

# COLLIDING SLAC BEAM LINE

Special Issue on  $\Psi(3105)$ ,  $\Psi(3695)$

December 5, 1974

"We have observed a very sharp peak..."

*From The Editor*

This special issue of the *Beam Line* is entirely devoted to a description of the recent discovery, at SLAC and at Brookhaven National Laboratory, of a new particle. Much of this description was written before the even more recent discovery at SLAC of a second new particle, which therefore plays only a minor role in our story. We have tried to aim this article at as broad a SLAC audience as possible; the last few pages, however, may strike some readers as pretty tough sledding. We are indebted to Bob Pearson and to Sam Berman for some explanations and some good ideas. We are also indebted to the people in SLAC Experimental Groups C and E, and to their LBL collaborators, for causing the excitement:  $\Psi(3105)$ ,  $\Psi(3695)$ .

--BK



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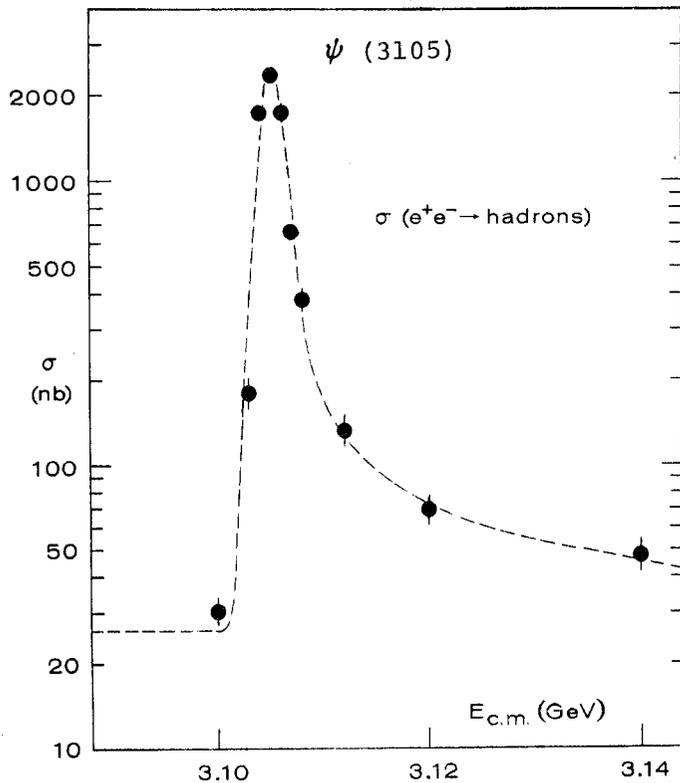
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## A. A BRIEF SUMMARY

The December 2, 1974, issue of *Physical Review Letters* contains papers which report the discovery of a new particle by a joint SLAC-LBL group working at SPEAR, and by a joint MIT-Brookhaven group working at the BNL accelerator. The SLAC physicists involved are from Experimental Groups C & E. At SLAC the new particle is called " $\Psi(3105)$ ," at Brookhaven, "J." The  $\Psi(3105)$  was found on November 8, and on November 20 a second, very similar particle was also discovered,  $\Psi(3695)$ . These resonances were discovered at SPEAR during a study of hadron production in  $e^+e^-$  annihilation. The resonances are very sharp, with an estimated width of about 50 keV. The corresponding lifetime of the resonant state is about  $10^{-20}$  second, roughly a factor of 1000 times longer than would be expected for prompt hadronic decay. The slow decay and other properties of the resonance appear to distinguish it sharply from the usual hadronic resonances.

Theoretical speculation at SLAC has tended to focus on two possible connections between the  $\Psi$  resonances and existing ideas. The first possibility is that the resonance is the long-sought Z particle, the neutral intermediate vector boson that may mediate the weak interactions. The second possibility is that the  $\Psi$  resonances are the first evidence for the postulated properties of *color* or *charm*, or both, that have been proposed as necessary additions to the quark model of the strongly interacting particles. If neither of these possibilities eventuates, the properties of the resonance are such that there is no other presently known explanation for its behavior.

The continuing SPEAR experimental program will search for additional resonances in what may be a series, and will analyze in more detail the decay products from the resonance with the aim of elucidating the constraints that must be operating to inhibit the "normal" rapid hadronic decay. The recent upgrading of the SPEAR storage ring (SPEAR II) has increased the maximum center-of-mass energy of the ring from about 5.0 to 8.6 GeV. This higher energy coupled with improved luminosity should prove invaluable in the continuing studies.



DISCOVERY OF A NARROW RESONANCE  
IN  $e^+e^-$  ANNIHILATION

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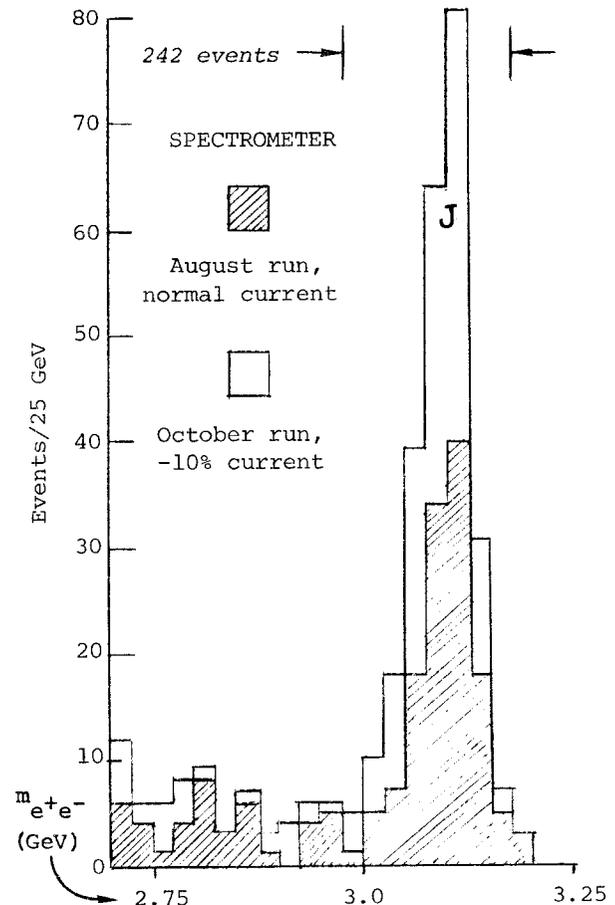
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#### ABSTRACT

We have observed a very sharp peak in the cross section for  $e^+e^- \rightarrow \text{hadrons}$ ,  $e^+e^-$ , and possibly  $\mu^+\mu^-$  at a center-of-mass energy of  $3.105 \pm 0.003$  GeV. The upper limit to the full width at half maximum is 1.3 MeV.

Work supported by the U. S. Atomic Energy Commission.



EXPERIMENTAL OBSERVATION OF A HEAVY  
PARTICLE J

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#### ABSTRACT

We report the observation of a heavy particle J, with mass  $m = 3.1$  GeV and width approximately zero. The observation was made from the reaction  $p + \text{Be} \rightarrow e^+ + e^- + X$  by measuring the  $e^+e^-$  mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory 30 GeV Alternating Gradient Synchrotron.

Researches reported herein have been supported by the U.S. Atomic Energy Commission.

## B. THE STARTING POINT: A REVIEW\*

In this section we plan to review some basic information about the physics of electron-positron colliding beams, about the results of the earlier experiments at SPEAR and elsewhere, and also about the particular way in which the earlier SPEAR experiment was carried out. Our intent will be to try to sketch in enough of a background so that the subsequent discussion of the new discovery, in Section C, will be fairly easy to understand.

### 1. The Annihilation Process

The collision between an electron and an "anti-electron" or positron can result in the unique matter-antimatter interaction called *annihilation*. When this happens, the original two particles vanish, leaving behind a transitory state of pure electromagnetic energy which is called a *virtual photon* or a *virtual gamma ray* (the state is "virtual" rather than "real" because it cannot, even in principle, be detected). This intermediate pure-energy state doesn't last very long: after dawdling around for about  $10^{-25}$  seconds it then rematerializes into two or more brand new particles which go flying off from the scene of the accident without even calling an ambulance. In the specific case of the SLAC-LBL experiment at SPEAR, one of the typical annihilation reactions that is studied is represented symbolically like this:



In words, this reaction reads *electron + positron goes to virtual photon, which then goes to pi-minus + pi-plus + pi-zero*. In many cases, there are more particles, and more kinds of particles, created than just the three pions shown here. The SLAC-LBL experimenters were interested in the creation of any of the large class of particles called *hadrons*. This class includes all particles which respond to the strong or nuclear forces in nature. The best-known members of the hadron family are protons and neutrons, which together form the nuclei of atoms. This family also includes lighter particles, such as pi-mesons (pions) and K-mesons, which appear to act as a kind of strong-force "glue" that causes the protons and neutrons in atomic nuclei to stick together. Much of the effort in high-energy-physics research is aimed at gaining a better understanding of the hadrons and of the strong forces which dominate their behavior.

\* The August and September 1974 issues of the SLAC Beam Line contain a two-part article, "An Introduction To Colliding-Beam Storage Rings," which some readers may find useful as general background information about SPEAR. Copies of this article are available from Bill Kirk, Bin 80.

### Perils of Modern Living

A kind of matter directly opposed to the matter known on the earth exists somewhere else in the universe, Dr. Edward Teller has said. . . . He said there may be anti-stars and anti-galaxies entirely composed of such anti-matter. Teller did not describe the properties of anti-matter except to say that there is none of it on earth and that it would explode on contact with ordinary matter.

--San Francisco Chronicle

*Well up beyond the tropicstrata  
There is a region dark and stellar  
Where, on a streak of anti-matter,  
Lived Dr. Edward Anti-Teller.*

*Remote from Fusion's origin,  
He lived unguessed and unawares  
With all his anti-kith and kin,  
And kept macassars on his chairs.*

*One morning, idling by the sea,  
He spied a tin of monstrous girth  
That bore three letters: A.E.C.  
Out stepped a visitor from Earth.*

*Then, shouting gladly o'er the sands,  
Met two who in their alien ways  
Were like as lentils. Their right hands  
Clasped, and the rest was gamma rays.*

--H. P. Furth, *The New Yorker*,  
November 10, 1956

### 2. Theoretical Expectations

When the SLAC-LBL experiment at SPEAR first began, a little more than a year ago, it was assumed that the cross section (probability) for hadron production from  $e^{-}e^{+}$  annihilation would not be very large. In fact, there were specific predictions, based on certain theoretical models of the structure of hadrons, that hadron production would have a definite relationship to the simpler process in which a pair of mu-mesons is created. (These particles,  $\mu^{-}$  and  $\mu^{+}$ , generally called *muons*, seem to be essentially heavy electrons.) This relationship was expressed as a ratio, R, between the probabilities for the two kinds of production processes:

$$R = \frac{\text{Cross section for hadron production}}{\text{Cross section for muon-pair production}}$$

The predictions concerning this ratio were based on theories which assumed that hadrons were not truly elementary particles in themselves but in fact were composed of more fundamental sub-particles called *quarks* or, more generally, *partons*. The actual value of the ratio, R, that was predicted ranged between 2/3 and 6, depending on the particular brand of quark or parton theory that was being used. But in any event it was assumed that R would

at least turn out to be a *fixed* number, whatever its actual value.

There was only one cloud on the horizon at that time as far as these predictions were concerned. Reports of unexpected experimental results had started to come in from the storage ring at Frascati, Italy; and these were soon followed by even more surprising measurements from the ring that had been built by reworking the Cambridge Electron Accelerator in Boston. Although the Frascati results appeared to have some inconsistencies, and CEA's measurements were not based on very extensive data, these reports were enough to give theorists some pause. And it was into this unresolved and puzzling situation that the SPEAR experimenters stepped as their study of hadron production began.

### 3. Frascati-CEA-SPEAR: The Surprise

By early spring of this year it had become apparent that the doubts raised by the Frascati and CEA measurements were indeed well-founded. Hadrons were being created in the SLAC-LBL experiment at SPEAR a good deal more copiously than predicted, and it was plain that the famous hadron/muon-pair ratio was not only quite large but also that it was steadily growing larger as the energies of the colliding  $e^-e^+$  beams were increased. Back in those days (it seems like years ago) the most common way of expressing the SPEAR results was to make a graph which showed the measured values of the hadron/muon-pair ratio plotted against the

center-of-mass energy (total energy of the two colliding beams). Such a graph, including the earlier data from Frascati and from CEA, is shown in Fig. 1 at the bottom of this page.

For our purposes, it will eventually be more useful to show the SPEAR data not as the ratio,  $R$ , but rather more straightforwardly as just the hadron-production measurements themselves. We'll do this in Section C, but before moving on we want to call attention to some of the reactions that theoretical physicists had to these earlier results.

### 4. A Troubled Mind

As Fig. 1 shows, the SPEAR results joined onto and extended upward the lower energy measurements that had been made at Frascati. They also joined onto and added much more extensive data to the higher energy CEA measurements. The result was a resounding confirmation of this earlier data, with the combined measurements from the three laboratories presenting rather convincing evidence that at least the simpler quark-model predictions could not be correct.

(It is important to try to emphasize this point. However, we feel a little timid about exclaiming that *The predictions were wrong!* because any reader worth his salt would respond to that with an irritated *SO WHAT?!* Although this reasonable question deserves an answer, we won't get around to trying to give that answer until we come to the discussion of quarks in Section D.)

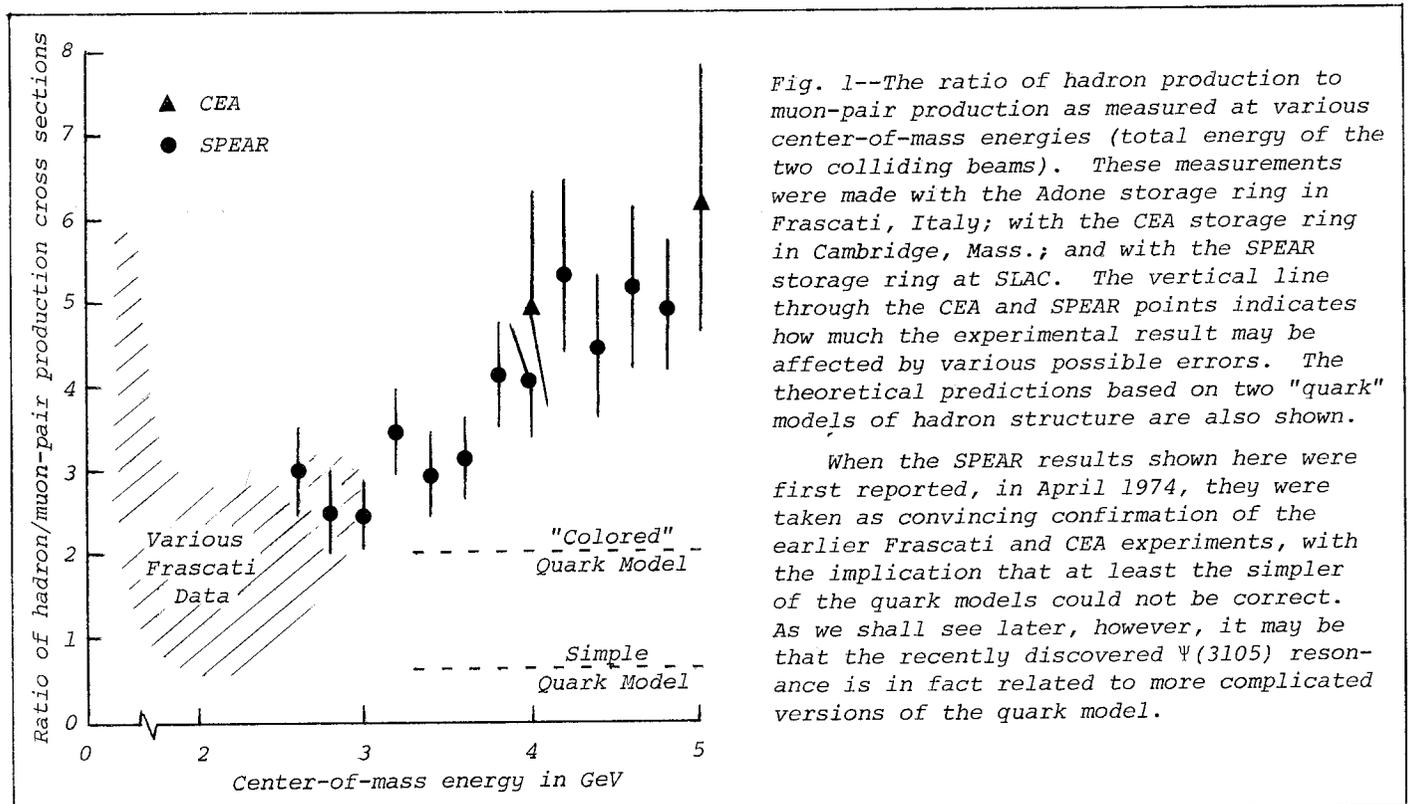


Fig. 1--The ratio of hadron production to muon-pair production as measured at various center-of-mass energies (total energy of the two colliding beams). These measurements were made with the Adone storage ring in Frascati, Italy; with the CEA storage ring in Cambridge, Mass.; and with the SPEAR storage ring at SLAC. The vertical line through the CEA and SPEAR points indicates how much the experimental result may be affected by various possible errors. The theoretical predictions based on two "quark" models of hadron structure are also shown.

When the SPEAR results shown here were first reported, in April 1974, they were taken as convincing confirmation of the earlier Frascati and CEA experiments, with the implication that at least the simpler of the quark models could not be correct. As we shall see later, however, it may be that the recently discovered  $\Psi(3105)$  resonance is in fact related to more complicated versions of the quark model.

Thus the early SPEAR results had the effect of giving most quark and parton theories of hadron structure a rather smart rap across the knuckles, and as a consequence whole platoons of theorists fell back in disarray. But unfulfilled expectations have a curious effect on physicists: the disappointment phase tends to end rather quickly (from about 30 seconds to two days, depending on whose particular ox is being gored) and is replaced by enthusiastic attack upon the new problem.\* There was speculation in several physics journals that the storage ring data might be explained by supposing that electrons and positrons themselves might not be the simple point-like (having no structure) particles they had always seemed to be: perhaps they had a tiny inner core that was hadronic--that is, which could have *direct* strong-force interactions with such particles as protons and pions without going through the intermediate virtual-photon state.

If it were true that electrons and other members of the small *lepton* family of particles (which includes muons and neutrinos) were actually "hadrons at heart," it would certainly have a revolutionary effect upon physics. Such ideas remain untested and speculative, however, and the more conservative approach that most theorists took was to look for ways to modify existing quark or parton models, or to check whether the calculations based on the original models had really been done correctly. As a result, the very strong statement that we tried to sneak past you earlier, *The predictions were wrong!* had to be watered down a bit to something like the following:

There are some problems in accounting for the SPEAR data with quark or parton models, but such models --especially those that add certain complications called *color* and/or *charm*--are certainly not dead.

And if this rather weasel-worded statement seems sort of anticlimactic after all the flap, well, that's just what it is. But hang in there; there's more flap ahead.

#### 5. Survey Experiments: Through No-Man's Land In Seven-League Boots

We turn now to a discussion of how the early part of the SLAC-LBL experiment at SPEAR was actually carried out. This is the last bit of background information needed to provide a context for the recent discovery. It may also

\* *When an investigator has developed a formula which gives a complete representation of the phenomena within a certain range, he may be prone to satisfaction. Would it not be wiser if he should say "Foiled again! I can find out no more about Nature along this line."?*

--Sir Arthur Eddington

serve the purpose of conveying some sense of the elements of luck, coincidence, intuition and just plain sweat that enter into the artful business of "doing" physics experiments.

(Our apologies if all this introductory "context" material is getting to be a drag; our concern is to try to make the discovery of the  $\Psi(3105)$  mean more to the reader than it did to your typical television watcher.)



When SPEAR first began operating, in the spring of 1972, the territory that lay before it extended from center-of-mass energies of about 2.6 to 5 GeV (1.3 to 2.5 GeV in each beam). The Frascati experiments had edged into the lower end of this region, and CEA had taken small samples of data at several higher energy points. But for the most part this new territory was as unexplored as the far side of the moon. In such cases, when there are only a few rather vague hints of what to look for and where to look for it, the usual strategy is to carry out a *survey experiment*. This sort of experiment is designed to cover the whole unexplored region in a systematic but necessarily superficial manner in order to map out its most obvious general features.

The limiting factor in a survey experiment is time. Suppose, for example, that an experiment has 300 hours of running time available, and that on the average it will take about 30 hours to make an accurate measurement at one particular energy setting of the storage ring. The experimenters can then choose to make accurate measurements at 10 different energies, or fairly accurate measurements at 15 different energies, or rather sloppy measurements at 20 different energies, and so on. In the case of Experiment SP-2, the SLAC-LBL joint effort, the group decided to make measurements that were fairly accurate at a total of 12 different center-of-mass energies, as follows:

				2.6	2.8		
3.0	3.2	3.4	3.6	3.8			
4.0	4.2	4.4	4.6	4.8	GeV		

Why didn't they measure 18 different energies, say? No particular reason; 12 seemed like the better compromise between accuracy and number of points. Why didn't they pick 2.7, 2.9, 3.1 (!) . . . instead? No particular reason to prefer odd numbers to even numbers. Wouldn't they have discovered the new particle about six months earlier if they had run at 3.1 GeV? Yes, probably, but luck plays a role this business, too. But when you're not so lucky, then the next best bet is to be fairly clever, and that's what we'll turn to now.

### C. THE NEW DISCOVERY

The SLAC-LBL experimental group presented the first public report of its hadron production data from SPEAR at the Washington, D.C. Conference of the American Physical Society, in April 1974. Figure 2 shows how the data looked at that time. For several months thereafter they continued to take additional data at SPEAR which increased the accuracy of the measurements to some extent but did not change the general pattern indicated in the figure. The SPEAR storage ring was shut down in June in order to carry out the modification program, called "SPEAR II," that was designed to increase the maximum beam energy from about 2.5 to 4.3 GeV (for each beam). During the down period, which lasted until mid-October, the experimenters analyzed the accumulated data and made plans for the next cycle of experimental operation. One of the high priority items they agreed upon was a more detailed study of the energy region around 3.2 GeV (the "curious" point in Fig. 2) to see if they could understand this most obvious bump in the curve. The opportunity to do this presented itself in late October, as SPEAR II came into routine operation with remarkably few bugs and glitches.

#### 1. The Curious Point: A Closer Look

Since the original survey aspect of their experiment (SP-2) had mapped the territory in giant energy strides of 0.2 GeV (200 MeV), the new work was aimed at filling in the gaps. A brief repeat measurement at 3.2 GeV was made to tie into the old data, after which the energy was moved up to 3.3 GeV. The result was a measured cross section of some 20-odd expected nanobarns (which even we could have guessed just by looking at Fig. 2). Then the ring energy was set to 3.1 GeV, and a series of 8 separate measurements was made at that point, with the following results (cross section in nanobarns):

#1 - 55	#5 - 25
#2 - 116	#6 - 26
#3 - 18	#7 - 23
#4 - 19	#8 - 23

Measurements #3 through #8 show a rather typical spread that is small enough to persuade

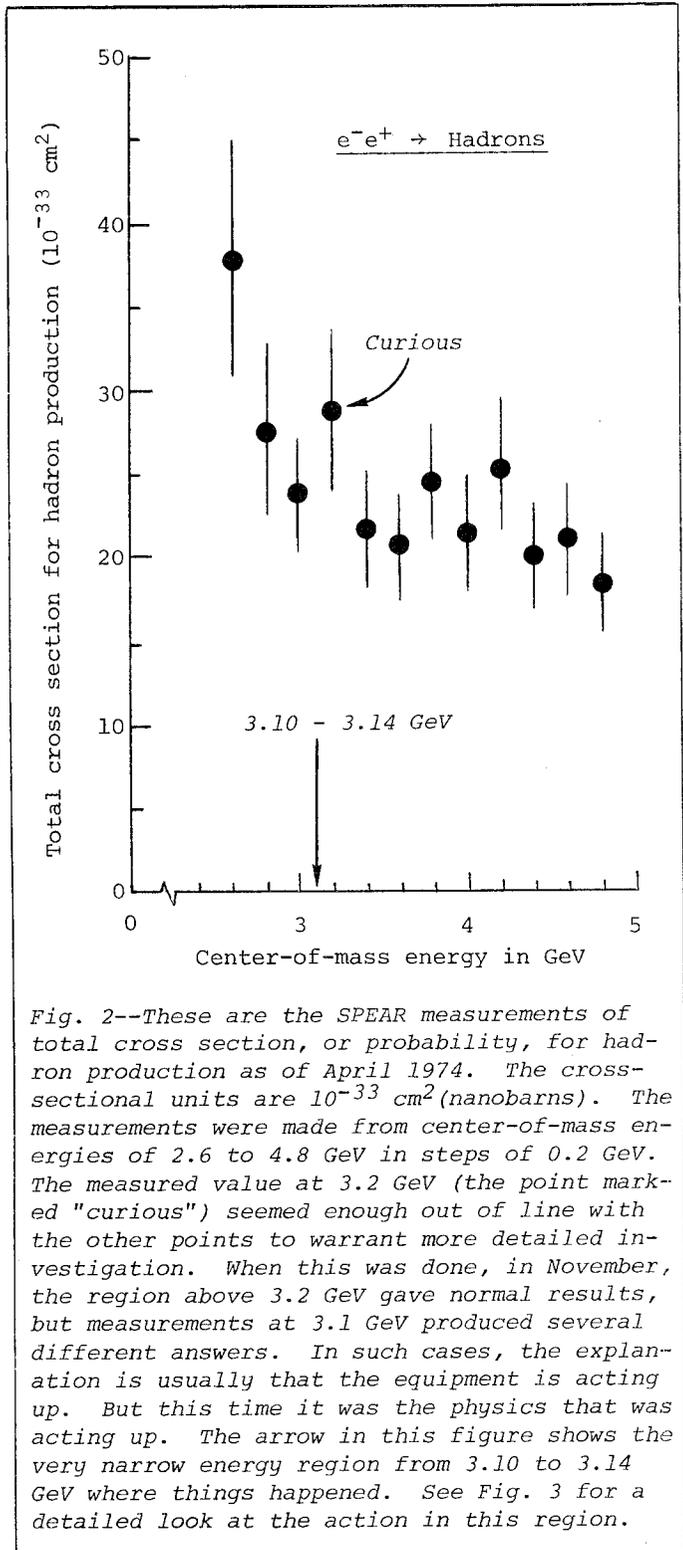


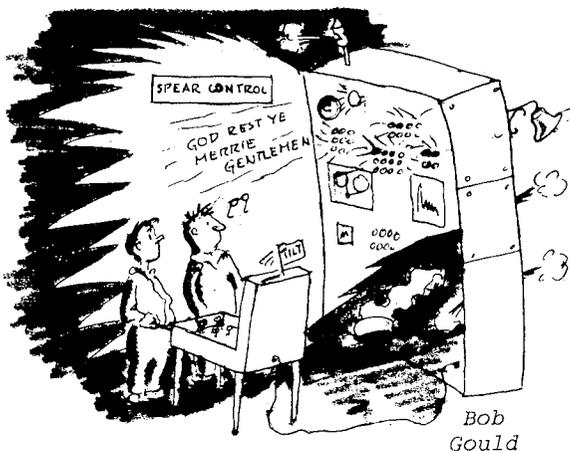
Fig. 2--These are the SPEAR measurements of total cross section, or probability, for hadron production as of April 1974. The cross-sectional units are  $10^{-33} \text{ cm}^2$  (nanobarns). The measurements were made from center-of-mass energies of 2.6 to 4.8 GeV in steps of 0.2 GeV. The measured value at 3.2 GeV (the point marked "curious") seemed enough out of line with the other points to warrant more detailed investigation. When this was done, in November, the region above 3.2 GeV gave normal results, but measurements at 3.1 GeV produced several different answers. In such cases, the explanation is usually that the equipment is acting up. But this time it was the physics that was acting up. The arrow in this figure shows the very narrow energy region from 3.10 to 3.14 GeV where things happened. See Fig. 3 for a detailed look at the action in this region.

an experimenter that he has probably measured the same thing six different times. But measurements #1 and #2 are a howling disaster--the first about twice as big and the second about five times as big as the average of the other six. When such wild excursions occur in an experimental measurement, there are usually two possible explanations:

1. The experimental apparatus is acting up (common).
2. The physics is acting up (rare).

The SPEAR experimenters therefore gathered up their 6 reasonable and 2 unreasonable measurements and went off to lick their wounds for a few days. They looked for bugs in the equipment (there are hundreds of gadgets and miles and miles of wires). They wrassled with the programs on their Sigma V computer. Finally, on Friday, November 8, they came to the conclusion that Explanation No. 1 was wrong--the equipment was OK--and therefore Explanation No. 2 must be right: there had to be some new physics hiding on the ragged edge of 3.1 GeV.

Convinced, they ran up all sheets full to the wind and began to edge SPEAR's energy upward from 3.1 GeV. And suddenly it all went ZAP! and everything lit up like a Christmas tree.



SPEAR's energy had been nudged upward in steps of 1 MeV; that is, 3.100 GeV, 3.101 GeV, 3.102 GeV, etc. The continuing series of measurements that were carried out on November 8, 9 and 10 indicated that the peak of the resonance was at about 3.105 GeV.

*We have observed a very sharp peak . . .*

Sharp indeed, as shown in Fig. 3. In fact, as the caption explains, the actual peak is even sharper than the curve indicates. This huge "bump" is evidence for the discovery of a new particle, or "resonant state," which the SPEAR experimenters have named

$\Psi(3105)$

The Greek letter is *psi* (pronounced "sigh"), and in words the new particle's name would read *psi thirty-one-oh-five*.

Often in the past the possible discovery of a new resonance has been treated rather cautiously, with the physicists preferring to wait for confirming results from other experiments.

But in the case of  $\Psi(3105)$  such caution was unnecessary for two reasons. First, through a remarkable coincidence there already *was* a confirming experiment. Second, the very size and sharpness of the resonant "bump" would have been overwhelming evidence even without confirmation. Since both of these reasons are important parts of our story, let's look at each of them in a little more detail.

## 2. "I Have Some Physics To Discuss . . ."

Experimental proposals submitted to SLAC are evaluated by a group of 10 senior physicists (four from SLAC and six from other institutions) called the Program Advisory Committee (PAC), which meets at SLAC every month or two. As luck would have it, the PAC had a meeting scheduled for Monday, November 11, the day after the famous weekend. At about 8 A.M. that morning, one

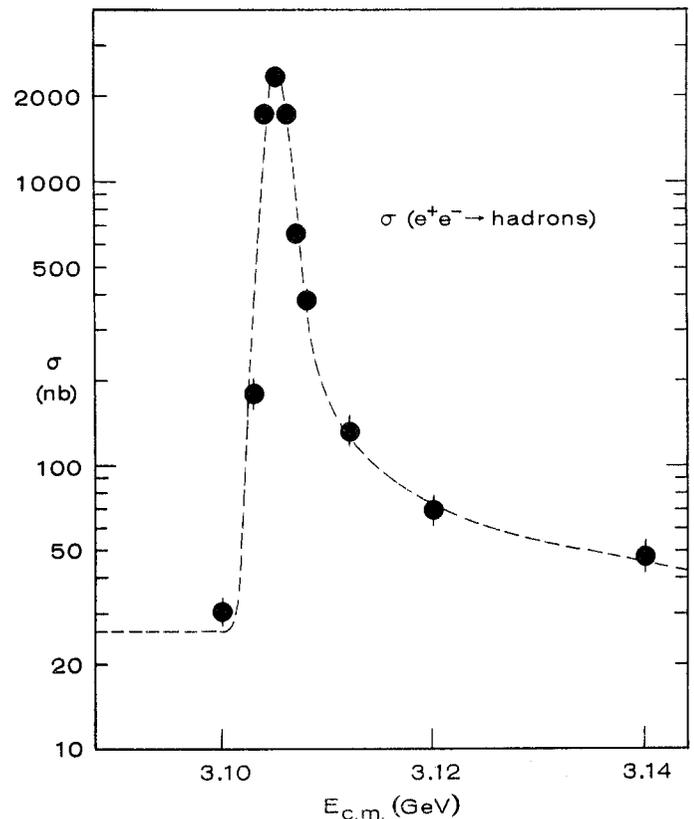


Fig. 3--The  $\Psi(3105)$  resonance as measured at SPEAR. The cross section ( $\sigma$ ) is expressed in units of  $10^{-33}$   $\text{cm}^2$  (nanobarns). Note the steep rise in cross section by about a factor of 100 as resonance is reached. The dashed line shows the amount of peak-broadening that is expected solely from the energy-spread in SPEAR's beams. Thus the actual width of the resonance is much smaller than the value of 1 or 2 MeV shown in the figure, and in fact has been estimated to be about .05 MeV. This remarkably sharp peak implies that the lifetime of the  $\Psi(3105)$  is about  $10^{-20}$  seconds--roughly 1000 times longer than a typical hadron resonance.

of the PAC members, Professor Samuel C. C. Ting of MIT, arrived at Professor Panofsky's office and said, "I have some physics to discuss with you." Whereupon he began to describe an experiment at Brookhaven National Laboratory (BNL) which a joint MIT-BNL group had been working on for several months, and which was designed to measure the production of electron-positron pairs in collisions of high-energy protons with a beryllium target. This description began to have a familiar ring to it when Ting mentioned an apparent resonance in his data at 3.1 GeV (which the MIT-BNL group has identified as the "J" particle; see page 2).

The eventual upshot of this remarkable coincidence was a joint announcement of the new discovery by the SLAC-LBL and MIT-BNL groups, and separate submission of papers that will appear in the December 2 issue of the journal *Physical Review Letters*.

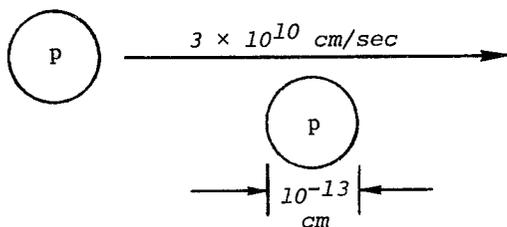
### 3. Broad And Narrow Resonances

So far we've referred to the  $\Psi(3105)$  as both a *particle* and a *resonance*. It could also be described as an *excited state*. Physicists tend to use these three names somewhat interchangeably, so we'll do the same. However, if your mental picture of a *particle* is something quite solid, with a fixed mass and a reasonable lifetime, it may be a little hard to swallow the fact that the "remarkably long life" of the  $\Psi(3105)$  particle is about

.00000000000000000001 second

or  $10^{-20}$  second. So a reasonable question is "Long compared to what?" which we'll now try to answer.

Let's ease into it by comparing two different kinds of "years." If by a "year" we mean the time it takes a small body to make one complete revolution around a larger body, then the earth's year around the sun is about 30 million seconds, while an electron's "year" around an atomic nucleus is about  $10^{-16}$  second. An even shorter time is the "day" it takes a proton to make one full rotation as a part of a nucleus: about  $10^{-22}$  second. And for the last example let's consider how long it takes one proton to zip past another at the speed of light:



The high-speed proton travels a distance of  $10^{-13}$  centimeters in about  $3 \times 10^{-24}$  second. And a striking thing about protons (or any of the strongly interacting particles) is the fact

that  $10^{-23}$  or  $10^{-24}$  second is enough time for an interaction to occur--creation of new particles, or simply a ricochet scattering collision. In fact, the reason why the strong-force interaction *is* strong is simply the fact that it acts so quickly. So the message here is this: When the strong or nuclear force is involved in an interaction, then things happen *fast*. And for particle physics,

"Fast" =  $10^{-23}$  or  $10^{-24}$  second

Energy and time. These very short periods of time we've been talking about cannot be directly measured. Instead, they are inferred from a certain fundamental relationship that exists between the *energy spread* or *width* of a resonance and its *lifetime*. This relationship (which is described by "the uncertainty principle") has the following general consequences:

Decay Process	Resonance Lifetime	Resonance Width	Resonance Energy
fast	short	broad	not well defined
slow	long	narrow	well defined

Most of the new particles or resonances that have so cluttered up the wall charts during the past 25 years are "fast" baryon or meson states (the two hadron sub-families) which quickly decay either into other excited states or into more stable particles. For those hadron states that do *not* decay rapidly, there is always a good reason (some fundamental conservation law) to explain why the rapid decay is inhibited. In fact, so general is this "good reason" rule that physicists often express it as a kind of First Principle:

*Everything that can happen does happen unless there is a good reason for it not to happen.*

Thus when a particle is observed to decay slowly for no apparent reason, then the reason that is not apparent may turn out to be something vitally important.

All of which brings us back to the  $\Psi(3105)$ , whose narrow resonance width of about 50 keV implies a lifetime of about  $10^{-20}$  second. This is roughly 1000 times longer than would be expected if it were free to decay through the usual hadronic channels. Why is it inhibited from doing so? What peculiar sort of beast is it that it won't play the typical strong-force games with the rest of the team? As this particular paragraph is being written (November 25), there are probably some hundreds of physicists around the world who are eagerly caught up in the fascination of this problem. At SLAC the speculation seems to be converging on two main possibilities, which we'll now try to describe.



#### D. SO WHAT DOES IT ALL MEAN?

Although it is obviously too soon to give a definitive answer to this question, recent speculation has tended to center on two main possibilities for the  $\psi(3105)$ :

1. That it may be the long-sought "Z" particle which mediates, or "carries," the fundamental force known as *the weak interaction*.
2. That it may be the first evidence for the properties of *color*, or *charm*, or both, that have been suggested as necessary additions to the *quark* picture of the strongly interacting particles.

Either of these two possibilities, if verified, would be a blockbuster whose impact on the fundamental studies of matter would be difficult to exaggerate. It is worth pointing out, however, that even if it is *neither* of these, the  $\psi(3105)$  is absolutely *certain* to have a significance far beyond that of "just another particle." We'll discuss the reasons for this assured general significance after first going over the two specific possibilities listed above.

##### 1. The Weak Interaction

Scientists believe that all of the possible interactions between matter are the result of only four fundamental forces:

Gravity  
Electromagnetism  
The Strong Force  
The Weak Force

Briefly, gravity is so weak compared to the other forces that it is not assumed to play any role in particle interactions. Electromagnetism is a well-understood, fairly strong force that can act over short or long distances. The range of the weak and strong forces is very short (in fact the weak force may have *zero* range).

The most common example of a weak-force process is the beta-decay (emission of an electron) of certain radioactive elements. Weak interactions also play a central role in the generation of energy by the sun and all other stars. Present theories of how the weak interaction works have been reasonably successful in describing processes that occur at relatively low energies, such as the two examples cited above. As the interaction energies increase, however, the theory begins to run into trouble. In fact, simple extrapolation of the present theory leads to the prediction that the weak force will gradually grow in strength as the energy increases, and that eventually it will become even stronger than the familiar electromagnetic force. At a sufficiently high level of energy, the increase in strength predicted by present theory would lead to a fundamental contradiction with certain physical principles that are believed to be a necessary part of any correct theory of the elementary particles ("would violate unitarity," is the jargon).

In view of this high-energy contradiction, there has been speculation for many years that present weak-interaction theory must be incomplete, and that the likely missing ingredient will turn out to be a special kind of particle which acts as the "carrier" of the weak force in much the same way that the photon is known to transmit the electromagnetic force. It has generally been assumed that such a particle would be quite massive (certainly heavier than a proton) but that it would not respond to the strong forces that are responsible for ordinary nuclear interactions.

The name given to this as-yet hypothetical particle is the

*Intermediate Vector Boson*

and if it exists it should have both electrically charged ( $W^+$  and  $W^-$ ) and neutral (Z) states. The potential importance of such particles is indicated by the fact that they have been eagerly

sought after in the early experimental program of every new higher energy accelerator from the Bevatron to the 400 GeV Fermilab machine. If they exist, however, none of the scores of experiments carried out to date has succeeded in directly producing them.

Is it you, Bo? From what we have learned so far of the properties of the  $\Psi(3105)$  resonance, this new particle could well be the neutral member, Z, of the intermediate vector boson family. As it happens, some additional clues concerning this possible identification can be expected from experiments now in progress at both Fermilab and at the European Center for Nuclear Research (CERN). The CERN experiments make use of neutrinos (which are something like electrons that have lost their electric charge) in the energy range of 1 to 3 GeV, while the Fermilab neutrino beam has an energy of about 40 GeV. The results already obtained at CERN can be used to predict what the Fermilab experiment should see, but this prediction would be strongly influenced by the existence of vector bosons. With a Z particle of 3 GeV mass, the Fermilab data would be reduced by a factor of about 8 from the value predicted by simple extrapolation of the CERN data. And in fact there is already some early evidence that the Fermilab measurements are coming in lower than expected.

## 2. The Quark Model Of Hadrons

A second major possibility for fitting the  $\Psi(3105)$  into an existing theory of the elementary particles concerns two different, but related, refinements that have recently been suggested to the very successful quark model of the strongly interacting particles. These two suggested additions are called *color* and *charm*, and we'll describe each of them after a brief review of the general quark idea.

During the last 25 years physicists have discovered an ever-increasing number of new particles, or resonant states, whose role in nature is not very clear. (When I.I. Rabi of Columbia heard about the discovery of the mu-meson, he said "Who ordered that?") By the mid-1950's there were already so many particles that the description "elementary" was getting a little hard to believe. And as the list grew it became more and more evident that the only way the physicists would ever be able to keep track of all the junk mail that was flooding in was to have a well-organized desk with hundreds of nice pigeon-holes for organizing the data. What was needed, that is, was some sort of ordering scheme that would classify all the particles into logical groups according to their various characteristics--perhaps a "Periodic Table of the Particles" analogous to Mendelyev's great taxonomic synthesis of the Elements.

The Eightfold Way. In the early 1960's such an ordering scheme was devised. Based on some

of the mathematical ideas of group theory, the earliest versions of the scheme were known as "SU(3)" or, informally, as "The Eightfold Way." Much of the power of the SU(3) classification scheme rested on the fact that all of the members of the large hadron family of particles could be thought of as composite structures that were built up from only three truly elementary constituents called "quarks" (plus their three antimatter counterparts, the antiquarks). This basic quark model of the structure of hadrons has been extensively elaborated during the intervening years, and it has proved itself to be an astonishingly successful theory in accounting for a great variety of experimental facts, in predicting the unknown properties of many particles, and even in predicting the existence of a previously unknown particle (the omega-minus, discovered at Brookhaven in 1964, with properties exactly as predicted by The Eightfold Way).

But it's not all gravy. Although the quark model's notable successes have convinced many physicists that it must contain a good deal of the truth, there are still a few problems. We list below three apparent shortcomings of the quark model for brief discussion. The first shortcoming is easy to understand, but it is not very important for what we've been talking about. The other two *are* important for our purposes, but (you might have guessed) they aren't so easy to figure out. If you really can't fight "symmetric statistics" and like that, it might be better to skip right over to *Colored Quarks* and just try it bareback.

1. Ain't none. No quarks have ever been observed experimentally. Individual quarks may be very massive, but even the 56 GeV collision energy of the CERN Intersecting Storage Rings (equal to 1700 GeV protons striking a proton target) has not been able to pry any loose. It may also be that quarks aren't *supposed* to be real, and the "threeness" of structure is simply a mathematical artifact. That idea bugs us, but then nature doesn't ask for our opinion.

2. Is three a crowd? In the basic 3-quark model, identical quarks can occupy the same "quantum state" (same rung on the ladder, say) within the particle they've built. But quarks are members of the class called *fermions*, and it is an iron-clad rule for all other fermions that identical particles cannot occupy the same quantum state (cannot have "symmetric statistics").

3. Why no decays? Again in the basic 3-quark model, there are certain kinds of decay processes that should occur at a reasonable rate, but in fact are not observed to occur at all. These decay processes have a name (*neutral, weak, strangeness-changing decays*), but it's such a horrible name that we'll just settle for *certain decay processes*.

The first shortcoming of quark theory noted above is a general problem, not connected to

the new resonance any more than it is to any other particular particle, so we ignore it here. Both the second and third shortcomings, however, do have possible connections with the  $\Psi(3105)$  which fall under the headings of *color* and *charm*, which we now explore in some detail.

### 3. Colored Quarks

Theoretical physicists worry about problems such as the identical fermions with "symmetric statistics" that we just described. Since this behavior is permitted nowhere else in nature, why should quarks beat the rap? Well, one solution to this problem is to assume that quarks *do not* in fact beat the rap, and that if quarks do indeed live happily together in the same quantum state, it must be because they *are not* identical particles.

Having taken this much of a plunge, it may seem that the next step is to try to figure out *why* the cohabiting quarks are not identical. But in fact physics doesn't try very hard to deal with *why* the world is the way it is. It is enough that the world *is*, and the questions that physics tries to answer usually begin with *what* or *how*. For the quarks, then, we simply make a guess that they have a certain intrinsic property that we don't yet know about (another "quantum number," perhaps something like electric charge) but which we assume is a basic distinguishing characteristic of every quark.

What to call the new whatever-it-is? Since guessing an appropriate name would be difficult, physicists enjoy inventing wildly inappropriate names instead. In this case the new intrinsic property that we assign to every quark is *color*, of which there can be only three possible kinds: (what else but) *red*, *white* and *blue*. As a result, the original set of 3 quarks,

$$P \quad N \quad \lambda \text{ (lambda)}$$

must be expanded to a new basic set of 9:

$$\begin{array}{lll} P_{red} & N_{red} & \lambda_{red} \\ P_{white} & N_{white} & \lambda_{white} \\ P_{blue} & N_{blue} & \lambda_{blue} \end{array}$$

In the original model a proton, for example, was assumed to consist of the quarks PPN, but in the colored-quark model it might consist of the quarks  $P_R P_W N_B$ , thus avoiding "identical" particles.

But what's the point? Isn't this just an arbitrary elaboration, with the term *color* used to describe some wholly unknown property? Aren't we going to a lot of trouble just to avoid a "symmetric statistics" problem that we don't even know is real?

The answer to these questions is "Yes, but . . ." Where the "but" might refer to the example of "strangeness"--a property discovered

about 20 years ago, which is observed to change in only certain ways and by certain amounts in particle interactions. This strangeness "bookkeeping" is a necessary part of the description of an interaction, and in a similar way it may turn out that color (regardless of what that actually "means") is also a fundamental property which must be accounted for by exact, simple-minded bookkeeping when particles interact.

The possible connection of the  $\Psi(3105)$  resonance with colored quarks is the following. All previously known hadronic states are assumed in this scheme to be examples of what is known as the "color-singlet" state--that is, they all have the same symmetry with respect to color. The new resonance, on the other hand, would be the first example of a different symmetry with respect to color. Since the strong interactions are assumed to conserve color symmetry, while the electromagnetic interactions need not do so, the  $\Psi(3105)$  would then be created only in electromagnetic processes such as  $e^+e^-$  annihilation. In certain ways this scheme is analogous to the transitions between different energy levels in an atomic nucleus, which can occur only through the electromagnetic process of absorption or emission of a photon.

### 4. Charmed Quarks

We noted earlier that present quark models do not explain why certain apparently allowable decay processes do not in fact occur. The elaboration of the quark idea by the addition of *charm* sets out to solve this problem in much the same way that *color* went after the problem of symmetric statistics. As before, the basic set of 3 quarks must be added to, but this time the set is expanded only to 4, rather than 9. (The basic set for combined charm and color would be 12.) The fourth quark is assumed to have the new intrinsic property, or quantum number, of charm (and what that "means" is again immaterial).

Although the addition of charm as a new quantum number may again, as in the case of color, seem rather arbitrary, such elaborations are only made in an effort to account for what actually does or does not happen in nature. The set of elementary constituents, and the range of their intrinsic properties, is the smallest group the theorist believes he needs to get the right "bookkeeping" in elementary particle interactions.

The idea of charm expressed here seems to be consistent with the presently known properties of the  $\Psi(3105)$  resonance. In particular, the long lifetime of the new particle could well result if it were actually a bound state of a charmed quark and its antiparticle, since its decay into hadrons that did not themselves contain charmed quarks would likely be quite slow.

### 5. Or Something Else

The  $\Psi(3105)$  resonance has a lifetime of about  $10^{-20}$  second. Why doesn't it decay into hadrons much more rapidly than that, as most resonances do? It may well be that the explanation for this unusual behavior is none of the possibilities we've discussed: not the intermediate vector boson, nor the suggested new quantum numbers of color or charm. But if it is none of these, then the behavior *has no other explanation that is presently known.*

This is the main reason why the Psi brothers, (3105) and (3695), are considerably more significant discoveries than the usual hadronic resonances. Certain of their properties are so at odds with those of ordinary particles that they may well prove a sort of "missing link" in elementary particle studies.

### E. WHAT NEXT?

Since space is beginning to run out, we'll just skip quickly through a few items in this section. There are two ways for SPEAR to go from here: find more particles, and get a better understanding of the kind of "debris" that comes out when the resonances decay. We'll discuss each very briefly, then finish with a note or two about non-SPEAR experiments and about PEP.

#### 1. Any more At Home Like You?

The discoveries of the  $\Psi(3105)$  and  $\Psi(3695)$  resonances at SLAC during a period of only 12 days has naturally led to speculation that there may be more new particles waiting to be discovered. There are various theoretical arguments both for and against a whole series of  $\Psi$ -like resonant states. However, since physics is fundamentally an experimental science, the possibility of new discoveries will simply remain an open question until it is tested in the continuing experimental program at SPEAR and elsewhere.

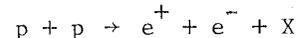
Thus the search for additional new particles will clearly be an important part of SPEAR's future work, but the nature of the resonant states that will be searched for makes this a rather time-consuming effort. Since the  $\Psi$  resonances are such narrow "spikes," any similar resonances that exist must be searched for by a series of very small energy steps. At SPEAR such steps are typically 1 MeV wide, and something like 15 minutes of running time is required to make a decent measurement at each step. Since the energy range which the upgraded storage ring (SPEAR II) will be able to span extends from about 2.5 to 8.6 GeV (that is, from 2500 to 8600 MeV), it is obvious that the search for new particles will not be completed by next Tuesday.

### 2. Sifting Through The Debris

It will be important to learn more about the particular patterns (decay modes) that the Psi brothers break up into when they expire. Such information will provide evidence about the properties of the particles, and may give some needed insight into the constraints that must be operating to prevent the particles from decaying in the "normal" rapid manner. The present large magnetic detector at SPEAR is not particularly well-suited to the detection of neutral particles, and some better means for identifying neutrals will probably be needed.

### 3. Other Than Storage Rings

You can bet your bottom dollar that there are a lot of experimental physicists, at SLAC and everywhere else, who are racking their brains for ways to create and study the Psi resonance particles with conventional accelerators. The MIT-BNL experiment found the 3.1 GeV resonance by studying the reaction



(where X is anything else). This work was done with the 30 GeV proton synchrotron at Brookhaven National Lab. We don't have space here to go into the pros and cons of storage rings vs. conventional accelerators, or proton machines vs. electron machines, in relation to further studies of the Psi resonances. Since these new particles are themselves electron-positron resonant states, it's plain that the larger  $e^+e^-$  storage rings (SPEAR II; Doris-DESY in Hamburg, Germany; and Adone in Frascati, Italy) have the inside track. But experiments at conventional accelerators would also have a number of advantages that storage rings couldn't match -- simultaneous measurements over a broad range of energies, for example, and additional information gained by measuring the angular distributions of the outgoing particles. Thus there is room, as usual, for almost everyone to play.

### 4. A Little PEP Talk

Presumably the Executive branch will soon reach its decision on whether to submit PEP to the Congress for authorization in Fiscal Year 1976. No matter how you slice it, the discovery of the the new resonances is bound to be a good thing for physics in general and for storage rings in particular. PEP would have the obvious advantage of much higher beam energy to explore the region beyond SPEAR. PEP would also have the less obvious advantage that it would be able to measure more accurately the width of narrow resonances such as the Psi particles (the much larger radius of the PEP ring would result in smaller fluctuations of the energy of the circulating beams). The physics prospect for PEP has been very bright from the start. Now it should be even more so.

--Bill Kirk