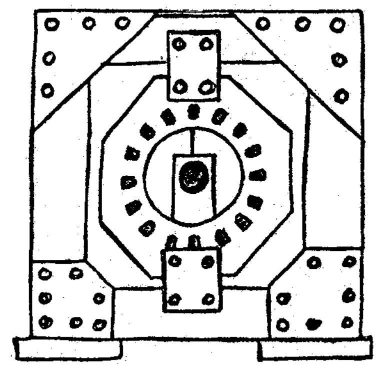
We move on now to the last item about the U particles--the two-body vs. three-body evidence in regard to the decay processes in which the observed $e^-\mu^+$ or $e^+\mu^-$ combination seem to be produced. This data is shown in the following figure.

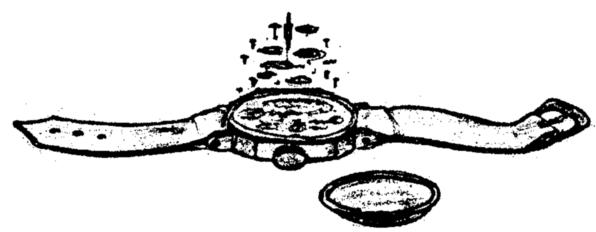


The distribution of observed electrons and muons in "U particle" events as a (complicated and not explained here) function of momentum, ρ. The dotted and dashed curves are the predicted distribution for two kinds of two-body decays. The solid curve is the prediction for three-body decays of a heavy lepton with a mass of 1.8 GeV. The solid curve is a rather good fit to the experimental data; the others are not.

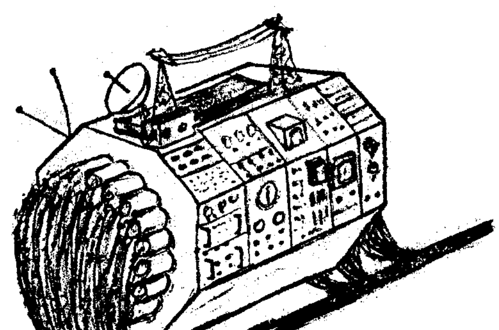
THE SPEAR MAGNETIC DETECTOR
AS SEEN BY

STRUCTURAL GROUP



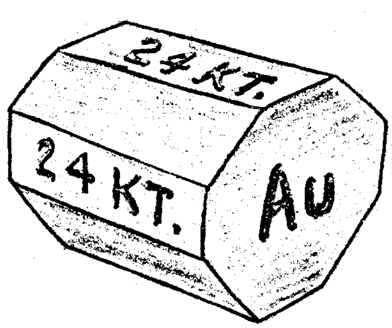


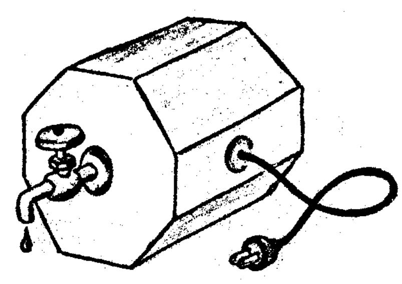
MECHANICAL ENGINEERING



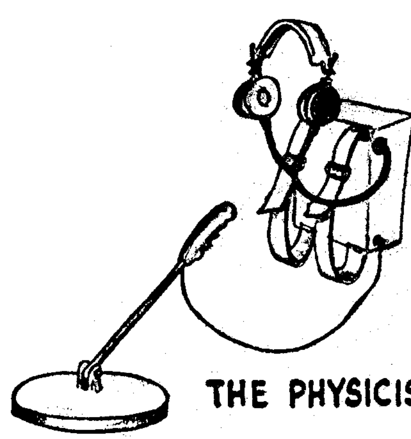
ELECTRONICS

ACCOUNTING





PLANT ENGINEERING

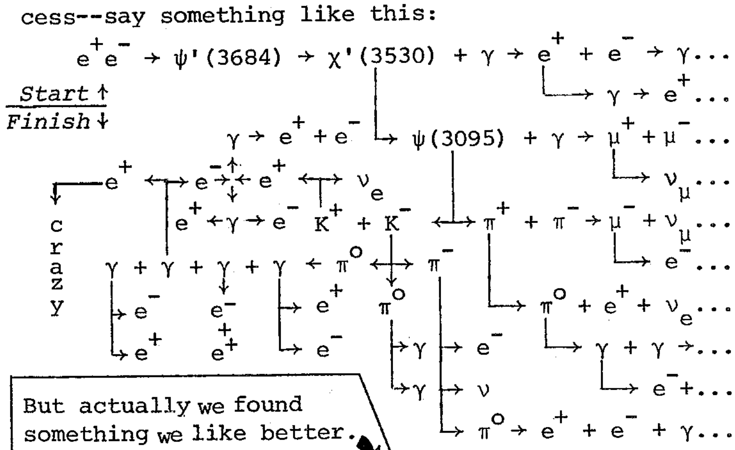


THE PHYSICIST

Sketches by George Lee

Detour 3: A Maze Of Inference

We originally had great plans for this *Detour*. We were going to start with the observation that no one has ever seen, heard or tasted an elementary particle, and consequently that everything that is known about these particles is known indirectly--by *inference*. Then our plan was to illustrate a long inferential chain by writing down what *really* happens in a complex decay process--say something like this:



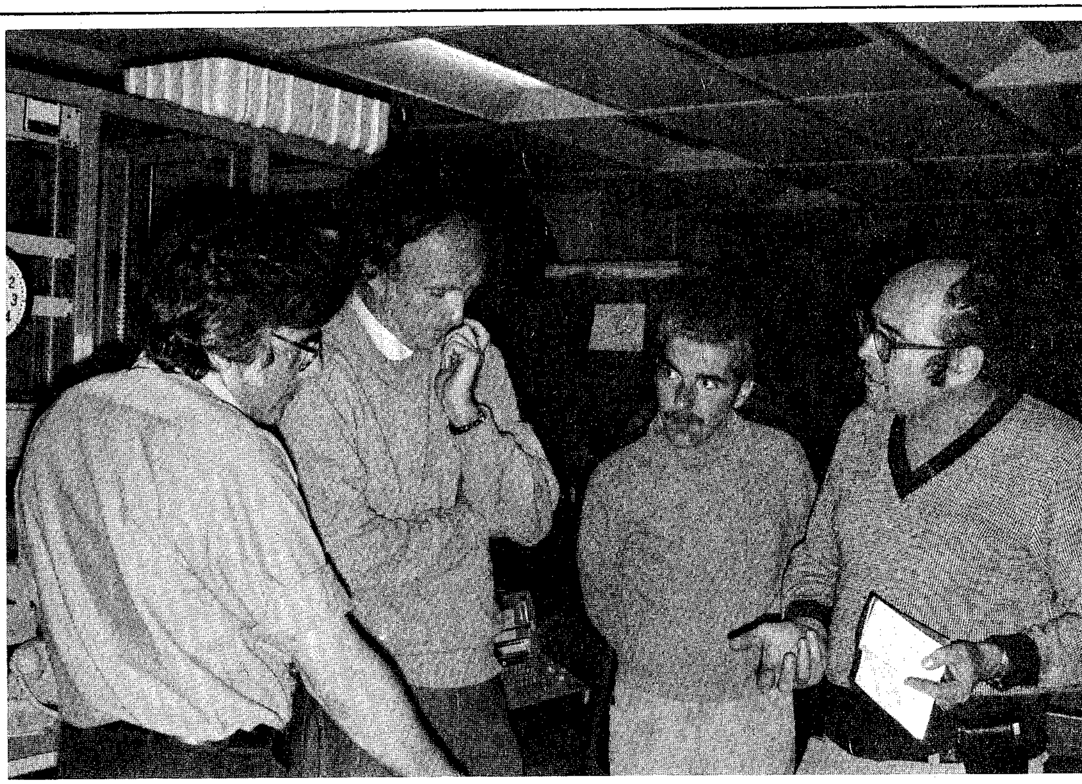
But actually we found something we like better.

A few months ago Werner Heisenberg and Wolfgang Pauli believed that they had made an essential step forward in the direction of a theory of elementary particles. Pauli happened to be passing through New York, and was prevailed upon to give a lecture explaining the new ideas to an audience that included Niels Bohr. Pauli spoke for an hour, and then there was a general discussion during which he was criticized sharply by the younger generation. Finally Bohr was called upon to make a speech summing up the argument.

"We are all agreed," he said, "that your theory is crazy. The question which divides us is whether it is crazy enough to have a chance of being correct. My own feeling is that it is not crazy enough."

The objection that they are not crazy enough applies to all attempts which have so far been launched at a radically new theory of the elementary particles. It applies especially to crackpots. Most of the crackpot papers that are submitted to *The Physical Review* are rejected, not because it is impossible to understand them, but because it *is* possible. Those which are impossible to understand are usually published. When the great innovation appears, it will almost certainly be in a muddled, incomplete and confusing form. To the discoverer himself it will be only half-understood; to everyone else it will be a mystery. For any speculation that does not at first glance look crazy, there is no hope.

--Freeman J. Dyson
Scientific American, Sept. 1958



From the left, William Chinowsky of UC-Berkeley; Martin Perl, SLAC; Francois Vannucci, SLAC (on leave from the Orsay Laboratory in France); and Gerson Goldhaber, UC-Berkeley; all members of the SLAC-LBL collaborative experimental group working at SPEAR.

Photo: UC-Berkeley

F. Some Lightweight Theory

1. THE POSSIBILITIES

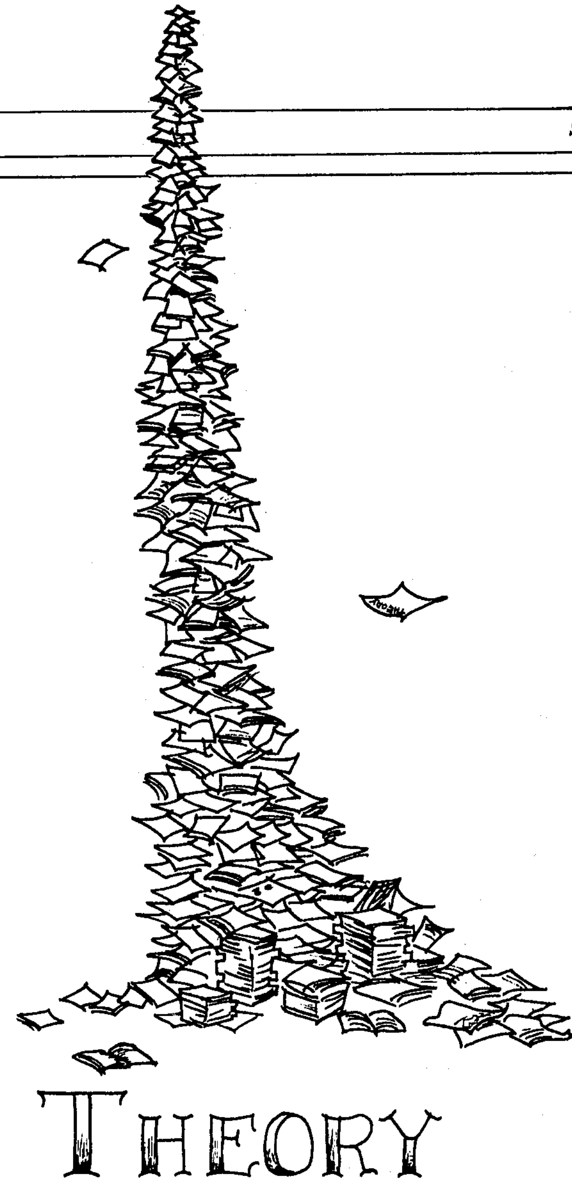
About a year ago, in a *Beam Line* article that described the then recently discovered ψ and ψ' particles, we gave a rundown of the three most interesting theoretical possibilities that had been proposed as explanations for the psi's existence and nature. We begin this section with a brief review of what has happened to those three ideas during the intervening time.

Intermediate vector boson. Back on pages *S-2* and *S-3* of this article we discussed the fact that three of the four fundamental forces in nature--the strong, electromagnetic and gravitational forces--are mediated or "carried" by certain particles (e.g., the photon is the carrier of electromagnetism). Many physicists believe that the fourth fundamental force, the weak or Fermi force, is also carried by a particle, as yet undiscovered, that long ago was given the name *intermediate vector boson* (which we'll abbreviate as "IVB"). For a number of years the IVB was thought to exist only in electrically charged states, W^+ and W^-, but more recently it has been surmised that there should also be a neutral version, Z^o. Soon after the original psi particle discoveries several theorists suggested that here, at long last, was the warmly anticipated Z^o.

This particular idea has gradually wasted away to silence during the past 12 months. There are at least three serious problems facing those who would identify the psi particles as IVB's. (1) The mass predicted for the W^+ and W^- states was about 40 GeV, a factor of about 10 larger than the psi particles, and although the IVB in its neutral manifestation, the Z^o, could well be less massive than its charged brothers, it was probably not *that* much less. (2) As it became clearer that the ψ and ψ' could be fitted into the class of strongly interacting particles called vector mesons, the inappropriateness of such behavior for the presumed carrier of the *weak* force became more and more evident. (3) With the discovery of the additional states related to the psi particles--the P_c and X, the χ and χ', and perhaps the ψ'' and ψ'''--the IVB idea went dead in the water since it seemed highly unlikely that a whole squadron of particles would be needed to carry the weak force.

The idea of color. Several years ago it was suggested that the three basic quarks from which the hadrons are thought to be built might each exist in three different "colored" states:

$$\begin{array}{lll} u_{red} & d_{red} & s_{red} \\ u_{white} & d_{white} & s_{white} \\ u_{blue} & d_{blue} & s_{blue} \end{array}$$



Based on an idea of J. D. Jackson at Berkeley, and reprinted from the April 1975 issue of the CERN COURIER.

Bob Gould

(Substitute *yellow* for *white* if the latter seems colorless to you.) The particular problem that the original suggestion of color was intended to solve is one called "antisymmetric statistics"; we won't discuss it here except to say that the present consensus appears to favor the idea of quarks in various colors. However, this conclusion has a hooker in it, namely, that any *real* particle has to be constructed in such a way that color cancels out. In this scheme a proton, for example, might consist of the three quarks $u_r u_w d_b$, and the effect of having one quark of each color is that the proton has no *net* color.

After the psi particles were discovered, a number of theorists suggested that perhaps they were the first examples of real particles for which color did *not* cancel out, and for a time this suggestion received a great deal of attention. At present, however, the idea of psi particles as colored states faces several serious problems, among which are the following three: (1) The $\psi(3.1)$ decays directly into hadrons. (2) Radiative decays of the ψ are only a small fraction of the total decay width. (3) There does not appear to be any significant production of ψ' particles at energies above the resonance peak of 3.684 GeV. All three of these experimental observations are inconsistent with the color model for the psi particles.

The idea of charm. As in the case of color, the idea that the basic three quarks needed to have something added to them--in this case a fourth, "charmed" quark, c,

$$u \quad d \quad s \quad c$$

was first suggested a number of years ago as a possible solution to a certain problem connected with presumably allowable decay processes that do not in fact seem to occur. With the discovery of the psi particles last fall there came a deluge of theoretical papers that touted the idea of charmed quarks in several different models. From the point of view of charmed-quark theories, the remarkably long life of the ψ and ψ' particles is explained as follows. The ψ and ψ' are assumed to consist of the quark-antiquark pair $c\bar{c}$, and the preferred decay mode for such a combination would be into a pair of lighter charmed mesons ($u\bar{c} + \bar{u}c$, for example). But these "normal" decays do not occur because the mass of the lightest charmed meson is about 2 GeV, which means that neither $\psi(3.1)$ nor $\psi'(3.7)$ is massive enough to provide the $\sim$ 4 GeV needed for a charmed meson pair.

This and several other explanations of the psi particles that were derived from charm theories were quite persuasive to many physicists; and in recent months, with the discoveries of the P_c, χ, χ' and X radiative transition states, the general theoretical idea of charm has come to seem even more promising. Continuing in this vein of "the good news," the reader may want to flip over to the chart at the bottom of page *S-28*, which shows the various particle states (or energy-level structure) that is predicted for "Charmonium" and also shows how closely these predictions correspond to the spectrum of particles that have presently been discovered. (We reemphasize the caution that the "fits" of the particle states to the Charmonium predictions, though on present knowledge not unreasonable, are nevertheless both tentative and arbitrary.)

Now for the bad news. Although the general charm idea is indeed quite promising, there are some problems. We list here four of them.

1. The charm model does not satisfactorily explain the ratio of the production of K-mesons to π-mesons observed at SPEAR, nor does it speak to the origin of the peculiar μ^+e^-, μ^-e^+ events (U particles).

2. On page *S-6* we computed the value of the hadron/muon-pair ratio, R, when both charmed and colored quarks were included in the basic building blocks: the answer was 10/3 or $3\frac{1}{3}$. But the measured value of R at the higher SPEAR energies is about 5 or $5\frac{1}{2}$.

3. Charm predicts numerous radiative transition states, and the recently discovered P_c, χ, χ' and X particles may well be these predicted states. But the *rate* at which these transitions occur is roughly ten times lower than the charm prediction, and the details of some of energy-level spacings are beginning to cause some theoretical gas pains.

> [Elementary particles] are now thought to be made up of the simpler things called quarks. A solitary quark has never been observed in isolation, in spite of many attempts to isolate one. Nevertheless, there are excellent grounds for believing they do exist. More important, quarks may be the last in the long series of progressively finer structures. They seem to be truly elementary.
>
> S. Glashow
> --*Scientific American*
> October 1975

> Furthermore, we have no assurance that the quarks, whether there are three or nine or 12 of them, are the fundamental particles of matter. . . . It is not unreasonable to assume 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 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.
>
> S. Drell
> --*Scientific American*
> June 1975

4. Not least of the problems is the fact that the charmed mesons predicted by the theory have not yet been found. Above a threshold energy of perhaps 3.9 GeV at SPEAR the charmed mesons that we earlier called $\mathcal{D}\bar{\mathcal{D}}$ ought to be produced in pairs. Where are they?

Summary. To recapitulate briefly, the hypothesis of the intermediate vector boson for the psi particles is dead; colored psi explanations are in deep trouble; and the idea of charm, though shaky in spots, looks pretty good. Although the specific charm theories that have so far been proposed may not be able to cut the mustard, something similar in character (one or more new quarks, and a fundamentally new property of nature that for the moment we've generically called "charm") appears to have a good chance of being right. Even assuming that a charm-like idea *is* correct, however, the experimental data from SPEAR and from DORIS appear to require more than simply a charm explanation, and we now turn to a discussion of what that "more" might be.

2. MORE QUARKS AND/OR HEAVY LEPTONS

In this section we take a more general look at the fundamental constituents or building blocks: the *quarks* that we assume make up all the different hadrons, and the *leptons* that seem to be in and of themselves elementary objects. We begin with a simple collection:

1. electron: e^-	3. u quark	+ 4 anti-particles
2. electron neutrino: ν_e	4. d quark	

(We ignore the unit of electromagnetic radiation, the photon, in the following discussion.) With this set of 4 particles, and occasional use of the 4 antiparticles, we can build up a description of [almost] everything that is or that happens in our particular corner of the universe. All atoms can be made, all thinking can be thought, and all stars can shine with just this simple collection. In fact, it is only in places of extreme singularity (cosmic ray showers, high energy physics laboratories) that events occur which our 4 + 4 starter set of basic objects is unable to account for.

In this situation it may appear that we have a choice: just settle for the 99.44% of the world that our simple 4 + 4 collection can explain, or else go chasing after the 100% by messin with our nice simple collection. But there is no choice in fact, because [almost] is not what physics is about. It is a whole-hog, Katy-bar-the-door, damn-the-torpedoes enterprise in which the aim is always 100% even if the present achievement is only 3.2 on the Richter scale. So we chase.

For a number of years it has been evident that at least the following additions were needed to the simple 4 + 4 collection:

> . . . Experiments observing the annihilation of the positron and electron with the creation of any of the species of elementary particles which have electric charges or magnetic moments would open up an almost unexplored region for study . . . it is to be expected that, except for form-factor effects, all particles with charges or moments will be produced in comparable quantities. This fact will make it possible to make meaningful mass searches for suspected particles with masses up to 3 GeV.
>
> . . . It would be of great interest to investigate whether there are any other resonances at higher q^2 than the presently discovered ρ, ω and ϕ resonances.
>
> . . . Also of interest are searches for "heavy leptons" which do not participate in the strong interactions. Speculation on the existence of such particles has recently . . .
>
> --*Proposal for a High Energy Electron Positron Colliding Beam Storage Ring at SLAC*, June 1965

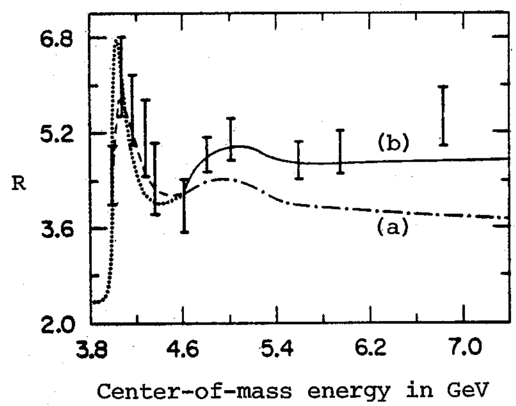
e^-	μ^-	u	s	+ 7 anti-particles
ν_e	ν_μ	d		

Adding the muon and its neutrino (ν_μ) and the *strange* quark settled most of the problems until the psi particles came along. Now, however, the gates to the zoo are open again, and our plan will be to check out some of the curious animals that are trying to sneak in.

In the chart below we test four possible additions to the basic set of 7 particles against four kinds of SPEAR experimental data to see if such additions (add 1 quark, 2 leptons . . .) appear sensible. The conclusion we arrive at is

Theory →	Start With 4 Leptons & 3 Quarks. Then Add:			
Experimental Data ↓	1 Quark	2 Leptons	2 or 3 Quarks	1 Quark 2 Lept.
Explain Hadron/Muon Ratio ≃ 5½?	*NO* 10/3	*NO* ≃ 3	*YES* ≃ 5	*MAYBE* ≃ 4½
Explain U Particle Events?	*NO*	*YES*	*NO*	*YES*
Explain ψ, ψ' Narrow ψ'', ψ''' Wide?	*YES*	*NO*	?	*YES*
Explain General ψ Spectroscopy?	*YES*	*NO*	?	*YES*

that each of the suggested addition schemes in the vertical columns has at least one loud *NO* in it except for the last one--add 1 new quark and 2 new leptons--which is burdened only by a *MAYBE*. We can look at this last suggestion in a different way by making the comparison that is shown in the following figure.



This figure compares the experimental values of the hadron/muon-pair ratio, R, from SPEAR with two different theoretical predictions. Curve (a) is the prediction of a four-quark model in which the fourth, charmed quark *c* has an electric charge of +2/3. Curve (b) is the prediction of the same four-quark model but with the addition of a new heavy lepton (and its neutrino) having a mass of about 2.3 GeV. As shown, Curve (b) is a pretty good fit to the data except at the higher energy point.

So, given these two kinds of evidence in support of the "add 1 + 2" idea, let's tentatively adopt the suggestion and thereby increase our collection of basic objects from 7 to 10:

$$\underbrace{\begin{matrix} e^- & \mu^- & U^- \\ \nu_e & \nu_\mu & \nu_U \end{matrix}}_{6\ leptons} \qquad \underbrace{\begin{matrix} u & c \\ d & s \end{matrix}}_{4\ quarks}$$

So if we had to give an answer now to the question of what the SPEAR and DORIS data on new particles is telling us about basic constituents, this 10-particle collection is probably what we've have to go with. And although we trot out this conclusion (tentative) with all kinds of intended enthusiasm, some readers may notice that we haven't let out a *Wow!* or a *Eureka!* very recently. That's because, as went sailing merrily along, a niggling little worry began to creep into our head. We'll now try to say what that worry is.

3. SOME FUNDAMENTAL PROBLEMS

Since we're beginning to run out of space, we'll be brief here and describe only one of many possible worries that theory is now beset with in trying to explain the psi and related particles. In brief, that worry is *TOO MANY!* The scheme we just tentatively adopted has 6 leptons and 4 quarks, for a total of 10. But we said earlier that there was some reason for thinking that each of the 4 kinds of quarks comes in 3 different colors, which if true means that our basic set is actually 6 leptons and 12 quarks. And now we have to remember, of course, that for these 18 particles there certainly have to be, like death and taxes, 18 corresponding antiparticles. Add up all those tomatoes and what you get is this "basic" collection of building blocks (?):

$$\text{Particles}\left\{\begin{matrix} e^- & \mu^- & U^- & \quad u_r u_w u_b & \quad c_r c_w c_b \\ \nu_e & \nu_\mu & \nu_U & \quad d_r d_w d_b & \quad s_r s_w s_b \end{matrix}\right.$$

$$\text{Anti-particles}\left\{\begin{matrix} e^+ & \mu^+ & U^+ & \quad \bar{u}_r \bar{u}_w \bar{u}_b & \quad \bar{c}_r \bar{c}_w \bar{c}_b \\ \bar{\nu}_e & \bar{\nu}_\mu & \bar{\nu}_U & \quad \bar{d}_r \bar{d}_w \bar{d}_b & \quad \bar{s}_r \bar{s}_w \bar{s}_b \end{matrix}\right.$$

For a winning total of, count 'em folks, just 36. A total of 36 begins to smack of the good old days, about 15 or 20 years ago, when the number of particles had grown so large--almost 30!--that it seemed obvious they couldn't *all* be "elementary." In fact, the solution that finally came from those earlier days was that quarks were invented! It's enough to give a body pause.

Some Things To Be Done

Since the only medicine that helps ailing theories is strong doses of new experimental fact, we use the few remaining lines here to list some of the areas of experimental study that now seem in need of close attention.

1. If they exist, find the predicted $D\bar{D}$ charmed mesons. For its ultimate confirmation, the charm theory needs evidence for charmed particles.

2. Verify that the U is actually a heavy lepton.

3. Look for charged psi's, ψ^+ and ψ^-. Stop.

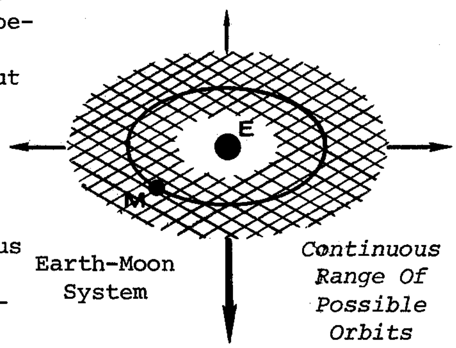
Acknowledgement. In writing this article, we've been helped greatly by three Invited Papers that were presented at the *1975 Lepton-Photon Symposium* that was held on the Stanford campus last August. The papers by Roy Schwitters and Gary Feldman of SLAC summarized much of the experimental data obtained by the SLAC-LBL collaboration working at SPEAR; and the paper by Haim Harari of the Weizmann Institute in Israel gave a masterful summary of some of the theoretical implications of the new particles. To the extent we've got our story straight here, they were indispensable; for whatever crookedness leaked through, they are blameless.

Detour 4: Charmonium

Our subject in this detour is two-body systems in which the two bodies or objects are bound together by a force that acts between them. We start with a big one.

1. Earth-Moon System

Gravity binds the earth and moon together in a stable system. The separation between the earth and moon is about 220,000 miles, but was at one time probably much smaller. There is a minimum orbit radius below which the system would become unstable (the moon would begin to be pulled apart by the earth's gravitational force). Above that minimum radius, there is *a continuous range of possible stable orbits* extending out far beyond the moon's present distance.

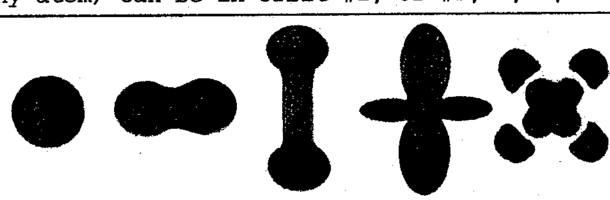


Earth-Moon System

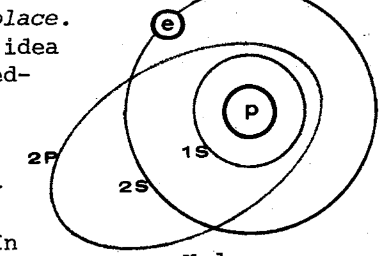
Continuous Range Of Possible Orbits

2. Hydrogen Atom

There are some problems connected with using the earth-moon system as a conceptual model of the proton-electron system that forms the hydrogen atom (see figure below). However, the idea of things orbiting around each other is deeply ingrained in most heads (including ours), so we are going to stick with it. But let's begin by picking out the most important difference between earth-moon and proton-electron: In the hydrogen atom there is NOT a "continuous range of possible stable orbits." Instead, there is a bottom rung on the ladder, then a fixed step up to another rung, then another fixed step up to . . . The electron in a hydrogen atom (or in any atom) can be in orbit #1, or #2, 5, 9, etc., but it cannot, for example, be "between #2 and #3" because *there is no such place.* We emphasize this idea to the point of tedium because, although it is easy to remember, it is impossible to conceive. In brief, then: In systems of orbiting particles, the orbits are discrete, step-like, quantized, clearly separated from each other.

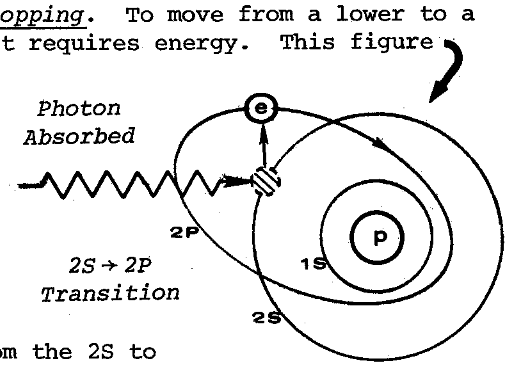


Hydrogen: the wave picture. The (standing-wave) patterns show the distribution of the electron for various energy states. Each different energy state of the hydrogen atom can be described as either a wave pattern, as shown here, or as a discrete orbit (1S, 2P, etc.) that is occupied by the electron. The wave description is prettier and somewhat less misleading that the orbit description, but since it is harder to think about we drop it in favor of the orbit description.

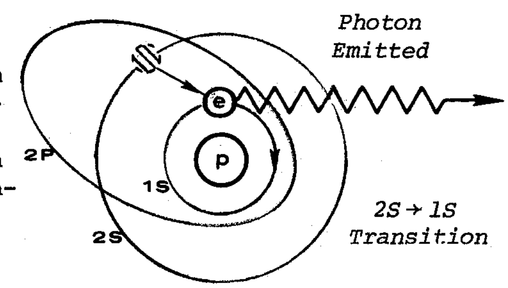


Hydrogen
Discrete Orbits

Orbit hopping. To move from a lower to a higher orbit requires energy. This figure shows the general idea. The electron absorbs an incoming photon and uses the captured energy to jump up from the 2S to the 2P level in hydrogen. This process works most effectively when the energy of the incoming photon is exactly the amount that is needed to make the jump--in this case just a few electron volts. The reverse process is shown in this figure. From a higher energy level the electron will spontaneously drop down to a lower level (2S to 1S in this example), in the process getting rid of its excess energy by emitting a photon. The energy of the emitted photon depends on the exact difference between the two energy levels, and in turn these differences vary in a very characteristic way from one element to another. This fact makes it possible, for example, to find out what some unknown substance is by first pumping in some radiation in order to excite the electrons to higher energy levels, and then identifying, say, iron, cobalt and manganese by recognizing the characteristic energies of the emitted radiation.



Hydrogen



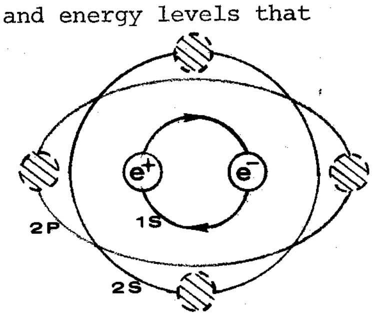
Hydrogen

The two processes we've just looked at, orbit changing by either absorption or emission of a quantum of electromagnetic radiation (a photon), are together called *radiative transitions*. So far the radiative transitions we've discussed are those of rather low energy associated with the orbit-hopping of electrons in atoms. The photon energies involved would range from about the 1 eV of visible light up to an ultraviolet or soft x-ray level of tens or perhaps hundreds of eV. Transition energies in the MeV range, where the photons are called gamma rays, are characteristic of radiative processes that occur in atomic nuclei. When a nucleus of lithium-7, for example, absorbs an incident proton and is thus excited to a high energy level, a common result is that the nucleus is converted to beryllium-8 with the emission of a 17-MeV gamma ray. These gamma-ray energies are part way along the road we want to travel here, but before we look for even higher energy radiative transitions, let's first pay a visit to an "atom" that it even simpler than hydrogen.

3. Positronium

The earth-moon and proton-electron two-body systems are rather strongly asymmetric: the earth is about 80 times as massive as the moon, and a proton is about 1800 times as massive as an electron. These mass disparities tend to make us think of orbits in which the lighter partner circles round the heavier, although the fact is that each of the partners moves in an orbit around the common center of gravity of the system (which for the earth-moon system is actually located within the volume of the earth). There is, however, a totally symmetric two-particle system that can be brought briefly into existence: a "hydrogen" atom in which the proton has been replaced by the antimatter counterpart of the electron--a positron. Since an electron and positron in close proximity to each other will eventually annihilate in a flash of 500 keV gamma rays, the experimenter who studies this system has not only to be quick about his measurement but also to have a means at hand for continuously generating new atoms of positronium.

Positronium is a theorist's delight. With no strong-force complications present, calculating the orbital patterns and energy levels that should exist becomes an exercise in pure and trustworthy old electrodynamics. A rich structure of energy levels--very atom-like--is predicted (the first few indicated in this sketch). In view of the joys of positronium theory, it is rather ironic that only recently has the first excited state of positronium been observed experimentally.

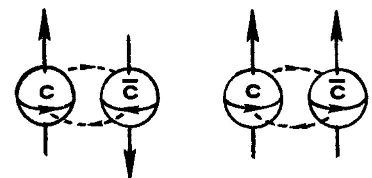


Positronium: An e^+e^- "Atom"
Discrete Orbits

4. Charmonium

Mesons are composed, it is thought, of a quark-antiquark pair which attract each other and thus form a two-body bound state. Very soon after the initial psi particle discoveries a number of theorists had hit the streets with special explanatory editions, the most persuasive of which, by popular acclaim, was the "charm" theory. The psi particles, so the theory went, were the first manifestation of a new fundamental property of matter--for want of a better name called "charm." This property was carried by a new, fourth kind of quark, c, and psi particles consisted of a $c\bar{c}$ pair. Here, indeed, was a two-body system with enough mass and general pizzazz to sink the Bismarck.

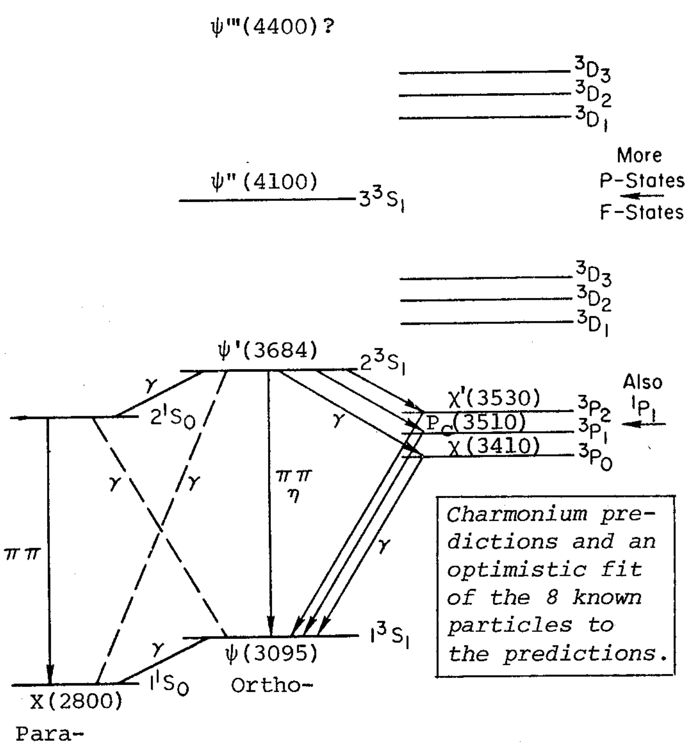
Charmonium: A $c\bar{c}$ "Atom"
Discrete Orbits



Para-Charmonium *Spins Antiparallel* — Ortho-Charmonium *Spins Parallel*

Using the theory that had been developed for Positronium as an analog, a number of theorists worked out the energy-level scheme for the $c\bar{c}$ charmed quark system. In light of *Positronium*, the name *Charmonium* for the $c\bar{c}$ system proved hard to resist. The predictions of one of the earliest of the Charmonium schemes are shown below. To this diagram we've added the 8 experimentally observed particles in the places where they *might* belong. Time will tell, but for the moment Charmonium has a lot going for it.

--Bill Kirk



Charmonium predictions and an optimistic fit of the 8 known particles to the predictions.