# 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)

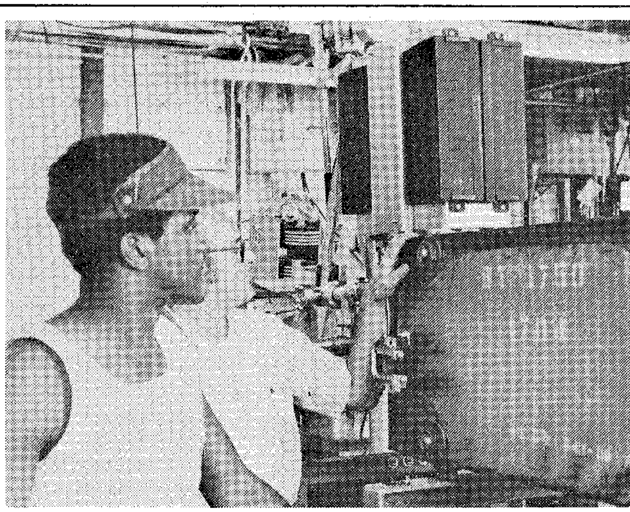
*Volume 6, Number 10* *October 1975*


In This Issue

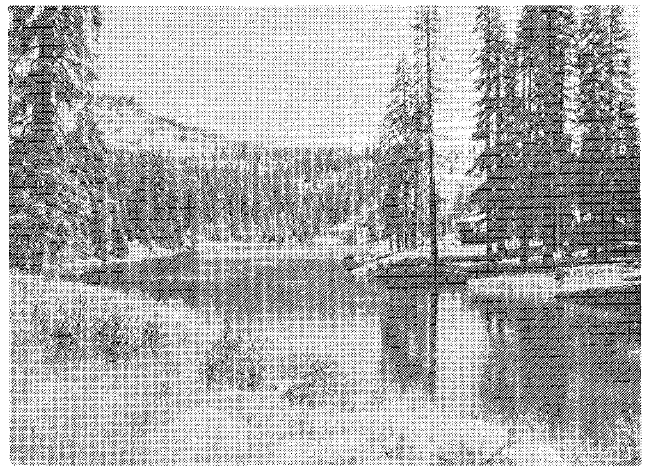


*Editor's Note:* Almost a year has now gone by since the discovery of the psi particles. During the past several months an additional six or seven new particles have been discovered at SPEAR and at the German storage ring DORIS. In this issue we begin a two-part article that is intended to provide up-to-date information on both the psi particles and the newer discoveries.

--Bill Kirk



Ed Johnson and Ray Culver are shown giving a final check to one of the new septum magnets used in the improved SPEAR injection system. This system is designed to improve SPEAR's performance by injecting electron and positron beams from the SLAC accelerator at an energy of 2.25 GeV, rather than the previous 1.5 GeV. See the story on page 2 of this issue.



Ron Koontz of SLAC's Accelerator Physics Dept. provided a memorable weekend for a group of this year's Summer Science students. See page 3 for the story.

. . . As for the problem of seeing quarks, theoretical physicists now tell us that we should not even try. Quarks exist, they say, but they can never be seen. They explain many of the properties of the strongly interacting particles. They carry most of the mass, as well as the charge, strangeness and charm quantum numbers, but they can never be shaken free from the groupings of three quarks, or quark and antiquark, out of which particles are built. A group at the Massachusetts Institute of Technology has invented a model in which the quarks are permanently confined in "bags" about $10^{-15}$ m across. Other groups, including one at Cornell University, have models in which the quarks are tied on strings. Until recently these models were regarded as purely phenomenological; just rigged up to fit the data. But at Palermo, and afterwards at the Erice summer school, near Palermo, it has become clear that fundamental field theories of elementary particles might provide very natural and attractive schemes in which quark-confinement could be achieved. This would be very exciting, since it could lead to a unified theory in which the strong, weak and electromagnetic interactions could be explained all at the same time.

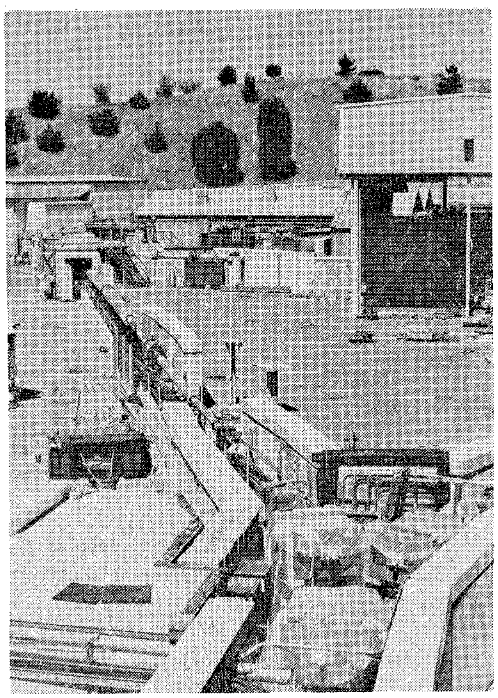
--David J. Miller
*Nature*
August 21, 1975

## HIGHER ENERGY INJECTION INTO SPEAR

*(Photos by John Harris)*

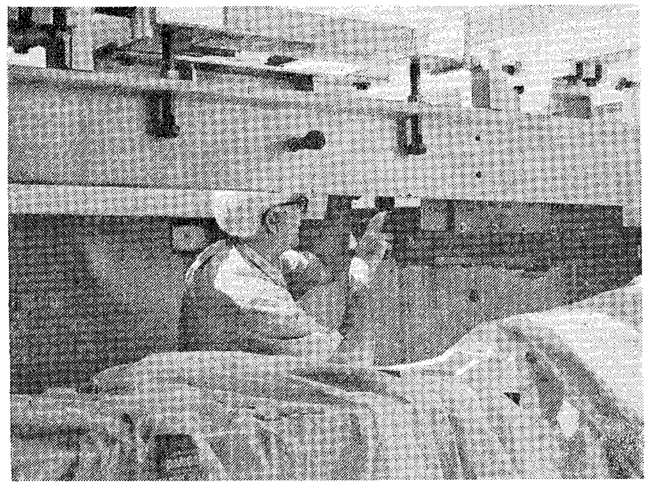
SPEAR gets its electrons and positrons from the main SLAC accelerator. The original SPEAR design was based upon injection of electrons and positrons into the storage ring at an energy of 1.5 GeV. A transport system was built which takes off from the upstream end of the beam switchyard and brings the particles out through the switchyard housing and into the research yard just north of End Station A. The line then separates, taking electrons to the northwest corner of the ring, and positrons to the southwest corner.

The time required to inject the two beams and to establish appropriate operating conditions for doing physics is a significant fraction of the total operating time--usually about 15%. In response to the present high demand for physics running time at SPEAR, the opportunity was taken this summer to upgrade the injection system. The injection energy into the ring has been increased to 2.25 GeV to take advantage of the greater intensity of accelerator beams that is available at this higher energy.



A view of the electron beam line running toward SPEAR in the background. At the "Y" in the foreground, electrons are deflected to the left and positrons to the right.

The way in which the injected beam actually enters the magnetic guide field of the storage ring has also been changed. In the new scheme the incoming beam crosses over the ring and is injected from an inside position on the ring circumference. This injection method makes it possible to avoid certain engineering problems that were encountered with the old design.

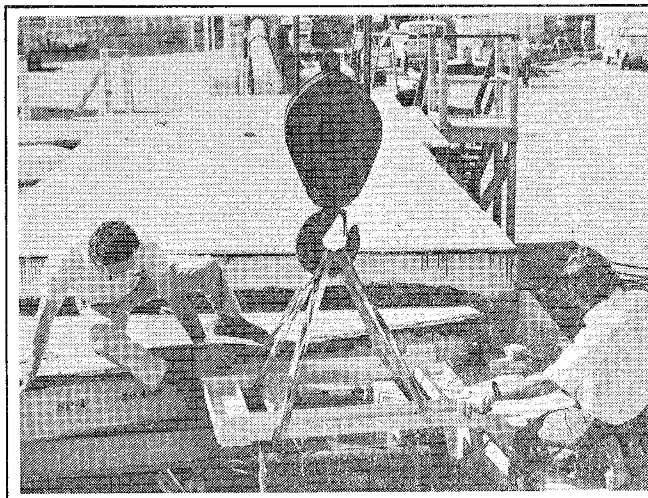


Evan Marshall is shown here checking the position of a quadrupole magnet in the new SPEAR injection system.

An additional advantage of the new, higher energy injection is that it should be possible to eliminate certain instabilities that the beams were subject to in the older method. These instabilities have, until now, acted to limit the maximum current that could be injected into SPEAR and have made the injection process more difficult to control. Tests with the new system have indicated that these particular instabilities will not be present at an injection energy of 2.25 GeV.

Beam optics design of the new system was done by Karl Brown, while the engineering design was the work of Dieter Walz, Bob Sukiennicki and Bill Brunk. Evan Marshall was responsible for field coordination of the project. Many other individuals at SLAC also contributed to this work, but a complete list would read like the SLAC telephone book.

--John Harris



Frank Stella (left) and Vern Cochran guide a bending magnet into position over the storage ring.

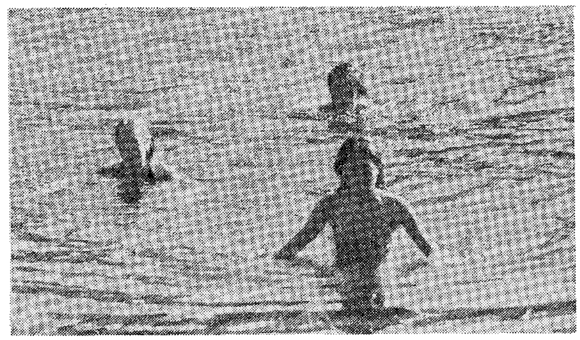
# SUMMER SCIENCE IN THE SIERRA

[*All photos by Ron Koontz.*]

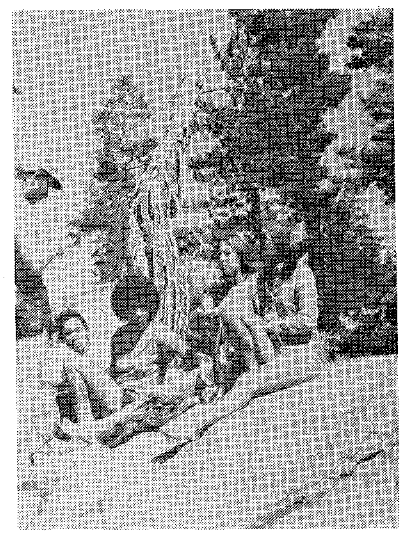
The Summer Science program at SLAC was not all work and no play. This summer 14 young science students spent a weekend in the Sierras during August. Home base for the group was the Koontz cabin in Bear Valley. The group arrived on Friday evening in time to enjoy a swim in Bear Lake. Saturday preparations were made for an overnight backpack trip to Heizer Lake. Camp was set up on the lake shore. After a brief rest part of the group went rock hopping across the peak tops to a second lake, Bull Run Lake. Dinner around a campfire was enjoyed by all.

Dawn comes early in the Sierra, and it brings with it a spectacular sunrise. Some were up early enough to see the sunrise, while others enjoyed a little more shuteye in their down sleeping bags. After breakfast, the long trek back to the cabin began. Weekends are only weekends and are over far too quickly. There was time on the way home for a stop at Slide Rock on the Stanislaus River, then back to the Bay Area and SLAC.

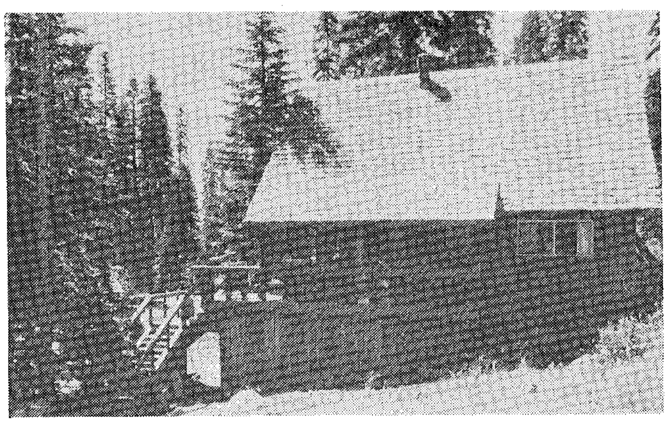
--Ron Koontz



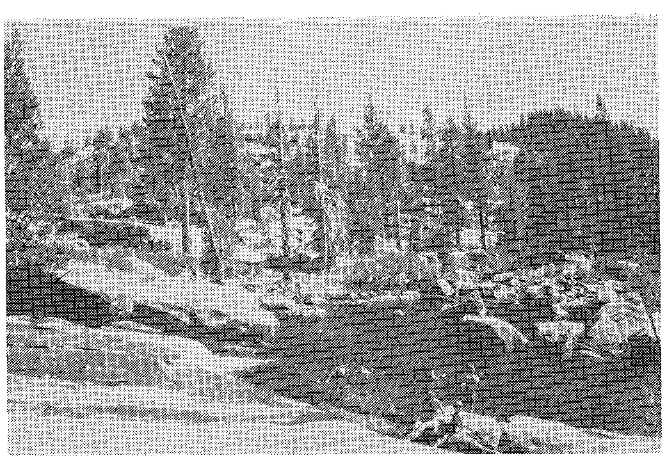
June Okazawa (right front) and friends enjoy a swim at Bear Lake.



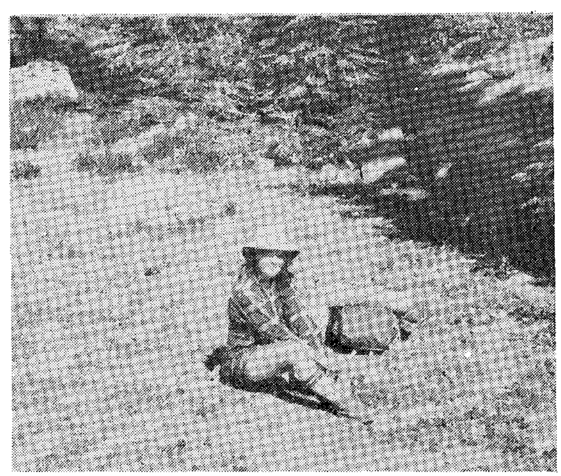
Taking a rest on the trail are, left to right, Craig Rasmussen, John Fok, Mary James, Karen Flammer and June Okazawa.



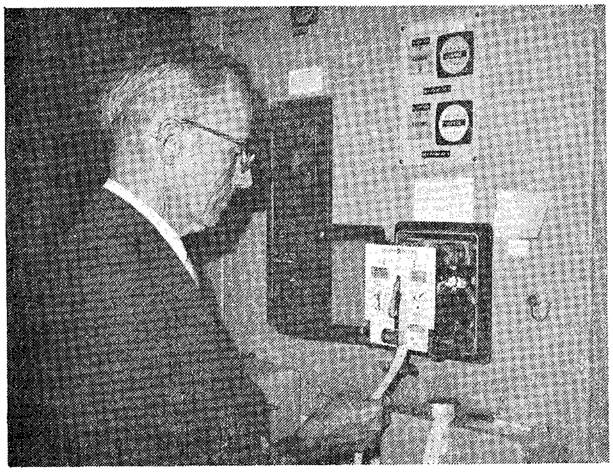
The Koontz cabin at Bear Valley.



A scene near Slide Rock on the Stanislaus River.



Angela Sanchez works on setting up the camp at Heizer Lake.



*--Photo by Paul Edwards*

## CASEY JONES RETIRES

"Casey" Jones, a well-known member of SLAC Plant Engineering, has contributed his knowledge of electrical engineering to the advancement of accelerator technology at Stanford University over a period of 29 years. This long association was finally ended by his retirement in August.

Casey was born in St. Louis County, Missouri, in 1910. Early in public school he developed an interest in science and engineering. He studied engineering at Lehigh University, graduating with a BSEE degree in 1934, in the midst of the great depression. Fortunately, Casey was able to land a job with Union Electric Co. in Missouri, an electric power utility. His position as an assistant load dispatcher with Union gave him some of the knowledge and experience that he was later to put to good use in connection with the self-imposed "brownouts" that have occurred at SLAC in recent years.

Casey subsequently moved on to a job with the Sperry Products Co. of New York City, where his work with the company's railroad rail welding machines and rail safety testing gear stimulated a lasting interest in railroading. After his Sperry experience, Casey also held positions with Engineering Laboratories, Inc., in Tulsa, Oklahoma; and with Brush Recorders, in Cleveland, Ohio.

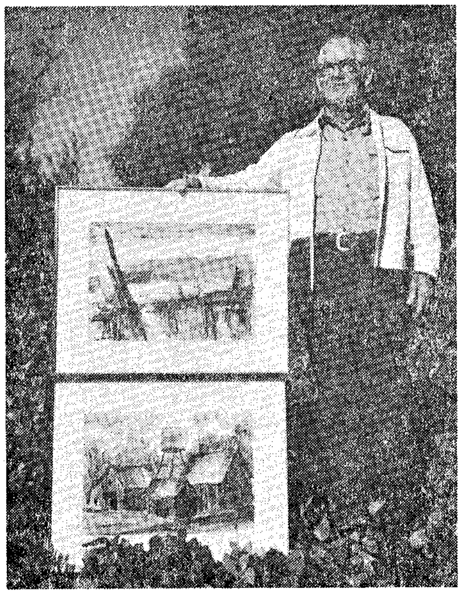
In 1946, after Casey and his family had moved from Ohio to California in order to live in a more moderate climate, he was attracted to Stanford University. After an interview with Professor W. W. Hansen, the inventor of the linear electron accelerator, Casey was appointed to a position as a Research Associate in the group of scientists and engineers who were building the Mark II linear electron accelerator. (Casey recalls an interesting story about Professor Hansen that is connected with his job interview: During the interview Hansen correctly surmised that Casey was low on funds as a result of his recent moving expenses, so he advanced Casey some money to relieve the situation. Some time later, after Hansen's untimely death, Casey learned that not only the advance but also his initial salary funds had come out of Hansen's own pocket. Casey still remembers Hansen with admiration: "There was a gentleman!")

Succeeding generations of the linear electron accelerator at Stanford included the Mark III and Mark IV machines, the latter being a sort of test accelerator upon which some of the ideas for the present SLAC machine were tried out. Casey's work with the Mark IV machine resulted in important contributions to the "Project M" proposal that eventually became the two-mile accelerator at SLAC. These contributions included carrying out the initial power studies, investigating the PG&E power services that would be required, and analyzing the problems related to the operation of direct current power supplies for accelerator duty.

At a recent get-together of SLAC's Plant Engineering electrical associates Casey expressed his personal satisfaction in having been a member of the group that built the two-mile accelerator. The fact that the project was completed on time and within budget has given him pleasure in the recollection.

Casey's associates here at SLAC are well aware of the breadth of his valuable contributions during his 29 years at Stanford, starting during the very earliest days of accelerator development, and extending right down to the present day. We will all miss his gentlemanly, sincere and thoughtful manner and his quiet humor.

--Paul Edwards



## NED LEE RETIRES

It was September, 1944, almost three years after Pearl Harbor, and in the control room of the 100-B reactor in Hanford, Washington, Enrico Fermi, Arthur Holly Compton and other pioneers of the dawning atomic age were gathered to bring the first production fission reactor to criticality. It was actually a somewhat ceremonial start up, since the reactor had already "gone critical" once before. But to the consternation of all those present, the ceremony turned out to be a failure--even with the control rods fully withdrawn, the reaction was still short of critical.

It was at that point that Fermi performed what has been called "the greatest feat of engineering of the Second World War." He recognized that some of the fission products, notably Xenon 135, had large cross sections for the capture of thermal neutrons. With the reactor in operation, an equilibrium state was reached in which the rate of formation of these isotopes balanced out the rate at which they were lost through radioactive decay. However, for several hours after shutting down the reactor the concentration of some of these "neutron eaters" gradually built up to a maximum level--thus "poisoning" the reactor--before tapering back down again. Fermi's ingenious solution was simply to recognize the problem for what it was and thus do nothing but wait until the poisons had decayed away.

One of the interested participants in this historic "ceremony" was Edward P. (Ned) Lee of SLAC's Plant Engineering Department--or formerly of PE, since Ned retired from SLAC in August.

Ned was employed by E. I. duPont de Nemours during the early 1940's, at a time when duPont was asked by the government to take on the job of establishing the Hanford Engineering Works in the state of Washington. A few years later Ned transferred to the General Electric Company when G. E. took over the operations at Hanford, and he eventually became the operations manager for all of the reactors at the Hanford site. When G.E. decided to enter the field of commercial nuclear power generation, Ned played a key role in selecting the site of the Vallecitos Atomic Laboratory near Pleasanton, California. At Vallecitos, the reactor program included research and develment work in nuclear physics, chemistry and metallurgy.

The VAL BWR (boiling water reactor) received the first operating license and was the first privately financed nuclear reactor in the country. In conjunction with PG&E, a steam turbine was tied to the reactor, and in 1956 this combination produced the first reactor-generated electrical power distributed by a public utility.

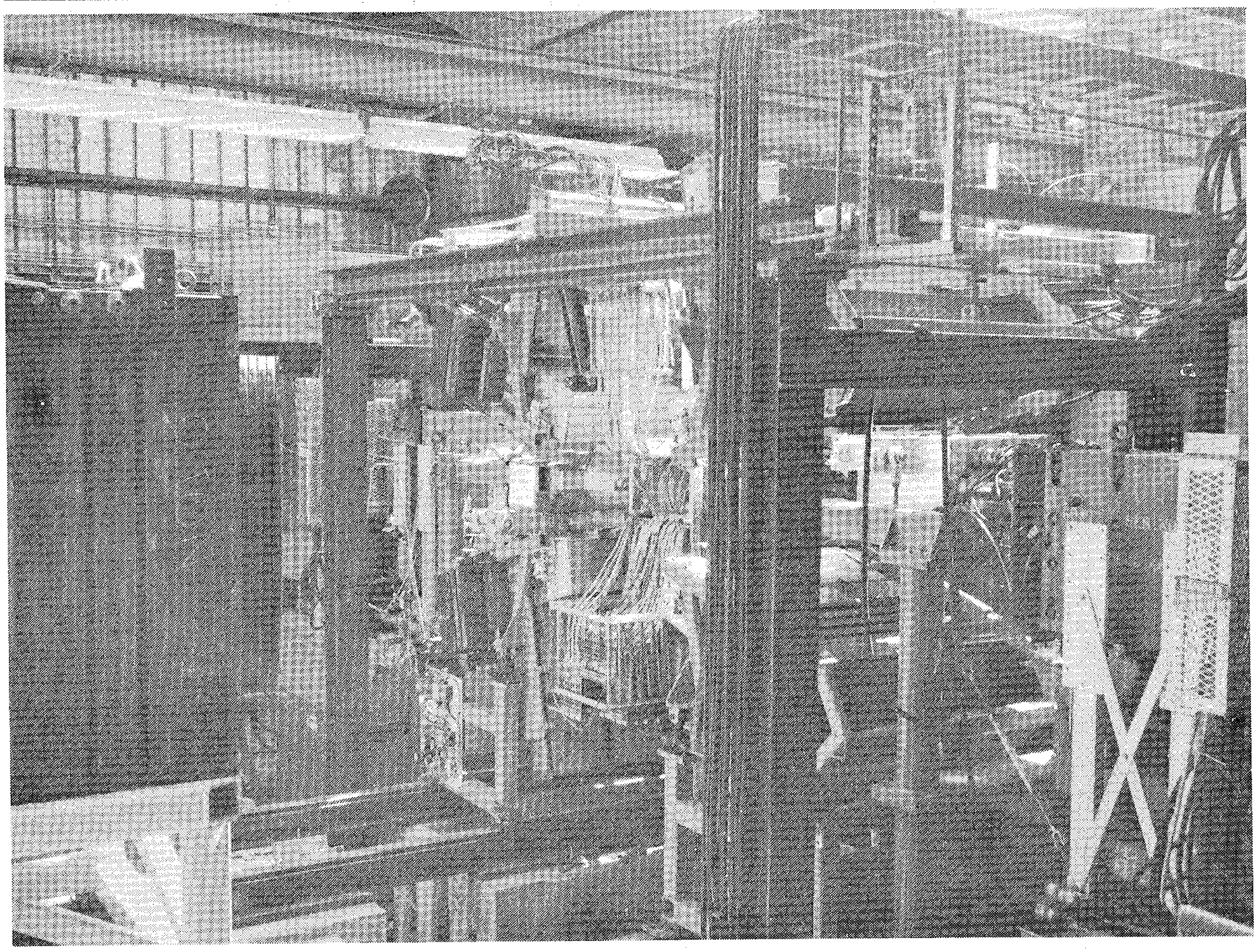
One of the local landmarks at Vallecitos is the body of water called Lake Lee, which was named for Ned Lee as a tribute to his many contributions to the reactor work at G.E. This lake was successfully stocked with bass and blue gill, and it has provided many hours of recreational pleasure for the employees and their families.

Lake Lee also serves as a reminder of one of Ned's favorite activities--the relaxed enjoyment of fishing. He is also an interested and talented participant in art, golf, bridge and music. While he was at Hanford, Ned played violin for several years with the Richland Symphony, and some time later he also played in the Symphony in Schnectady, New York. Many of Ned's coworkers at SLAC are aware of his avid interest in art, with watercolor being his favorite medium. He is an active member and a Trustee of the Palo Alto Art Club.

Ned first came to Stanford in 1961, when the SLAC-to-be was known as Project M. His chief area of responsibility, called the Test Systems Group, included the Mark IV accelerator at the Microwave Laboratory on campus, where accelerator components were developed and tested during the early design stages of the SLAC project. Later Ned transferred to the Plant Engineering Dept., which was then headed by Ken Copenhagen. In PE Ned participated in the development of the SLAC facility throughout the complete design, construction and operations phases.

Many of us at SLAC will sorely miss Ned's well-considered advice and his subtle humor in a great variety of subjects. As Alex Tseng mentioned at the retirement luncheon that was given for Ned, he was often pressed into service as counsellor and advisor--in short, as "psychiatrist"--to many of his friends and coworkers. Indeed, his judgment has earned the highest respect in the administration and fiscal management of Plant Engineering over the last decade. Our best wishes go with Ned and his wife Jean Anne as they enter upon this new phase of their lives.

--Bill Lusebrink



## SPEAR EAST INTERACTION AREA CHANGEOVER

Unlike the SPEAR west interaction area (west pit), where the SPEAR magnetic detector is a more or less permanent fixture (at least until the Mark II detector comes along in a couple of years), the east pit undergoes a total rearrangement at least once a year. During the recent summer shutdown, Experiment SP-16 (a HEPL study of $e^+e^- \to e^+e^-$, $e^+e^- \to 2\gamma$, and $e^+e^- \to \mu^+\mu^-$) was removed, and two compatible experiments were installed (a third experiment was added in September). These new experiments are

SP-14: A UC-San Diego study of deep inelastic two-photon processes.

SP-19: A study by the Princeton-Maryland-Pavia collaboration of charged-particle inclusive reactions.

SP-27: A study of $\psi'$ spectroscopy by Princeton-Maryland-Pavia and UC-San Diego.

The photo on this page shows a part of the recent installation. The large mass of iron and lead on the left is a part of SP-19 (the detectors were not yet installed when the photo was taken). The equipment inside the steel frame in the center is for SP-14 and SP-27. This set up contains four detector arrays consisting of multiwire proportional chambers (MWPC's), sodium iodide crystals and miscellaneous counters for SP-14. Some of the NaI crystals that will be used in SP-27 are visible near the center of the photo. The major part of SP-19 is hidden behind a shielding-block wall, which is part of a scheme that permits access to the experimenters' electronics while there are beams circulating in the SPEAR ring.

In addition to massive rearrangement in the pit itself, major modifications and additions were made in the experimenters' shack, Bldg. 221, and the SPEAR control room.

The number of people who contributed to the turn-around is so large that it is very difficult to single out specific individuals for credit. Virtually every department at SLAC was involved to a greater or lesser extent. The number of visiting users was unusually great, and Summer Science students, summer employees, and contract and T&M workers all played a part. It was a good job well done. Now let's see some physics coming rolling out.

--Herb Weidner

# In Memoriam:
# Irby Crawford

Irby Crawford, SLAC's Transportation Supervisor, passed away on Tuesday, October 14, at the Kaiser Hospital in Santa Clara following an illness of about 2½ months. Irby went to the hospital on August 1, and it was soon learned that he had contracted spinal meningitis. His recovery appeared to be progressing satisfactorily, but on October 12th he was transferred to the Cardiac Ward at the hospital after suffering severe chest pains. His last words to his wife may have been, "Shari, have them take these damn tubes and machines away and just bring me a hamburger!" Shortly thereafter he lapsed into a coma. On Monday the 13th it was decided that surgery would be necessary, and a pacemaker was put on his heart, which had been beating erratically. We knew that the following few hours would be critical. . . .

Irby Earl Crawford was born on July 19, 1911, in Big Springs, Howard County, Texas. He and his wife, Shari Brewer Crawford, have lived in Campbell ever since they moved to California in late 1963. Several times that had been on the verge of moving closer to San Francisco so that Shari would not have such a long commute to her work as a cost accountant at the Presidio. She had also had similar accounting work at the U.S. General Depot in Fort Worth. Irby is survived by three daughters and two sons, along with six grandchildren. Irby had been a Mason, had been affiliated with The Order Of The Eastern Star, and a member of the Shrine and Elks Club. His fun-loving personality made him popular whereever he was and often served to cheer up his coworkers at SLAC.

Irby was in the automotive-maintenance business during nearly all of his adult life. He worked for 23 years in Fort Worth for the Hilliard Motor and Car Rental Co., where he sometimes had as many as 700 cars to care for. He started out in the depression days of 1932 as a mechanic, then worked his way up to shop foreman and eventually to car/truck manager. His job required him to travel all over the U.S. making deliveries or pickups, and this travel experience undoubtedly added to the store of tall tales that he could dispense. He switched from Fort Worth to Dallas in 1956 as Manager of the Earl Hayes Company, but still in the same car rental service business. It was on one of Irby's trips to the West Coast in December, 1962, that he applied for work at SLAC. He was interviewed the following summer, and just over a year later, in August 1964, he was hired and began his "fix-it" work in one of the sheds near the Sector 30 gate that were shared with Salvage and with the Labor Pool.

Many people do not realize the amount of work and care that is involved in maintaining the cars, fork lifts, and other gasoline-driven vehicles at SLAC. A number of these vehicles are surplus items from other Federal installations; Irby made a number of trips to look at jeeps, pickups and other vehicles that had been declared surplus. Even the GSA vehicles that we rent require a fair amount of maintenance and repair to keep them in good running condition. Irby continually saw to it that our vehicles were kept in operation, even when it meant a lot of extra personal time to get the work done. Remember the jeeps? They provided SLAC with useful transportation while we had them, but the time and effort required to keep them running was terrific. Perhap's Irby's most frustrating problem was the rather careless attitide that too many of our drivers had toward the vehicles they used: no gas left for the next fellow, empty coffee cups and food wrappers and cigarette butts, windows left down and doors unlocked, etc.

Irby was so dedicated to seeing to it that SLAC's fleet of more than 120 vehicles was kept in top shape that he occasionally wore himself out in the process. In the files there are comments about Irby's work such as "dependable," "none more loyal," excellent initiative," and "wouldn't ask others to do anything that we won't do himself." But these still leave unmentioned such things as his early arrivals at SLAC to get the bus going and his work with pool cars and the like. His dealings with GSA succeeded in keeping our vehicles rolling when other groups were not able to, and he worked constantly to keep us supplied with gasoline and with spare parts--even for the bicycles on site.

With Irby's passing we will certainly feel our loss in many ways: a helping hand wherever needed, advice on all automotive problems, a quick quip, unfailing courtesy, an occasional growl about taking care of the fleet. All these and many more were characteristic of Irby. We will surely miss having him around.

All of us at SLAC extend our sincere sympathies to Irby's family at this time of their, and our, great loss.

--Harry Changnon

## SYNCHROTRON RADIATION RESEARCH MEETING

Many exciting research results and plans for future experiments will be discussed at the Second Annual Users Meeting of the Stanford Synchrotron Radiation Project (SSRP) on October 23 and 24, 1975. The meeting will be held in the SLAC Auditorium, and interested observers from SLAC are welcome to attend. SSRP began operation as a multidisciplinary national facility for research utilizing the very intense ultraviolet and x-ray beams produced by the SPEAR storage ring at SLAC. The unique properties of this radiation have opened up new horizons in research in physics, chemistry, biology, materials sciences and many associated sub-fields.

The high intensity of the synchrotron radiation (one million times greater than that obtainable from conventional sources) has led to the rapid development of a number of techniques, such as the study of local atomic environment by means of extended x-ray absorption-edge fine structure (EXAFS), studies in protein crystal structure by x-ray diffraction, and surface physics studies by photoemission techniques.

Although intended primarily as a forum for the exchange of ideas and results among users of SSRP, this meeting has attracted the attention of scientists throughout the world. Expected at the meeting are about 90 scientists from the United States and over a dozen from abroad, including representatives from Canada, England, France, Italy, Japan, Sweden and West Germany. The activities and plans for synchrotron radiation research at nine other laboratories throughout the world will be presented, along with about 25 reports on work at SSRP, in two days of technical sessions starting at 8:30 AM and extending to 5:30 PM each day.

--Herm Winick

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Mr. Lick has fixed on Mount Hamilton, in Santa Clara County, Cal., as the most eligible site for the establishment of the observatory in which the great telescope is to be located. Mount Hamilton is 4,448 feet high.

--*Scientific American* October 1875

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1. The value of a CREF retirement unit as of the end of August was $35.86.
2. A recent fortune cookie of our acquantance contained the following message:

   *The important thing is to express yourself*
   *The important thing is to express yourself*
   *The important thing is to express yourself*

## SHARED JOBS: AN INTERESTING NEW IDEA

People who must or who prefer to work less than full time have always had a most difficult time finding employment. A new concept is beginning to catch on: two people sharing one full-time job. The job can be shared by each of the two working 4 hours per day, one in the morning and one in the afternoon.

The advantages to the employee are personal. The disadvantages of course are economic; and there can be fringe benefit problems to be worked out in each case.

The disadvantages to the employer include a larger headcount, and more people to interact with and train. However, the advantages to the employer include having two trained employees in one job who can substitute for each other or absorb peak work overloads, having a diversity of talents available, and in some cases increased productivity.

Here at SLAC we are trying two things in this area:

1. When a job requisition is sent to the Personnel Department, the group leader should indicate if he would like the notation *Can be shared by two half-time people* to appear on the posting.

2. The Employee Relations Department (x2358) would like to hear from present full-time employees who would rather work half time. Perhaps something can be worked out. (In fact, the Employee Relations Department welcomes inquiry from anyone who might want to investigate working any amount less than full time; often mutually satisfactory arrangements can be made.)

--Doug Dupen

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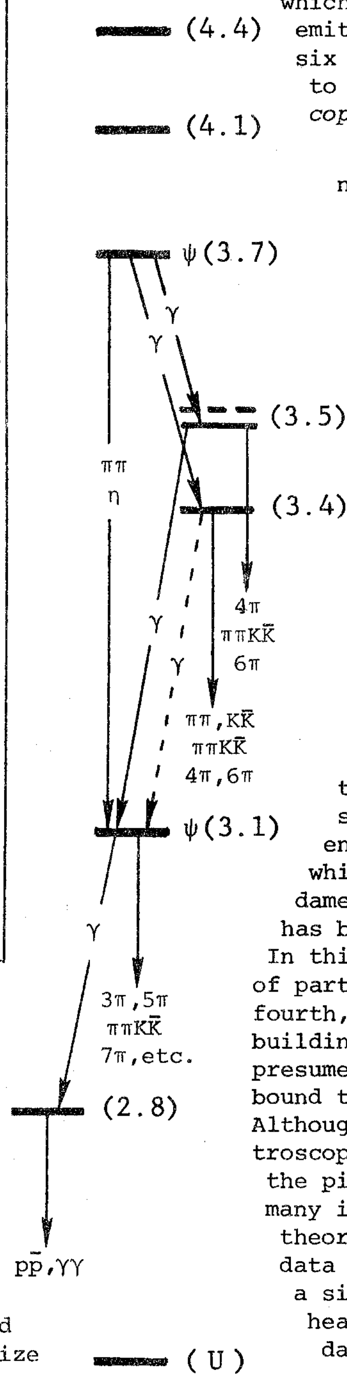
# More New Particles

## PART I

*THIS IS THE FIRST PART OF A TWO-PART ARTICLE THAT HAS TWO PURPOSES. THE FIRST PURPOSE IS TO REPORT ON WHAT HAS BEEN LEARNED ABOUT THE ORIGINAL TWO PSI PARTICLES, ψ(3.1) AND ψ(3.7), SINCE THEIR DISCOVERY LAST FALL. THE SECOND PURPOSE IS TO DESCRIBE THE NEWER DISCOVERIES, MADE RECENTLY AT SPEAR AND AT THE GERMAN STORAGE RING DORIS, OF AN ADDITIONAL HALF-DOZEN NEW PARTICLES, SOME OF WHICH ARE (AND THE OTHERS MAY BE) RELATED TO THE TWO PSI PARTICLES.*

*PART I (This Month)*






# A. A Brief Summary

The curved band running down the center of this page contains nine horizontal bars (one dashed) which represent (a) the two previously known psi particles with masses of 3.1 and 3.7 GeV, and (b) six or seven other new particles, or "resonances." The states at 2.8, 3.4 and 3.5 (maybe two states) GeV are definitely connected to the psi particles; the arrows symbolize various transition or decay processes in which gamma rays (γ) and/or particles are emitted in characteristic patterns. The six arrow-connected states are beginning to be identified as the *psi spectroscopy.*

The other three states, not connected, may or may not be related to the psi particles. The upper two, at 4.1 and 4.4 GeV, are "bumps" that occur when the $e^+e^-$ collisions at SPEAR result in the creation of strongly interacting particles (hadrons) such as pi and K mesons. The lowest state shown, the U ("unknown") particle, has a mass somewhere between 1.6 and 2.0 GeV. It may be that a pair of U particles emerge from the decay of a single heavier particle that is created in the "bump" region near 4 GeV. A second and even more striking possibility is that the U is a "heavy lepton"--that is, the third member of the particle family that includes the electron and the mu-meson (muon).

These new particle discoveries, together with other experimental results from SPEAR and DORIS, have given strong support to those theories which postulate the existence of a fundamentally new property of matter that has been given the (nutty) name "charm." In this theory the basic three-quark model of particle structure has added to it a fourth, charmed, quark, as an elementary building block, and the psi particles are presumed to consist of the charmed quark bound together with its own antiparticle. Although this theory predicts a psi spectroscopy that is in general very much like the picture on this page, it still leaves many important problems unresolved. Some theorists believe that the experimental data support the idea of a fifth, or even a sixth, basic quark, and perhaps also heavy leptons. More SPEAR and DORIS data is eagerly awaited.

# B. Some Background Information

Certain parts of this article contain technical information that may be more detailed than most readers would wish. The most detailed of this stuff has been put on separate pages that are called *Detours* so they can easily be avoided by Turnpike drivers. Although the remainder of the article is aimed toward a fairly general audience, this aim has become more difficult to achieve as the psi story has grown more complex. For readers who may wish to dig either deeper or wider into the study of elementary particles, the articles listed at the bottom of this page may be of interest.*

In this section we spend a couple of pages on some of the basic information about colliding beams and about particle physics.

## 1. THE ANNIHILATION PROCESS

In the SPEAR storage ring beams of electrons ($e^-$) and positrons ($e^+$) circulate in opposite directions. At two points on the circumference of the ring the beams are made to pass through each other and thus to set up the possibility of an $e^+e^-$ collision. The particular kind of collision that will concern us here is called *annihilation*. This process can only occur when the collision involves a particle and its antimatter counterpart, an antiparticle. The process of $e^+e^-$ annihilation proceeds in two steps. First, the $e^+e^-$ pair creates a very short lived intermediate state called a *virtual photon* or *virtual gamma ray* ($\gamma_V$). Then the pure electromagnetic energy of the virtual photon rematerializes into any of a large number of possible combinations of newly created particles. In the shorthand notation of physics the process is written:

$$e^+e^- \to \gamma_V \to \text{created particles}$$

(In what follows we'll usually leave out the $\gamma_V$ for the sake of brevity.) The particles emerging from the annihilation process can be grouped into three classes:

(1) $e^+e^- \to e^+e^-$ (e pair)

(2) $e^+e^- \to \mu^+\mu^-$ (muon pair)

(3) $e^+e^- \to \pi^+\pi^-\pi^0$
$\to K^+K^-$
$\to \pi\pi K\bar{K}$ (hadrons)
$\to p\bar{p}$
$\to$ etc.

Although it is class (3)--electron-positron annihilation into hadrons--that will be our chief concern when we get to the SPEAR and DORIS experimental results, we want to take a minute here to talk about classes (1) and (2).

## 2. FAMILIES AND FORCES

The first two classes of interactions above involve only particles that belong to the *lepton* family. This complete family contains only 8 members: the electron and its neutrino; the muon and its neutrino; and the four antiparticles of these four particles. The leptons are distinguished from the other major particle family--the much larger (hundreds) *hadron* family--by the following essential difference. Hadrons are affected by, or "feel," the strong or nuclear force that is responsible for binding together the protons and neutrons in the nuclei of atoms. The leptons, in contrast, are those particles which specifically *do not* feel the strong force. Thus the e-pair and muon-pair production processes given in classes (1) and (2) above are known as purely *leptonic* processes. Because of their comparative simplicity, leptonic interactions are often used to study the two other kinds of forces that play a role in particle physics: electromagnetism, and the so-called "weak" or Fermi force.

The relationships between particles and forces are an essential part of the study of the elementary particles. The following table summarizes some of these relationships.

| *Force →* | *Strong* | *Electro-magnetic* | *Weak* | *Gravit-ational* |
|---|---|---|---|---|
| Range | $10^{-13}$cm | Infinite | $10^{-15}$cm | Infinite |
| Relative strength | 100 | 1 | $10^{-9}$ | $10^{-37}$ |
| Particles acted upon | Hadrons | All charged particles | Hadrons Leptons | All |
| "Carrier" of force | Hadrons | Photons | ? | Gravitons |
| Example | Nuclear forces | Atomic forces | Radio-activity | Planetary orbits |

*Previous *Beam Line* articles on SPEAR and psi:
1. "An introduction to colliding-beam storage rings," August & September, 1974.
2. Special issue on psi, December 5, 1974.
3. "More on psi," January, 1975.
4. "Psi photoproduction," March 20, 1975.

Useful *Scientific American* articles:

5. Chew, Gell Mann, Rosenfeld, "Strongly interacting particles," February, 1964.
6. Weisskopf, "The three spectroscopies," May, 1968.
7. Panofsky, Kendall, "The structure of the proton and neutron," June, 1971.
8. Drell, "Electron-positron annihilation and the new particles," June, 1975.
9. Glashow, "Quarks with color and flavor," October, 1975.

Also, a recent *Nature* article:

10. Leader, Williams, "Unified gauge theories of elementary particles," September 11, 1975.

Now let's add a few words of additional explanation about each of these four kinds of fundamental forces:

*Gravitation.* In particle physics, the masses we deal with are so small, and the intrinsic strength of the gravitational force is so extremely weak, that the effects of gravity are completely ignored

*Electromagnetism.* The electromagnetic force affects all particles that are electrically charged (+ or -), whether they be hadrons or leptons. The theory of electromagnetism as it applies to the elementary particles is called *quantum electrodynamics*, or *QED* for short, and it is by all odds the most successful theory in high energy physics. Because of this success, QED often serves as a model for trying to understand the other forces. QED is also subjected to frequent severe tests, in experiments such as the $e^+e^-$ leptonic interactions mentioned above, in an effort to extend the (already very large) range of its validity. Much of the effectiveness of the SPEAR experiments on hadron production can be attributed to the fact that the virtual photon intermediate state out of which the hadrons are created is itself a purely electromagnetic phenomenon, whose properties are precisely described by quantum electrodynamics.

*The strong force.* The strong force has the property that it can act only over a range that is comparable to the size of a single elementary particle. Thus it is effective only when two hadrons are essentially touching each other (as they are in the nucleus of an atom). At this minute range, however, the strong force is about 100 times as strong as the electromagnetic force. An alternate way of stating the same thing is to say that strong-force interactions occur on a time scale that is roughly 100 times faster than electromagnetic interactions, a typical strong interaction time being about $10^{-23}$ second.

*The weak force.* The range given for the weak force in the table above, $10^{-15}$ cm, is thought to be an *upper* limit. This is a difficult idea to get any sort of a feeling for. We've gradually got used to the idea that the force between two objects is "carried" by something. The force with which a magnet attracts a piece of iron can be described with great accuracy as an "exchange" of the composite wave-particle things called photons. Similarly, the earth and moon exchange gravitons, and the force that binds protons and neutrons together is carried by the pions and other particles that they exchange in atomic nuclei. For the weak force, however, there is not yet compelling evidence that it is "carried" over *any* finite distance. (Even $10^{-15}$ cm rates as "finite" in particle physics.) If there is a weak-force carrier, then the extremely short range dictates that this hypothetical particle--the *intermediate vector boson* (IVB)--must be very massive. (For a force of infinite range such as electromagnetism or gravitation the carrier has zero mass and thus travels always at the velocity of light.) For a time soon after the discovery of the $\psi(3.1)$ there was speculation that the long-sought IVB had finally been found. But the expected mass of the IVB is closer to 40 than to 4 GeV, and subsequent data on some of the psi's properties have now pretty much laid this possibity to rest.

## 3. "POINT" LEPTONS & "STRUCTURED" HADRONS

A very important distinction between the lepton and hadron families of particles is this: The lepton experiments so far performed have not given any evidence that leptons have any "size" or internal structure. Electrons have been probed down to distances of about $10^{-15}$ cm, and at this level of "resolving power" they still appear to be point-like objects. Stated somewhat differently, there is no evidence that leptons may be composed of any smaller, simpler entities. So far as we now know they are in fact *elementary* particles.

This is not the case for the hadrons. For these particles, such as the proton, we have abundant experimental evidence that they are somewhat diffuse objects whose structure is spread out over a certain volume of space. Hadrons have a diameter or a size of about $10^{-13}$ cm (really huge, man). The hadrons' spread-out structure, and also the fact that there are so many different varieties of the damned things, made it seem quite evident as long as 20 years ago that the hadrons could not *all* be "elementary" in any meaningful sense, and consequently that the hadrons might well be built up from some simpler, "truly" elementary objects.

In the early 1960's there was put forward a theory of hadronic structure which postulated that the vast circus of hadronic states could all be explained as various combinations of only three basic constituents called *quarks*. This theoretical model has proved to be remarkably successful both in explaining the spectrum of known hadrons and in predicting the existence of certain new states that were subsequently discovered. And in the late 1960's, experiments on "deep inelastic" electron-proton scattering at SLAC added strong evidence in support of the quark model when they disclosed the presence of minute scattering centers ("partons") within the larger volume of the individual protons.

In broad outline, then, this is the way matters stood until about 1973, when the early experimental results from the $e^+e^-$ storage rings at Frascati, Italy, at CEA in Cambridge, and later at SPEAR began to come in. In an oversimplified nutshell, the problem in high energy physics was--and still is--to "explain the hadrons," and in the minds of many physicists the most likely source of such an explanation was the idea of three simple bricks, the quarks, from which the whole big banana might be built.

# Detour 1: Quarks

This is the first of four detours off the beaten track. It adds something to the business of building-block quarks as the basis for the hadrons, but it can be skipped if looks too hairy.

*Mesons and baryons*. In the previous section we often referred to "the large family of hadrons." How large? Well, the hadron family has two subgroups: the *mesons* (middleweights), of which roughly 100 are known; and the baryons (heavyweights), of which about 200 have been found. The chart on this page lists the baryons that had been reasonably surely identified as of about six months ago. There are 112 flyspecks on the chart, and 112 antiflyspecks, and even if we happen to notice that there are really only six *kinds* of baryons (N,Σ,Δ,Λ,Ξ,Ω) the chart still looks like a linear ant attack.

*Three quarks*. So what to do with all those particles or "resonances" or "states?" The answer is to leap in with a construction plan by which bricks and mortar can be fitted together to form hundreds of different designs. Our bricks will be quarks of 3 different kinds which we'll give the following names: *u*, *d* and *s*. The letters are from the words *up*, *down* and *sideways* (or *strange*), which refer to a triangular arrangement in which the three quarks are sometimes displayed:

*Quarks* (s) (u) (d) $(\bar{u})$ $(\bar{s})$ $(\bar{d})$ *Antiquarks*

Quarks are assumed to have certain intrinsic properties such as spin and strangeness. Some of these assumed properties are similar to those of ordinary particles and some are very different. We'll be concerned here with only the assumed values of electric charge:

| | $u$ | $d$ | $s$ | $\bar{s}$ | $\bar{d}$ | $\bar{u}$ |
|---|---|---|---|---|---|---|
| Charge | $+\frac{2}{3}$ | $-\frac{1}{3}$ | $-\frac{1}{3}$ | $+\frac{1}{3}$ | $+\frac{1}{3}$ | $-\frac{2}{3}$ |

Although neither quarks nor any other fractionally charged object has ever been observed in nature, there may be a reasonable (but not simple) explanation. There is some weight of theoretical opinion which holds that quarks may well be the basic stuff of which hadrons are made and yet still never be observable as separate entities.

*How the bricks fit*. According to the theory, quarks can combine with each other in only two different ways: (1) as a quark-antiquark pair, which makes *mesons*, or (2) as a quark (or antiquark) triplet which makes *baryons*. As an example, the particles at the very bottom of the chart are the familiar proton and neutron, which are thought to be constructed in the following way:

proton = (uud) neutron = (udd)

As more general examples, the quark structure of mesons and baryons can be any of the following, and many more, combinations:

Mesons: $(u\bar{u})$ $(d\bar{u})$ $(u\bar{s})$ $(s\bar{s})$ $(d\bar{s})$ etc.

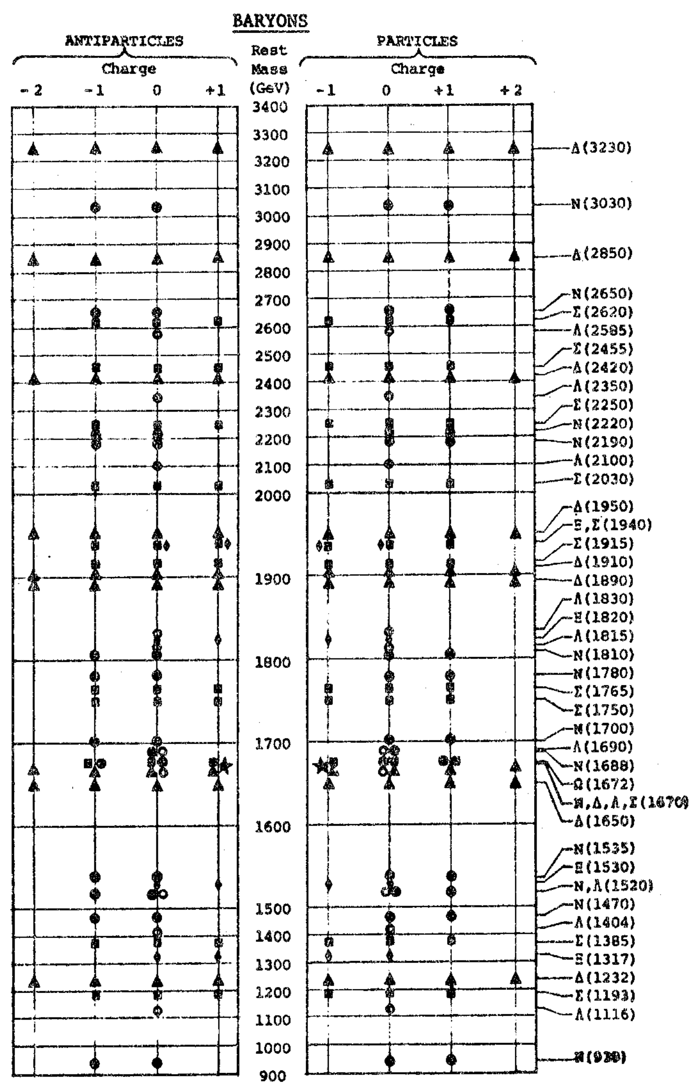
Baryons: (uud) (usd) $(\bar{u}\bar{s}\bar{s})$ (sss) etc.

In the chart, note that the nucleons (N) and other baryon types "recur" at higher energies: N(1470), (1520), (1535), etc. Each recurrence of the proton, for example, is still the same combination of quarks (*uud*), with the difference being that each higher energy recurrence represents a different pattern of motion of the three quarks inside the "excited" state of the proton.

*Six classes of baryons*

The baryons shown in the chart have the following six class names:

● N (Nucleon) ■ Σ (Sigma) ◆ Ξ (Xi)
○ Λ (Lambda) ▲ Δ (Delta) ★ Ω (Omega)



# C. The SPEAR Data In General

In this section we take a broad look at the SPEAR experimental data accumulated by the joint SLAC-LBL physics group. Our main concern will be with these topics:

1. The ratio of hadron production to the production of muon pairs.
2. The search for other sharp resonances.
3. Observation of "jets" in hadron production at higher SPEAR energies.

## 1. THE HADRON/MUON-PAIR RATIO

There is a certain quantity that plays a central role in much of the $e^+e^-$ experimentation and in assessing its significance. This quantity is the following experimentally measured ratio:

$$R = \frac{e^+e^- \rightarrow \text{hadrons}}{e^+e^- \rightarrow \mu^+\mu^-}$$

In words, the quantity is the ratio between the cross section (or probability) for producing hadrons and the cross section for producing a pair of muons in the electron-positron annihilation process. It's worth a few words to find out why this particular ratio, R, is considered to be so important. We saw earlier that leptons such as electrons and positrons appear to be point-like objects. They also belong to the group of particles which possess an intrinsic angular momentum, or spin, of ½ unit (the ½-unit group is called the "fermions"). As it happens, the quarks we've been talking about are also assumed to be point-like fermions, and as such their behavior is expected to be similar in certain ways to that of the leptons.

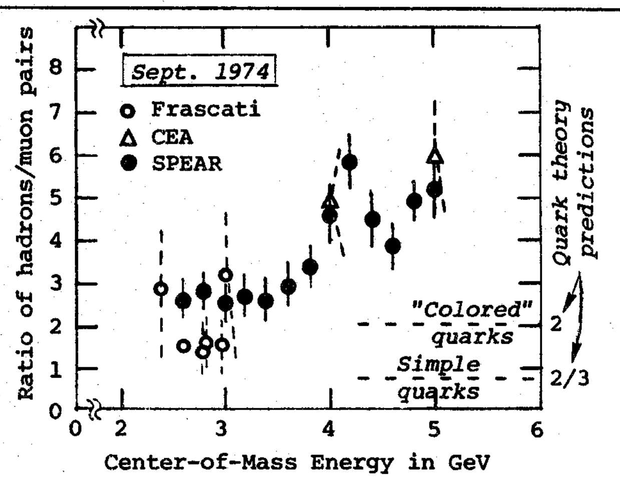
In particular, the similarities should make it possible to calculate (at sufficiently high energies) the ratio between creation of a lepton-pair (muons in this case) and creation of quarks (which instantly "clothe" themselves and become the pions, protons and other kinds of hadrons that are actually observed in the experiment). This calculation consists simply of writing down the values of electric charge that are carried by the quarks, squaring those values, and then adding up the squares. Like this:

$$\begin{aligned} R &= (2/3)^2 + (-1/3)^2 + (-1/3)^2 \\ &= 4/9 + 1/9 + 1/9 \\ R &= 2/3 \end{aligned}$$

So the quark theory in its simplest form, with only the three quarks $u$, $d$ and $s$ that we have mentioned so far, predicts that hadrons should be created in $e^+e^-$ collisions 2/3 as copiously as pairs of muons. More complex versions of the quark theory give different answers, but before we look into these other theoretical models, let's first go back to what the earliest experimental measurements of the ratio R were like.

*Early measurements of R.** The first measurements of the hadron/muon-pair ratio were made several years ago at the 1.5 GeV $e^+e^-$ storage ring at Frascati (near Rome), and shortly thereafter at the ring that had been built by conversion of the Cambridge Electron Accelerator (CEA) at Harvard. The Frascati measurements were in the center-of-mass energy (total energy of both beams) region below 3 GeV, while CEA measured points at 4 and 5 GeV. Neither the Frascati nor CEA results were consistent with the predicted R value of 2/3. The subsequent measurements of R that began to be made at SPEAR confirmed the unexpected Frascati and CEA answers, and all of these data taken together started to take on the trappings of an intriguing mystery.

The following graph shows how the experimental situation looked about a year ago, in September 1974.




Twelve months ago this collection of experimental measurements from Frascati, CEA and SPEAR was causing a lot of excitement in high energy physics circles. The values of R predicted by the simple and "colored" quark models, 2/3 and 2, respectively, were clearly too small for the data, for one thing; but even more striking was the fact that all theories had predicted a *constant* value of R, whereas the experiments appeared to show that R was increasing rather steadily with increasing energy. The discrepancy between theory and experiment at that time gave rise to a great deal of speculation--more quarks were needed; or perhaps leptons "were really hadrons at heart"; and what was that big bump at about 4 GeV? But take heart, because September 1974 was only two months before November 1974 and the discovery of the psi particles.

*See the September 1974 issue of the *Beam Line* for a more complete history of R measurements than we have space for here.

The particular aspect of the data from a year ago that excited attention was the fact that the measured values of R were increasing as the $e^+e^-$ collision energies were increased. There were readily at hand various theoretical explanations for why R should be 2, or 10/3, or 4, or even larger; but that it should not be a *constant* value--no matter what the actual number--was a circumstance that theorists found hard to digest. (The separate box on this page explains how some of the predicted R values larger than 2/3 are arrived at.) We will not, however, dwell upon this year-old conundrum, because subsequent developments have shown that the not-constant appearance of R is a little deceptive. To see why this is so, we now move forward in time to about June of this year in order to find out what the SPEAR experiments had been able to add to the study of the hadron /muon-pair ratio.

*Two ψ's, two plateaus, and a bump.* Discovery of the two remarkable new particles, ψ(3.1) and ψ(3.7) occurred last November. At that time the storage-ring improvement program called "SPEAR II" was well along and was subsequently completed in the spring of this year. This work made it possible to operate SPEAR at energies up to about 3.8 Gev for each beam, about a 50% increase in maximum beam energy from the previous 2.5 GeV. This energy increase made accessible to the SLAC-LBL experimenters the center-of-mass energy region from 5 to almost 8 GeV, and during the spring and early summer the group carried out a systematic exploration of this unknown territory. The measurements of the hadron/muon-pair ratio in this new region are shown plotted, together with the earlier results, in the figure at the bottom of this page.

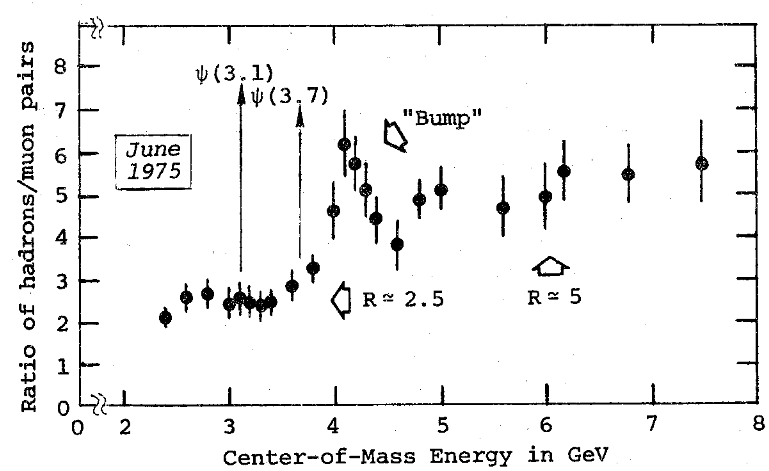
As the figure shows, extending the R measurements out to higher energies results in a general picture that seems quite different from that of a year ago. Last year's "steadily rising" interpretation of the data no longer seems tenable. Instead, there appear to be two broad areas--from about 2 to 4 GeV, and from 4½ to 7½ GeV--where the value of R does not change very significantly. R is about 2.5 in the lower energy region, and about 5 or a little greater in the higher energy region. The other obvious features of the data shown in the figure are the two sharp psi spikes (actually much taller than the figure has room to show), and the fairly wide "bump" region from about 4 to 4½ GeV. (We postpone further discussion of the significance of this newer R picture until after we have looked, in Section E, at an even more recent and detailed mapping of R over the full SPEAR energy region.)

### *Computing Other Values Of R*

Earlier we saw that R can be predicted by summing the squares of the values of electric charge that are assumed to be carried by each of the quarks in a theoretical model. For the simple quark model we've talked about so far, the 3 basic quarks $u$, $d$ and $s$ yield a predicted R value of 2/3. We now see how R comes out when a more complex model (more quarks, or different quarks) is used. We consider (but do not attempt to justify until later) four possible elaborations of the basic 3-quark idea: (1) To the quarks $u$, $d$ and $s$ must be added a fourth, *charmed* quark $c$. (2) Each of the 3 basic quarks comes in 3 *colors*. (3) The basic set of quarks requires *both charm and color*. (4) The basic set of quarks is both charmed and colored *and* its members carry *integral* rather than *fractional* values of electric charge.

Now let's calculate R for each of these four possibilities:

1. *Charm:* $(2/3)^2 + (-1/3)^2 + (-1/3)^2 + (2/3)^2 = \frac{10}{9}$
2. *Color:* $3[(2/3)^2 + (-1/3)^2 + (-1/3)^2] = 2$
3. *Both:* $3[(2/3)^2 + (-1/3)^2 + (-1/3)^2 + (2/3)^2] = \frac{10}{3}$
4. *Integral:* $(1)^2 + (1)^2 + (-1)^2 + (-1)^2 = 4$




The SPEAR II improvement program resulted in an extension of the storage ring's energy range from 5 to about 7.8 GeV (center-of-mass). With the added data from these higher energies the previous picture of R was seen to be rather deceiving. In the full range of data there now appear to be two plateaus in the value of R: about 2.5 at the lower level, and 5 to 5½ at the higher level. The smaller "bump" region between the two plateaus marks the energy range where apparently some new processes begin to happen (more about this later). The two sharp psi resonances, if drawn to scale, would rise through the (or any) ceiling.

## 2. SEARCH FOR OTHER NARROW RESONANCES

The $\psi(3.1)$ was discovered at SPEAR on November 8, 1974. It was a beauty. On November 20, less than two weeks later, the $\psi(3.7)$ particle was discovered at SPEAR, and it was also a beauty. For a period of perhaps three or four weeks after that the SPEAR experimenters seemed to share the fond but perhaps not totally rational hope that SPEAR was just one big nickelodeon--you just pop your coin into the slot and out comes another startling new particle discovery. Oh well, it was certainly a gas while it lasted.

Let's recall that the most distinctive characteristic of the psi particles is their inexplicably long life. For a very massive hadron of "typical" behavior, the expected lifetime before it decays into other, lighter particles is about $10^{-23}$ second (which is about the time needed for a particle traveling at the velocity of light to traverse the $10^{-13}$ cm diameter of a proton). Let's call this ridiculously brief (and unmeasurable) period of time a *blip*. In the case of the two psi particles the lifetimes, which are inferred from other data, turned out to be not the typical one *blip* but rather a few hundred *blips* for the (3.7) and about 1000 *blips* for the (3.1). These extended lifetimes manifest themselves experimentally in the shape of the resonance "bump" that characterizes the process in which the particles are produced (we'll discuss this shape in the next Section), so the key "signature" that is looked for in a search for other psi-like resonances is a sudden and sharp increase in particle production that occurs only within a very narrow SPEAR energy region.

During the past several months the SLAC-LBL group has completed the search for other narrow, psi-like resonances over the full energy range available for this purpose at SPEAR: about 3.2 to 7.6 GeV (combined energy of both beams). The search was conducted by stepping the SPEAR energy upward in increments of 1.9 MeV (more than 2000 steps were required) at intervals of a few minutes --just long enough to find out whether a large change in the particle production rate had occurred at the new energy setting.

No more big, narrow jobs. This extensive and fine-toothed search produced a negative result in the sense that no additional narrow, psi-like resonances were found at SPEAR. It is important to be clear about two different factors in giving this result:

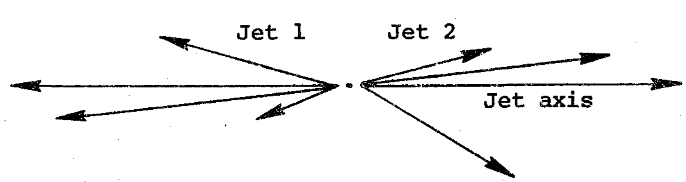
1. The search method is not sensitive to broad resonances such as the bump at 4.1 GeV seen in earlier figures. Other broad resonances have indeed been found at SPEAR, but they are not (at least superficially) psi-like.

2. The overall "strength" of a resonance is measured in the peculiar unit *nanobarn-MeV*, which is a combination of particle-production probability (cross section) and resonance width. What the search established was the fact that it is quite unlikely that there are other rather narrow resonances which have a strength greater than about 5 to 10% of that of the $\psi(3.1)$ in the region from 3.2 to 7.6 GeV. The Frascati storage ring has made a similar search for new narrow resonances at energies below 3.2 GeV--also with a negative result.

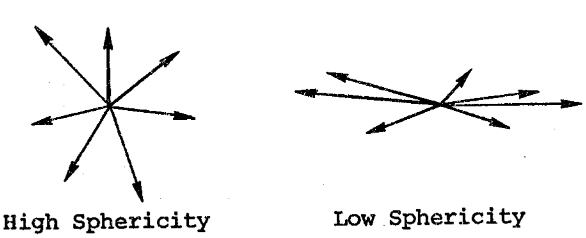
## 3. OBSERVATION OF "JETS" AT SPEAR

The earlier SPEAR experimental data was taken at combined beam energies ranging from about 2.4 to 4.8 GeV. In this energy region the $e^+e^-$ annihilation process gave rise to the creation of new particles in what might be called a "spherically symmetric" manner. That is, the process could be thought of as, first, the creation of a kind of virtual photon "fireball," which then "boiled off" new particles with equal probability in all directions. (There are some actual theoretical models which are based on a "thermodynamic" principle of this kind.) In this kind of a picture, all the energy from the annihilation process is concentrated in a single spot of very high "temperature," and when the spot or fireball radiates away its heat in the form of new particles it does so uniformly (on the average) in all directions.

With the advent of SPEAR II and the higher energies that became possible, this picture of spherical symmetry began to change. At an energy of 6.2 GeV, and even more so at 7.4 GeV, it was observed that the new particles emerged from the annihilation process in patterns that had a preferred direction (or rather two such directions back-to-back, so that an axis was formed). Such a clustering of particles around a certain direction, like this

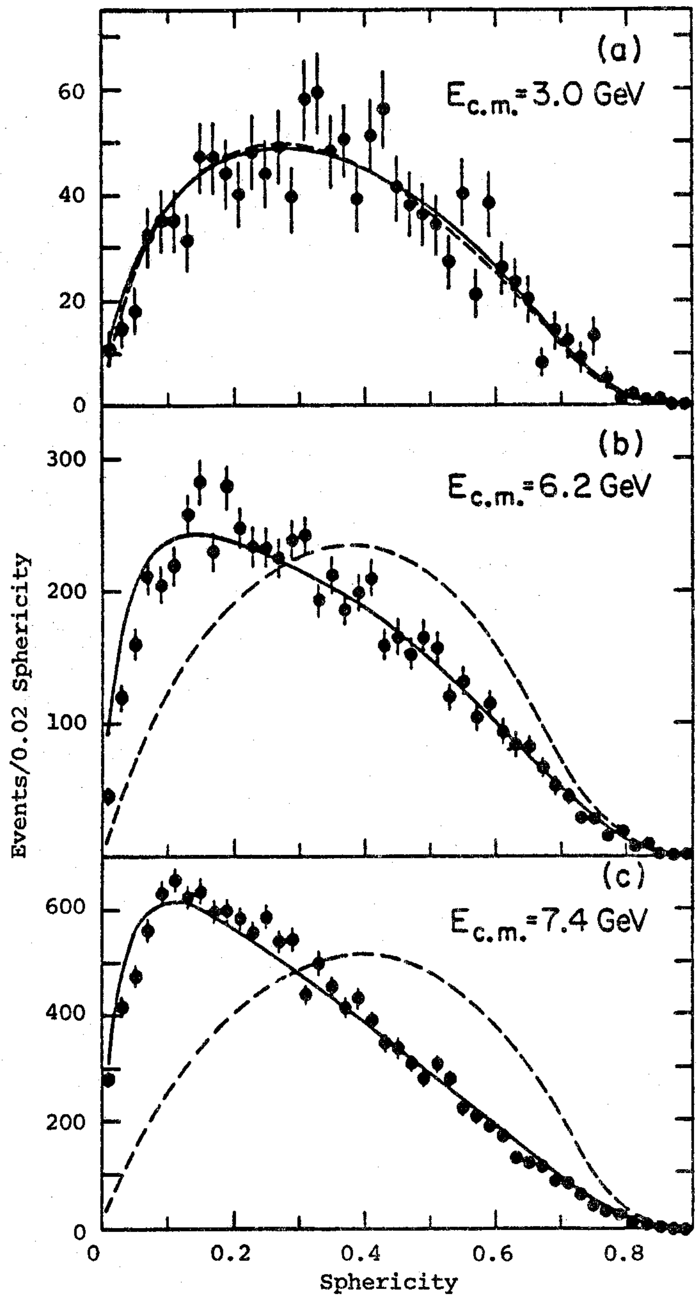



is called a *jet*, and two such clusterings back-to-back form a *jet axis*. The experimenters who study these things have invented a way to describe just how "jetty" a particular interaction is by measuring its "sphericity." A sketch can illustrate the general idea without worrying about a lot of details:



How this sphericity measurement applies to the SPEAR data is illustrated in the three-part figure on this page. The precise information conveyed by the figure is not particularly important for our purposes. The general idea is that the "shape" of the particle distributions changes from that of, say, a basketball at 3.0 GeV to a football at 6.2 GeV and then to a cigar at 7.4 GeV.

*So what?* This evidence for jets at SPEAR is actually very important, for reasons which we'll now discuss. Although there is no generally accepted theory that describes exactly what is happening when jets are produced, the existence




Observed sphericity distributions for 3 or more prong hadron events at SPEAR at energies of 3.0, 6.2 and 7.4 GeV. See text for details.

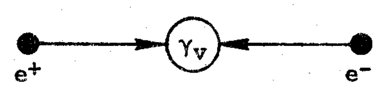
of jets is assumed to lend general support to the idea that hadrons are composed of simpler, more fundamental constituents such as quarks. There is a further bit of evidence from the SPEAR data that makes this possible interpretation even more persuasive, namely that the directional properties observed in the two processes

$$e^+e^- \rightarrow \text{hadrons} \quad \text{and} \quad e^+e^- \rightarrow \mu^+\mu^-$$

appear to be similar. The significance of this similarity is that muons are point-like, spin-½ elementary objects that would be expected to produce a jet-distribution pattern that is the same as that produced by the point-like, spin-½ elementary objects that quarks are also assumed to be.

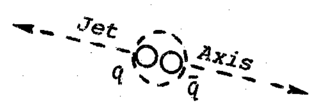
What the jet structure in hadron production at SPEAR seems to imply, then, is a sequential, three-step process that proceeds as follows:

(1)



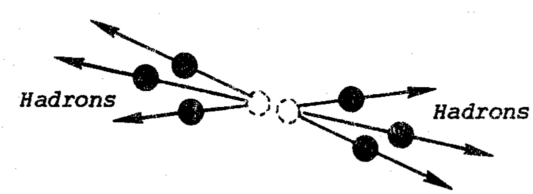

In Step (1), $e^+e^-$ annihilate to form a virtual photon ($\gamma_v$). This virtual photon intermediate state itself has no preferred "jettiness" or directionality.

(2)




In Step (2), the virtual photon forms a quark-antiquark pair ($q\bar{q}$), and it is this pair which determines the direction that will become the jet axis for this particular event. Both the $q\bar{q}$ pair and the virtual photon are shown as open circles to indicate that neither can be directly observed--that is, their existence must be inferred from indirect evidence.

(3)




In Step (3), the $q\bar{q}$ pair interact with each other to produce the various combinations of hadrons that finally materialize and are detected by the experimental apparatus. The hadrons produced in this process tend to retain the direction established by the initial $q\bar{q}$ pair--they emerge, that is, along the jet axis. The jet structure established in this process becomes more pronounced as the $e^+e^-$ collision energy is increased.

# D. Psi(3.1) & Psi(3.7)

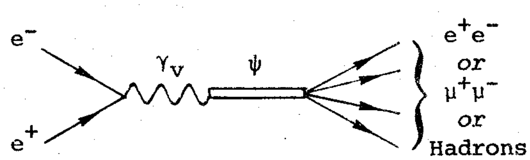
In this section we focus specifically on the properties of the $\psi(3.1)$ and $\psi(3.7)$ resonances--which we'll sometimes refer to by their fuller names: $\psi(3095)$ and $\psi(3684)$. We divide the description into the following parts:

1. The nature of the psi resonances.
2. Where the psi particles fit in.
3. Figuring out some psi properties.

This section will end with the summary tables of psi properties that appear in Detour 2.

## 1. THE NATURE OF THE PSI RESONANCES

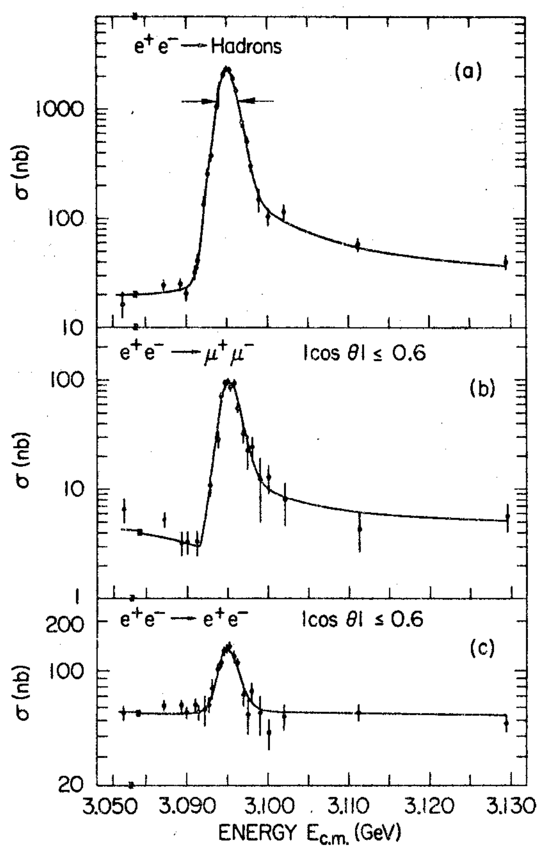
Psi particles are created at SPEAR in an $e^+e^-$ annihilation process that can be pictured in the following way:




In words, this process would read: *$e^+e^-$ annihilate to form a virtual gamma ray, which then creates a psi particle, which then decays into $e^+e^-$ or $\mu^+\mu^-$ or any of a large number of possible combinations of hadrons.* (In about 20% of the cases, the created psi particle is converted back into a second virtual gamma ray, and *it* then produces the final observed particles.)

Psi particles are created at SPEAR most copiously when the combined energy of the two SPEAR beams is exactly equal to either of the psi masses: 3.095 GeV or 3.684 GeV. The figure on this page illustrates how sharply the cross section (or rate of particle production) rises in the case of the $\psi(3095)$ when the SPEAR energy is dead solid perfect on 3.095 GeV. From the shapes of the production curves in the figure it isn't too difficult to get a feeling for why processes of this kind are called *resonant* production, or equivalently why the created particles are also known as *resonances*. This resonant behavior is in many ways similar to what happens with tuning forks, microwave cavities, tank circuits, wine glasses, large speakers in small rooms, and many etceteras.

Although the resonant peaks in the figure appear to quite sharp, there are two different effects at work at SPEAR that cause the curves to be very substantially broadened or smeared out: (1) synchrotron radiation emitted by the circulating beams causes the particles within the beam bunches to have somewhat different energies. (2) Sometimes the particles that annihilate each other first spit out some of their energy in the form of a gamma ray. To see how strongly these two effects operate, let's look for a moment at the tallest peak shown in the figure. The two small arrows on the sides of the peak enclose an energy width of about 2.5 MeV. But if we were able to subtract out the smearing effects of the synchrotron and gamma radiation, the true width of the peak would emerge as only 0.05 MeV, or about 50 times narrower than what is shown. The fact that the peaks shown in the figure are asymmetric, with a fairly abrupt rise on the left and a long slow fall-off on the right, is attributable to the gamma radiation we just talked about. This slow fall-off is called the *radiative tail* of the resonance, and it is characteristic of all high-energy processes in which electrons or positrons participate.




These three curves show the cross sections or production probabilities for $e^+e^-$ annihilation into $e^+e^-$, $\mu^+\mu^-$, and hadrons in the region of the $\psi(3095)$ resonance. As described in the text, the measured curves shown here are roughly 50 times broader than the intrinsic resonant behavior because of certain radiation effects. Note that the vertical scale is logarithmic. The upper curve is particularly remarkable for the roughly 100-fold increase in cross section that occurs at 3.095 GeV SPEAR center-of-mass energy.

## 2. WHERE THE PSI PARTICLES FIT IN

The $\psi(3.1)$ and $\psi(3.7)$ resonances have now been studied in enough detail so that it is possible to start giving some fairly confident answers about them. On perhaps the most fundamental level, it seems pretty clear that the psi particles are *hadrons*, and more specifically that they belong to the particular class of hadrons that are called *vector mesons*.

(As we go through this section, sounding pretty much like we know what we're doing, it would be wise to keep the following fact in mind. There is a rather common particle known as the mu-meson or muon whose properties are very well known and whose behavior can be predicted to a fare-thee-well. That is, we understand practically all there is to understand about muons except for one thing: Why are they there? What role do they play in making the world tick? Muons have been members in good standing of the elementary particle zoo for about 30 years, and no one has yet figured out what they are *for*. So as we blow up a storm of information about the properties of the psi particles, etc., let's reflect that the kind of knowing that goes with name, rank and serial number may not produce much understanding.)

The vector mesons are a somewhat special class of particles because they have many of the same characteristics ("quantum numbers") as the very special particle, the photon, that is the "carrier" of the electromagnetic force. Back at the beginning we discussed the fact that the elementary particles could be grouped into two major families--the small family of leptons such as the electron, and the very large family of hadrons such as the proton. But the photon has the unique distinction of being neither one; it's in a category all by itself.

Before we discuss the photon's relation to the vector mesons, let's first list the particles we're talking about, along with some of their characteristics, in the following table.

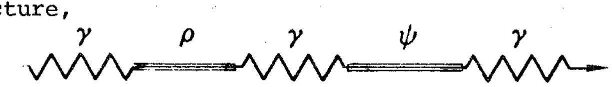
| Vector Mesons | Mass in GeV | Total Decay Width in MeV | Decay Width To Electrons in keV |
|---|---|---|---|
| Rho ($\rho$) | 0.770 | 150 | 6.5 |
| Omega ($\omega$) | 0.783 | 10 | 0.8 |
| Phi ($\phi$) | 1.020 | 4 | 1.3 |
| $\psi(3095)$ | 3.095 | 0.07 | 4.8 |
| $\psi(3684)$ | 3.684 | 0.23 | 2.1 |
| ?(4100) | 4.150 | ~ 275 | 4.0 |

As we talked about earlier, decay widths are related to the lifetime of a particle--the wide resonances are short-lived. Widths are also related to "branching ratios," that is, to the likelihood that one particular decay process out of all possible decays will occur. In the table, for example, we can figure out that the $\psi(3684)$ decays into electrons about 1% of the time:

$$\frac{\text{Decay into electrons}}{\text{Decay into anything}} = \frac{2.1\ \text{keV}}{230\ \text{keV}}$$

The decay widths into electrons shown in the table are characteristic of vector mesons. The obvious striking discrepancies in the table are the extremely narrow total decay widths for the two psi particles. Where a rho meson, for example, will go $\rho \to \pi^+\pi^-$ quick as a flash, the psi's dawdle around forever before undergoing a similar hadronic decay. This sort of $10^3$ procrastination has several possible explanations which we'll discuss eventually. For our present purpose we now want to see what the connection is between the vector mesons and the photon.

A useful but peculiar-seeming way or expressing the photon-vector meson relationship is to say that the photon actually spends a certain fraction of its time *being* vector mesons. In a picture,




Another way of stating the same idea is to say that the photon (even though it is not a hadron) *contains* or has mixed in with it a small percentage of all the vector mesons. And when the photon happens to be wearing its rho or omega or phi or psi hat, then it also *acts* like a hadron by responding to the strong force.

This hadronic aspect of the not-hadron photon was first discovered about 10 years ago, and it came as a great surprise to physicists who imagined that the fundamental forces--weak, strong, and electromagnetic--were entirely distinct from each other. A major development of the last decade, however, has been an increasing realization that there are connections and similarities --perhaps even an underlying sameness that will eventually make it possible to understand the three forces as simply different manifestations of a single ubiquitous force. The search for such an underlying identity--for what is called a "unified" theory--is presently arousing great interest and attention in particle physics research.

## 3. FIGURING OUT SOME PSI PROPERTIES

To arrive at the conclusion that the psi particles are hadrons and in fact vector mesons requires some work that was not evident in the previous section. In this section we try to rectify that oversight by describing a couple of examples of how such information is obtained. To begin with, mesons are chiefly characterized by three particular quantum numbers or attributes which we will very briefly define:

J is a particle's spin angular momentum, or just *spin*, and is a measure of how rapidly the particle spins on its axis. In the microscopic world of the particles things don't work the same way as they do in the large. A top, for example, can spin at any old speed, but for the elementary particles spin is *quantized* in certain discrete amounts. Baryons can have 1/2 unit of spin, or 3/2, or 5/2, etc., while mesons must have spin in integer amounts: 0, 1, 2, etc.

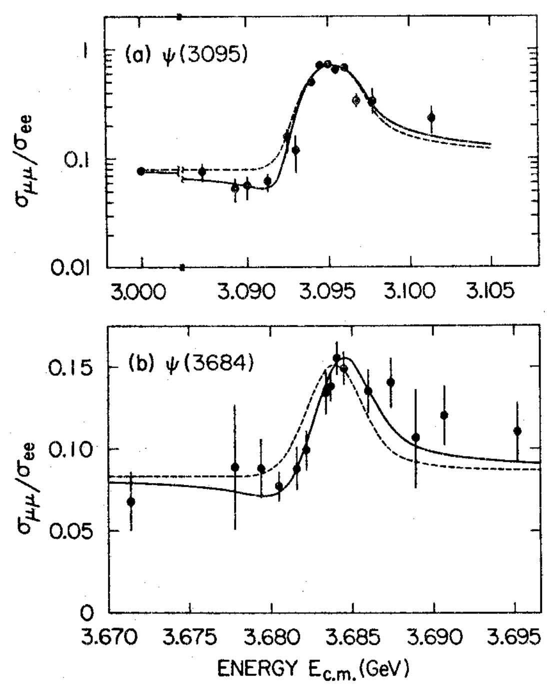
P is a thing called *intrinsic parity*. Whatever it is, it is not easy to visualize, but it is related to the fact that nature does not distinguish between left and right in the strong or electromagnetic interactions (not true for the weak interactions). P is also connected with J in a complicated way that we will ignore here.

C is an intrinsic property called *charge conjugation*. Again it is not easily to visualize but is connected with the fact that particles and antiparticles are interchangeable for the strong and electromagnetic interactions.

These three quantum numbers for mesons are usually written together like this:

$$J^{PC}$$

For the vector mesons the values of $J^{PC}$ are $1^{--}$ (which is spoken "one-minus-minus"). The photon




This figure illustrates the production of muons in the regions of the two psi resonances. The direct production process $e^+e^- \rightarrow \mu^+\mu^-$ will interfere destructively with the resonant process $e^+e^- \rightarrow \psi \rightarrow \mu^+\mu^-$ in the energy region below the peak if the psi particles have the same quantum numbers as the photon, $J^{PC} = 1^{--}$. The dashed curve gives the expected result for no interference, while the solid curve is the prediction for maximum interference. The data are consistent with maxiumum interference, confirming the vector meson nature of the psi's.

is also $1^{--}$.

Now let's see how the $J^{PC}$ assignments for the psi particles were arrived at.

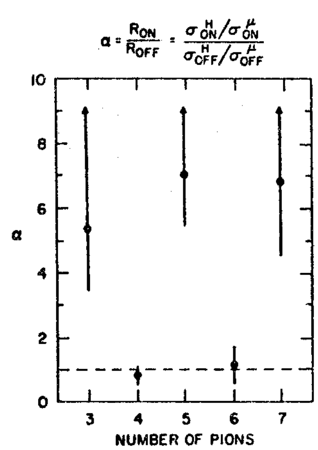
*Interference effect*. We consider two processes that occur at SPEAR:

$$e^+e^- \rightarrow \gamma_V \rightarrow \mu^+\mu^-$$

$$e^+e^- \rightarrow \gamma_V \rightarrow \psi \rightarrow \mu^+\mu^-$$

The first reaction is the direct production of muon pairs, and the second reaction is the production of muon pairs via the $\psi$ resonances. Now if the photon and the psi have the same quantum numbers, then there should be an interference between the two reactions in the energy region near resonance. By an "interference" we mean that the two processes should compete with each other destructively at a certain energy and thus reduce the total production of muons at that energy. The figure on the left shows what happened when this test was carried out. The interference effect was in fact observed, and this established the fact that the psi's quantum numbers were $1^{--}$ like the photon. (This assumes the expected circumstance that P and C are conserved in this interaction.) Confirmation for the assignment of J = 1 was also obtained by observing the angular distribution pattern made by the decay muons; this distribution was consistent with possible spin assignments of J = 1, 2 or 3, but 2 and 3 were eliminated by certain other tests.

*Decay modes*. Two other quantum numbers (G parity and Isospin--which we won't define) were inferred by observing the decay modes of the psi particles. The key fact in this inference was whether the psi's decayed into both odd and even numbers of pions. This was tested by making the comparison that is illustrated in the figure.




This figure compares the ratio of pion production to muon-pair production at two different energies: 3.095 GeV, which is "on" the lower psi resonance; and 3.000 GeV, which is "off" resonance. The results indicate that the $\psi(3.1)$ decays with a strong preference for an odd number of pions. In fact all the decays with an even number of pions can be identified with the "second-order" decay mode:

$$e^+e^- \rightarrow \gamma \rightarrow \psi \rightarrow \gamma \rightarrow \text{even \# pions}$$

This result establishes the quantum number assignments I = even, G = minus.

# Detour 2: Psi Properties

In this second Detour we gather together in Tables some of the more important experimental information that has been learned about the psi particles. In the "Decay Modes" Tables, the "branching ratio" refers to the fraction of the time a psi particle will decay into the particular particles listed. For example, the $\psi(3095)$ decays to an $e^+e^-$ pair 6.9% of the time. This branching ratio number is directly related to the "decay widths" shown in the other Table: note that the $\psi(3684)$ decays into $e^+e^-$ 1% of the time and also that its decay width to $e^+e^-$ is 2.2 KeV, or 1% of the total decay width of 225 KeV.

There are some interesting patterns in the psi decay modes. The $\psi(3095)$ decays readily into 3, 5 or 7 pions ($\pi$), but much less so into 2, 4 or 6 pions. (In fact the even-pion decays probably all come from the "second-order" decay process $\psi \rightarrow \gamma \rightarrow 2,4,6\ \pi$.) The $\psi(3684)$ decays 57% of the time into $\psi(3095)$ + anything, 2% of the time into either $e^+e^-$ or $\mu^+\mu^-$, and the remaining 41% of the time into $\rightarrow$(things we haven't yet figured out).

Most theories of the elementary particles make extensive and detailed predictions of how particles with a certain set of properties should decay, and the painstaking experimental work that is carried out to determine all these decay modes and other properties provides the most stringent tests of theory and is in fact the bread-and-butter business of high energy physics.

| *Some Psi Properties* | $\psi(3095)$ | $\psi(3684)$ |
|---|---|---|
| $J^{PC}$ | $1^{--}$ | $1^{--}$ |
| Mass | 3095 ± 0.004 GeV | 3864 ± 0.005 GeV |
| Decay Widths | | |
| $\psi \rightarrow e^+e^-$<br>$\psi \rightarrow \mu^+\mu^-$ | 4.8 ± 0.6 KeV | 2.2 ± 0.3 KeV |
| $\psi \rightarrow$ Hadrons | 59 ± 14 KeV | 220 ± 56 KeV |
| $\psi \rightarrow$ All | 69 ± 15 KeV | 225 ± 56 KeV |
| $\frac{\psi \rightarrow \text{Hadrons}}{\psi \rightarrow \text{All}}$ | 0.86 ± 0.02 | 0.981 ± 0.003 |
| $\frac{\psi \rightarrow e^+e^-}{\psi \rightarrow \text{All}}$ | 0.069 ± 0.009 | 0.0097 ± 0.0016 |
| Cross Sections (peak) | | |
| $\psi \rightarrow e^+e^-$ | 130 nb | 40 nb |
| $\psi \rightarrow \mu^+\mu^-$ | 100 nb | 6 nb |
| $\psi \rightarrow$ Hadrons | 2300 nb | 560 nb |

DECAY MODES OF THE $\psi(3095)$

| Mode | Branching Ratio (%) | # Events Observed |
|---|---|---|
| $e^+e^-$ | 6.9 | 2000 |
| $\mu^+\mu^-$ | 6.9 | 2000 |
| $\rho\pi$ | 1.3 | 153 |
| $2\pi^+2\pi^-$ | 0.4 | 76 |
| $2\pi^+2\pi^-\pi^0$ | 4.0 | 675 |
| $3\pi^+3\pi^-$ | 0.4 | 32 |
| $3\pi^+3\pi^-\pi^0$ | 2.9 | 181 |
| $4\pi^+4\pi^-\pi^0$ | 0.9 | 13 |
| $\pi^+\pi^-K^+K^-$ | 0.4 | 83 |
| $2\pi^+2\pi^-K^+K^-$ | 0.3 | |
| $K_SK_L$ | - | $\leqslant 1$ |
| $K^0K^{0*}(892)$ | 0.2 | 57 |
| $K^{\pm}K^{\mp *}(892)$ | 0.3 | 87 |
| $K^{0*}(892)K^{0*}(1420)$ | 0.4 | 30 |
| $K\ K^*(1420)$ | - | $\leqslant 3$ |
| $K^*(892)K^*(892)$ | - | $\leqslant 3$ |
| $K^*(1420)K^*(1420)$ | - | $\leqslant 3$ |
| $K^*(892)K^*(1420)$ | - | $\leqslant 3$ |
| $p\bar{p}$ | 0.2 | 105 |
| $\Lambda\bar{\Lambda}$ | 0.2 | 19 |
| $p\bar{p}\pi^0$<br>$\bar{n}p\pi^-$<br>$\bar{p}n\pi^+$ | 0.4 | 87 |

DECAY MODES OF THE $\psi(3684)$

| | |
|---|---|
| $e^+e^-$ | 1.0 % |
| $\mu^+\mu^-$ | 1.0 |
| $\psi(3095)$ anything | 57 |
| $\psi(3095)\pi^+\pi^-$ | 32 |
| $\psi(3095)\eta$ | 4 |
| $\psi(3095)\gamma\gamma$ | $\leqslant 6.6$ |
| $\rho^0\pi^0$ | $\leqslant 0.1$ |
| $2\pi^+2\pi^-\pi^0$ | $\leqslant 0.7$ |
| $p\bar{p}$ | $\leqslant 0.03$ |

#3



# More New Particles

## PARTS I & II

(This is a combined version of the original two-part article.)

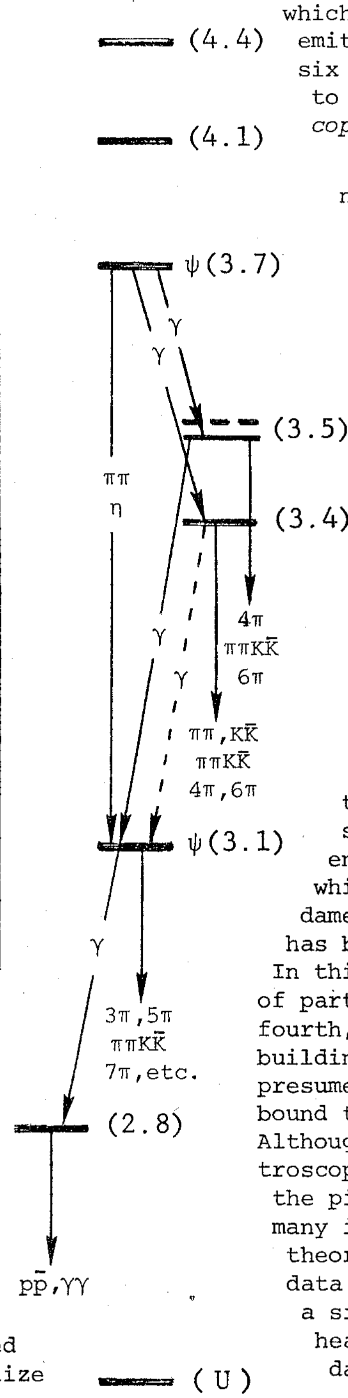
*Contents*



*THIS ARTICLE HAS TWO PURPOSES. THE FIRST IS TO REPORT ON WHAT HAS BEEN LEARNED ABOUT THE ORIGINAL PSI PARTICLES, $\psi(3.1)$ & $\psi'(3.7)$, SINCE THEIR DISCOVERY IN NOVEMBER 1974. THE SECOND PURPOSE IS TO DESCRIBE THE MORE RECENT DISCOVERIES, AT SPEAR AND AT THE GERMAN STORAGE RING DORIS, OF AN ADDITIONAL 6 OR 7 NEW PARTICLES, SOME DEFINITELY RELATED TO THE PSI'S, THE OTHERS PERHAPS SO.*

## A. A Brief Summary

The curved band running down the center of this page contains nine horizontal bars (one dashed) which represent (a) the two previously known psi particles with masses of 3.1 and 3.7 GeV, and (b) six or seven other new particles, or "resonances." The states at 2.8, 3.4 and 3.5 (maybe two states) GeV are definitely connected to the psi particles; the arrows symbolize various transition or decay processes in which gamma rays ($\gamma$) and/or particles are emitted in characteristic patterns. The six arrow-connected states are beginning to be identified as the *psi spectroscopy*.




The other three states, not connected, may or may not be related to the psi particles. The upper two, at 4.1 and 4.4 GeV, are "bumps" that occur when the $e^+e^-$ collisions at SPEAR result in the creation of strongly interacting particles (hadrons) such as pi and K mesons. The lowest state shown, the U ("unknown") particle, has a mass somewhere between 1.6 and 2.0 GeV. It may be that a pair of U particles emerge from the decay of a single heavier particle that is created in the "bump" region near 4 GeV. A second and even more striking possibility is that the U is a "heavy lepton"--that is, the third member of the particle family that includes the electron and the mu-meson (muon).

These new particle discoveries, together with other experimental results from SPEAR and DORIS, have given strong support to those theories which postulate the existence of a fundamentally new property of matter that has been given the (nutty) name "charm." In this theory the basic three-quark model of particle structure has added to it a fourth, charmed, quark, as an elementary building block, and the psi particles are presumed to consist of the charmed quark bound together with its own antiparticle. Although this theory predicts a psi spectroscopy that is in general very much like the picture on this page, it still leaves many important problems unresolved. Some theorists believe that the experimental data support the idea of a fifth, or even a sixth, basic quark, and perhaps also heavy leptons. More SPEAR and DORIS data is eagerly awaited.

# B. Some Background Information

Certain parts of this article contain technical information that may be more detailed than most readers would wish. The most detailed of this stuff has been put on separate pages that are called *Detours* so they can easily be avoided by Turnpike drivers. Although the remainder of the article is aimed toward a fairly general audience, this aim has become more difficult to achieve as the psi story has grown more complex. For readers who may wish to dig either deeper or wider into the study of elementary particles, the articles listed at the bottom of this page may be of interest.*

In this section we spend a couple of pages on some of the basic information about colliding beams and about particle physics.

## 1. THE ANNIHILATION PROCESS

In the SPEAR storage ring beams of electrons ($e^-$) and positrons ($e^+$) circulate in opposite directions. At two points on the circumference of the ring the beams are made to pass through each other and thus to set up the possibility of an $e^+e^-$ collision. The particular kind of collision that will concern us here is called *annihilation*. This process can only occur when the collision involves a particle and its antimatter counterpart, an antiparticle. The process of $e^+e^-$ annihilation proceeds in two steps. First, the $e^+e^-$ pair creates a very short lived intermediate state called a *virtual photon* or *virtual gamma ray* ($\gamma_v$). Then the pure electromagnetic energy of the virtual photon rematerializes into any of a large number of possible combinations of newly created particles. In the shorthand notation of physics the process is written:

$$e^+e^- \rightarrow \gamma_v \rightarrow \text{created particles}$$

(In what follows we'll usually leave out the $\gamma_v$ for the sake of brevity.) The particles emerging from the annihilation process can be grouped into three classes:

$$\begin{array}{lll} (1) & e^+e^- \rightarrow e^+e^- & \text{(e pair)} \\ (2) & e^+e^- \rightarrow \mu^+\mu^- & \text{(muon pair)} \\ (3) & e^+e^- \rightarrow \pi^+\pi^-\pi^0 & \\ & \quad\;\;\; \rightarrow K^+K^- & \\ & \quad\;\;\; \rightarrow \pi\pi K\bar{K} & \text{(hadrons)} \\ & \quad\;\;\; \rightarrow p\bar{p} & \\ & \quad\;\;\; \rightarrow \text{etc.} & \end{array}$$

Although it is class (3)--electron-positron annihilation into hadrons--that will be our chief concern when we get to the SPEAR and DORIS experimental results, we want to take a minute here to talk about classes (1) and (2).

## 2. FAMILIES AND FORCES

The first two classes of interactions above involve only particles that belong to the *lepton* family. This complete family contains only 8 members: the electron and its neutrino; the muon and its neutrino; and the four antiparticles of these four particles. The leptons are distinguished from the other major particle family--the much larger (hundreds) *hadron* family--by the following essential difference. Hadrons are affected by, or "feel," the strong or nuclear force that is responsible for binding together the protons and neutrons in the nuclei of atoms. The leptons, in contrast, are those particles which specifically *do not* feel the strong force. Thus the e-pair and muon-pair production processes given in classes (1) and (2) above are known as purely *leptonic* processes. Because of their comparative simplicity, leptonic interactions are often used to study the two other kinds of forces that play a role in particle physics: electromagnetism, and the so-called "weak" or Fermi force.

The relationships between particles and forces are an essential part of the study of the elementary particles. The following table summarizes some of these relationships.

| *Force →* | *Strong* | *Electro-magnetic* | *Weak* | *Gravit-ational* |
|---|---|---|---|---|
| Range | $10^{-13}$cm | Infinite | $10^{-15}$cm | Infinite |
| Relative strength | 100 | 1 | $10^{-9}$ | $10^{-37}$ |
| Particles acted upon | Hadrons | All charged particles | Hadrons Leptons | All |
| "Carrier" of force | Hadrons | Photons | ? | Gravitons |
| Example | Nuclear forces | Atomic forces | Radio-activity | Planetary orbits |

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*Previous *Beam Line* articles on SPEAR and psi:

1. "An introduction to colliding-beam storage rings," August & September, 1974.
2. Special issue on psi, December 5, 1974.
3. "More on psi," January, 1975.
4. "Psi photoproduction," March 20, 1975.

Useful *Scientific American* articles:

5. Chew, Gell Mann, Rosenfeld, "Strongly interacting particles," February, 1964.
6. Weisskopf, "The three spectroscopies," May, 1968.
7. Panofsky, Kendall, "The structure of the proton and neutron," June, 1971.
8. Drell, "Electron-positron annihilation and the new particles," June, 1975.
9. Glashow, "Quarks with color and flavor," October, 1975.

Also, a recent *Nature* article:

10. Leader, Williams, "Unified gauge theories of elementary particles," September 11, 1975.

Now let's add a few additional words of explanation about each of these four kinds of fundamental forces:

*Gravitation*. In particle physics, the masses we deal with are so small, and the intrinsic strength of the gravitational force is so extremely weak, that the effects of gravity are completely ignored.

*Electromagnetism*. The electromagnetic force affects all particles that are electrically charged (+ or -), whether they be hadrons or leptons. The theory of electromagnetism as it applies to the elementary particles is called *quantum electrodynamics*, or *QED* for short, and it is by all odds the most successful theory in high energy physics. Because of this success, QED often serves as a model for trying to understand the other forces. QED is also subjected to frequent severe tests, in experiments such as the $e^+e^-$ leptonic interactions mentioned above, in an effort to extend the (already very large) range of its validity. Much of the effectiveness of the SPEAR experiments on hadron production can be attributed to the fact that the virtual photon intermediate state out of which the hadrons are created is itself a purely electromagnetic phenomenon, whose properties are precisely described by quantum electrodynamics.

*The strong force*. The strong force has the property that it can act only over a range that is comparable to the size of a single elementary particle. Thus it is effective only when two hadrons are essentially touching each other (as they are in the nucleus of an atom). At this minute range, however, the strong force is about 100 times as strong as the electromagnetic force. An alternate way of stating the same thing is to say that strong-force interactions occur on a time scale that is roughly 100 times faster than electromagnetic interactions, a typical strong interaction time being about $10^{-23}$ second.

*The weak force*. The range given for the weak force in the table above, $10^{-15}$ cm, is thought to be an *upper* limit. This is a difficult idea to get any sort of a feeling for. We've gradually got used to the idea that the force between two objects is "carried" by something. The force with which a magnet attracts a piece or iron can be described with great accuracy as an "exchange" of the composite wave-particle things called photons. Similarly, the earth and the moon exchange gravitons, and the force that binds protons and neutrons together is carried by the pions and other particles that they exchange in atomic nuclei. For the weak force, however, there is not yet compelling evidence that it is "carried" over *any* finite distance. (Even $10^{-15}$ cm rates as "finite" in particle physics.) If there is a weak-force carrier, then the extremely short range dictates that this hypothetical particle--the *intermediate vector boson*--must be very massive. (For a force of infinite range such as electromagnetism or gravitation, the carrier has zero mass and thus travels always at the velocity of light.) For a time soon after the discovery of the $\psi(3.1)$ there was speculation that the long-sought IVB had finally been found. But the expected mass of the IVB is closer to 40 than to 4 GeV, and subsequent data on some of the psi's properties have now pretty well laid this possibility to rest.

## 3. "POINT" LEPTONS & "STRUCTURED" HADRONS

A very important distinction between the lepton and hadron families of particles is this: The lepton experiments so far performed have not given any evidence that leptons have any "size" or internal structure. Electrons have been probed down to distances of about $10^{-15}$ cm, and at this level of "resolving power" they still appear to be point-like objects. Stated somewhat differently, there is no evidence that leptons may be composed of any smaller, simpler entities. So far as we now know they are in fact *elementary* particles.

This is not the case for the hadrons. For these particles, such as the proton, we have abundant experimental evidence that they are somewhat diffuse objects whose structure is spread out over a certain volume of space. Hadrons have a diameter or size of about $10^{-13}$ cm (really huge, man). The hadrons' spread-out structure, and also the fact that there are so many varieties of the damned things, made it seem quite evident as long as 20 years ago that the hadrons could not *all* be "elementary" in any meaningful sense, and consequently that the hadrons might well be built up from some simpler, "truly" elementary objects.

In the early 1960's there was put forward a theory of hadronic structure which postulated that the vast circus of hadronic states could all be explained as various combinations of only three basic constituents called *quarks*. This theoretical model has proved to be remarkably successful both in explaining the spectrum of known hadrons and in predicting the existence of certain new states that were subsequently discovered. And in the late 1960's, experiments on "deep inelastic" electron-proton scattering at SLAC added strong evidence in support of the quark model when they disclosed the presence of minute scattering centers ("partons") within the larger volume of the individual protons.

In broad outline, then, this is the way matters stood until about 1973, when the early experimental results from the $e^+e^-$ storage rings at Frascati, Italy, at CEA in Cambridge, and later at SPEAR began to come in. In an oversimplified nutshell, the problem in high energy physics was--and still is--to "explain the hadrons," and in the minds of many physicists the most likely source of such an explanation was the idea of three simple bricks, the quarks, from which the whole big banana might be built.

# Detour 1: Quarks

This is the first of four detours off the beaten track. It adds something to the business of building-block quarks as the basis for the hadrons, but can be skipped if it looks too hairy.

*Mesons and baryons*. In the previous section we talked about "the large family of hadrons." How large? Well, the hadron family has two subgroups: the *mesons* (middleweights), of which roughly 100 are known; and the *baryons* (heavyweights), of which about 200 have been found. The chart on this page shows the baryons that had been reasonably surely identified as of about six months ago. There are 112 flyspecks on the chart, and 112 antiflyspecks, and even if we happen to notice that there are really only six different *kinds* of baryons (N,Σ,Δ,Λ,Ξ,Ω), the chart still looks like a linear ant attack.

*Three quarks*. So what to do with all these particles or "resonances" or "states"? The answer is to leap in with a construction plan by which bricks and mortar can be fitted together to form hundreds of different designs. Our bricks will be quarks of 3 different kinds which we'll give the following names: *u*, *d* and *s*. The letters are from the words *up, down and sideways* (or *strange*), which refer to the triangular arrangement in which the 3 quarks are sometimes shown:

*Quarks* $u$ $s$ $d$ $\qquad$ $\bar{u}$ $\bar{s}$ $\bar{d}$ *Antiquarks*

Quarks are assumed to have certain intrinsic properties such as spin and strangeness. Some of these properties are similar to those of ordinary particles, and some are very different. We'll be concerned here with only the assumed values of electric charge:

| | $u$ | $d$ | $s$ | $\bar{s}$ | $\bar{d}$ | $\bar{u}$ |
|---|---|---|---|---|---|---|
| Charge | $+\frac{2}{3}$ | $-\frac{1}{3}$ | $-\frac{1}{3}$ | $+\frac{1}{3}$ | $+\frac{1}{3}$ | $-\frac{2}{3}$ |

Although neither quarks nor any other fractionally charged object has ever been observed in nature, there may be a reasonable (but not simple) explanation. There is some weight of theoretical opinion which holds that quarks may well be the basic stuff of which hadrons are made and yet still never be observable as separate entities.

*How the bricks fit*. According to the theory, quarks can combine with each other in only two different ways: (1) as a quark-antiquark pair, which makes *mesons*; or (2) as a quark (or antiquark) triplet, which makes *baryons*. As an example the particles at the very bottom of the chart are the familiar proton and neutron, which are thought to be built up like this:

proton = $uud$ $\qquad$ neutron = $udd$

As more general examples, the quark structure of mesons and baryons can be any of the following, and many more, combinations:

Mesons: $u\bar{u}$ $d\bar{u}$ $u\bar{s}$ $s\bar{s}$ $d\bar{s}$ etc.

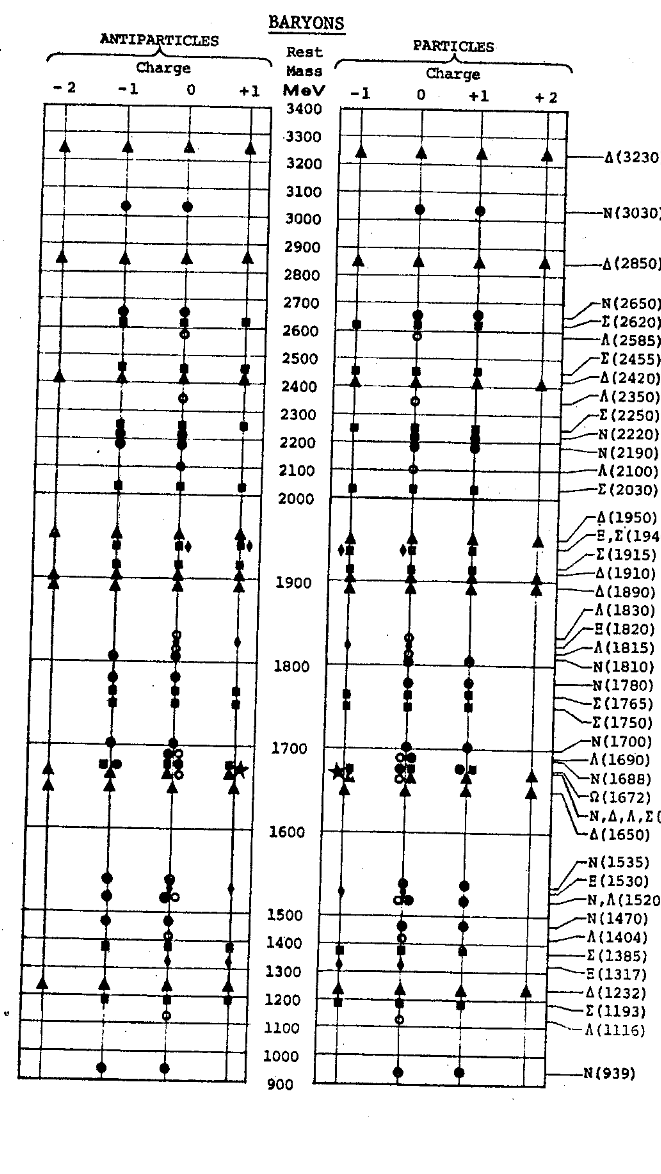
Baryons: $uud$ $usd$ $\bar{u}\bar{s}\bar{s}$ $\bar{s}\bar{s}\bar{s}$ etc.

In the chart, note that the nucleons (N) and other baryon types "recur" at higher energies: N(1470), N(1520), N(1535), etc. Each recurrence of the proton, for example, is still the same combination of quarks (*uud*), with the difference being that each higher energy recurrence represents a different pattern of motion of the three quarks inside the "excited" state of the proton.

*Six classes of baryons*

The baryons shown in the chart below have the following six class names:

● N (Nucleon) ■ Σ (Sigma) ♦ Ξ (Xi)
○ Λ (Lambda) ▲ Δ (Delta) ★ Ω (Omega)



# C. The SPEAR Data In General

In this section we take a broad look at the SPEAR experimental data accumulated by the joint SLAC-LBL physics group. Our main concern will be with these topics:

1. The ratio of hadron production to the production of muon pairs.
2. The search for other sharp resonances.
3. Observation of "jets" in hadron production at higher SPEAR energies.

## 1. THE HADRON/MUON-PAIR RATIO

There is a certain quantity that plays a central role in much of the $e^+e^-$ experimentation and in assessing its significance. This quantity is the following experimentally measured ratio:

$$R = \frac{e^+e^- \rightarrow \text{hadrons}}{e^+e^- \rightarrow \mu^+\mu^-}$$

In words, the quantity is the ratio between the cross section (or probability) for producing hadrons and the cross section for producing a pair of muons in the electron-positron annihilation process. It's worth a few words to find out why this particular ratio, R, is considered to be so important. We saw earlier that leptons such as electrons and positrons appear to be point-like objects. They also belong to the group of particles which possess an intrinsic angular momentum, or spin, of ½ unit (the ½-unit group is called the "fermions"). As it happens, the quarks we've been talking about are also assumed to be point-like fermions, and as such their behavior is expected to be similar in certain ways to that of the leptons.

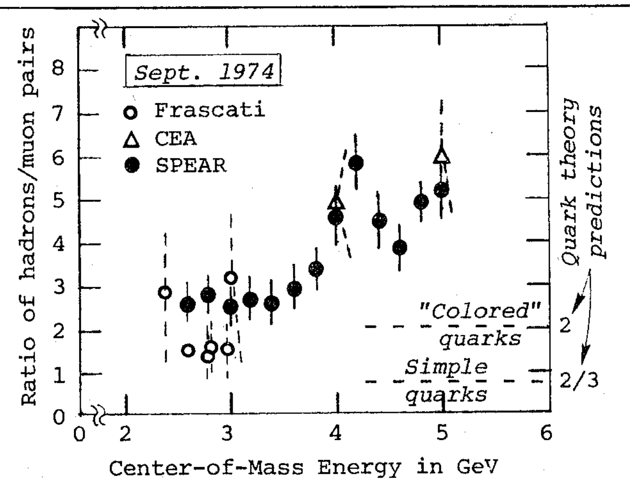
In particular, the similarities should make it possible to calculate (at sufficiently high energies) the ratio between creation of a lepton-pair (muons in this case) and creation of quarks (which instantly "clothe" themselves and become the pions, protons and other kinds of hadrons that are actually observed in the experiment). This calculation consists simply of writing down the values of electric charge that are carried by the quarks, squaring those values, and then adding up the squares. Like this:

$$R = (2/3)^2 + (-1/3)^2 + (-1/3)^2$$
$$= 4/9 + 1/9 + 1/9$$
$$R = 2/3$$

So the quark theory in its simplest form, with only the three quarks $u$, $d$ and $s$ that we have mentioned so far, predicts that hadrons should be created in $e^+e^-$ collisions 2/3 as copiously as pairs of muons. More complex versions of the quark theory give different answers, but before we look into these other theoretical models, let's first go back to what the earliest experimental measurements of the ratio R were like.

*Early measurements of R*.* The first measurements of the hadron/muon-pair ratio were made several years ago at the 1.5 GeV $e^+e^-$ storage ring at Frascati (near Rome), and shortly thereafter at the ring that had been built by conversion of the Cambridge Electron Accelerator (CEA) at Harvard. The Frascati measurements were in the center-of-mass energy (total energy of both beams) region below 3 GeV, while CEA measured points at 4 and 5 GeV. Neither the Frascati nor CEA results were consistent with the predicted R value of 2/3. The subsequent measurements of R that began to be made at SPEAR confirmed the unexpected Frascati and CEA answers, and all of these data taken together started to take on the trappings of an intriguing mystery.

The following graph shows how the experimental situation looked about a year ago, in September 1974.




Twelve months ago this collection of experimental measurements from Frascati, CEA and SPEAR was causing a lot of excitement in high energy physics circles. The values of R predicted by the simple and "colored" quark models, 2/3 and 2, respectively, were clearly too small for the data, for one thing; but even more striking was the fact that all theories had predicted a *constant* value of R, whereas the experiments appeared to show that R was increasing rather steadily with increasing energy. The discrepancy between theory and experiment at that time gave rise to a great deal of speculation--more quarks were needed; or perhaps leptons "were really hadrons at heart"; and what was that big bump at about 4 GeV? But take heart, because September 1974 was only two months before November 1974 and the discovery of the psi particles.

*See the September 1974 issue of the *Beam Line* for a more complete history of R measurements than we have space for here.

The particular aspect of the data from a year ago that excited attention was the fact that the measured values of R were increasing as the $e^+e^-$ collision energies were increased. There were readily at hand various theoretical explanations for why R should be 2, or 10/3, or 4, or even larger; but that it should not be a *constant* value--no matter what the actual number--was a circumstance that theorists found hard to digest. (The separate box on this page explains how some of the predicted R values larger than 2/3 are arrived at.) We will not, however, dwell upon this year-old conundrum, because subsequent developments have shown that the not-constant appearance of R is a little deceptive. To see why this is so, we now move forward in time to about June of this year in order to find out what the SPEAR experiments had been able to add to the study of the hadron /muon-pair ratio.

*Two ψ's, two plateaus, and a bump*. Discovery of the two remarkable new particles, ψ(3.1) and ψ(3.7) occurred last November. At that time the storage-ring improvement program called "SPEAR II" was well along and was subsequently completed in the spring of this year. This work made it possible to operate SPEAR at energies up to about 3.8 Gev for each beam, about a 50% increase in maximum beam energy from the previous 2.5 GeV. This energy increase made accessible to the SLAC-LBL experimenters the center-of-mass energy region from 5 to almost 8 GeV, and during the spring and early summer the group carried out a systematic exploration of this unknown territory. The measurements of the hadron/muon-pair ratio in this new region are shown plotted, together with the earlier results, in the figure at the bottom of this page.

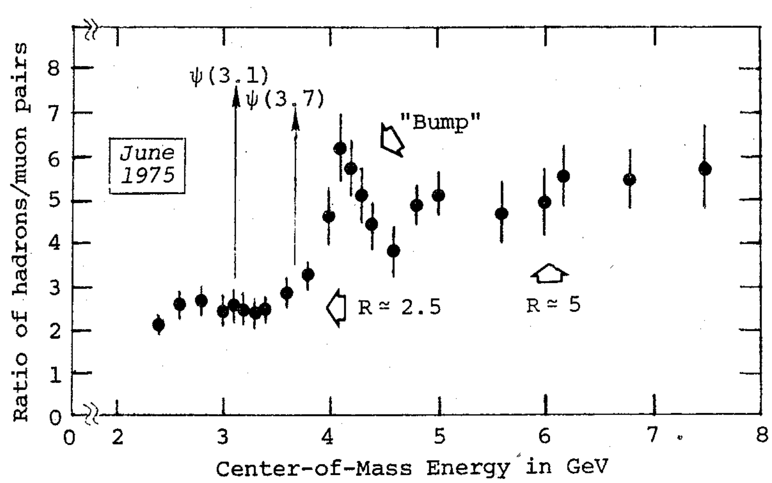
As the figure shows, extending the R measurements out to higher energies results in a general picture that seems quite different from that of a year ago. Last year's "steadily rising" interpretation of the data no longer seems tenable. Instead, there appear to be two broad areas--from about 2 to 4 GeV, and from 4½ to 7½ GeV--where the value of R does not change very significantly. R is about 2.5 in the lower energy region, and about 5 or a little greater in the higher energy region. The other obvious features of the data shown in the figure are the two sharp psi spikes (actually much taller than the figure has room to show), and the fairly wide "bump" region from about 4 to 4½ GeV. (We postpone further discussion of the significance of this newer R picture until after we have looked, in Section E, at an even more recent and detailed mapping of R over the full SPEAR energy region.)

*Computing Other Values Of R*

Earlier we saw that R can be predicted by summing the squares of the values of electric charge that are assumed to be carried by each of the quarks in a theoretical model. For the simple quark model we've talked about so far, the 3 basic quarks $u$, $d$ and $s$ yield a predicted R value of 2/3. We now see how R comes out when a more complex model (more quarks, or different quarks) is used. We consider (but do not attempt to justify until later) four possible elaborations of the basic 3-quark idea: (1) To the quarks $u$, $d$ and $s$ must be added a fourth, *charmed* quark $c$. (2) Each of the 3 basic quarks comes in 3 *colors*. (3) The basic set of quarks requires *both charm and color*. (4) The basic set of quarks is both charmed and colored *and* its members carry *integral* rather than *fractional* values of electric charge.

Now let's calculate R for each of these four possibilities:

1. *Charm:* $(2/3)^2 + (-1/3)^2 + (-1/3)^2 + (2/3)^2 = \frac{10}{9}$
2. *Color:* $3[(2/3)^2 + (-1/3)^2 + (-1/3)^2] = 2$
3. *Both:* $3[(2/3)^2 + (-1/3)^2 + (-1/3)^2 + (2/3)^2] = \frac{10}{3}$
4. *Integral:* $(1)^2 + (1)^2 + (-1)^2 + (-1)^2 = 4$




The SPEAR II improvement program resulted in an extension of the storage ring's energy range from 5 to about 7.8 GeV (center-of-mass). With the added data from these higher energies the previous picture of R was seen to be rather deceiving. In the full range of data there now appear to be two plateaus in the value of R: about 2.5 at the lower level, and 5 to 5½ at the higher level. The smaller "bump" region between the two plateaus marks the energy range where apparently some new processes begin to happen (more about this later). The two sharp psi resonances, if drawn to scale, would rise through the (or any) ceiling.

## 2. SEARCH FOR OTHER NARROW RESONANCES

The ψ(3.1) was discovered at SPEAR on November 8, 1974. It was a beauty. On November 20, less than two weeks later, the ψ(3.7) particle was discovered at SPEAR, and it was also a beauty. For a period of perhaps three or four weeks after that the SPEAR experimenters seemed to share the fond but perhaps not totally rational hope that SPEAR was just one big nickelodeon--you just pop your coin into the slot and out comes another startling new particle discovery. Oh well, it was certainly a gas while it lasted.

Let's recall that the most distinctive characteristic of the psi particles is their inexplicably long life. For a very massive hadron of "typical" behavior, the expected lifetime before it decays into other, lighter particles is about $10^{-23}$ second (which is about the time needed for a particle traveling at the velocity of light to traverse the $10^{-13}$ cm diameter of a proton). Let's call this ridiculously brief (and unmeasurable) period of time a *blip*. In the case of the two psi particles the lifetimes, which are inferred from other data, turned out to be not the typical one *blip* but rather a few hundred *blips* for the (3.7) and about 1000 *blips* for the (3.1). These extended lifetimes manifest themselves experimentally in the shape of the resonance "bump" that characterizes the process in which the particles are produced (we'll discuss this shape in the next Section), so the key "signature" that is looked for in a search for other psi-like resonances is a sudden and sharp increase in particle production that occurs only within a very narrow SPEAR energy region.

During the past several months the SLAC-LBL group has completed the search for other narrow, psi-like resonances over the full energy range available for this purpose at SPEAR: about 3.2 to 7.6 GeV (combined energy of both beams). The search was conducted by stepping the SPEAR energy upward in increments of 1.9 MeV (more than 2000 steps were required) at intervals of a few minutes --just long enough to find out whether a large change in the particle production rate had occurred at the new energy setting.

*No more big, narrow jobs*. This extensive and fine-toothed search produced a negative result in the sense that no additional narrow, psi-like resonances were found at SPEAR. It is important to be clear about two different factors in giving this result:

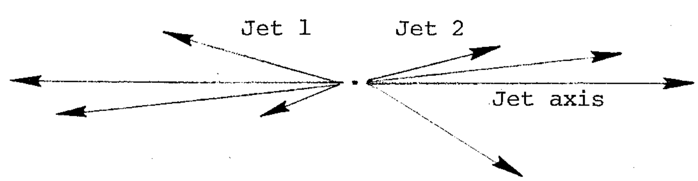
1. The search method is not sensitive to broad resonances such as the bump at 4.1 GeV seen in earlier figures. Other broad resonances have indeed been found at SPEAR, but they are not (at least superficially) psi-like.

2. The overall "strength" of a resonance is measured in the peculiar unit *nanobarn-MeV*, which is a combination of particle-production probability (cross section) and resonance width. What the search established was the fact that it is quite unlikely that there are other rather narrow resonances which have a strength greater than about 5 to 10% of that of the ψ(3.1) in the region from 3.2 to 7.6 GeV. The Frascati storage ring has made a similar search for new narrow resonances at energies below 3.2 GeV--also with a negative result.

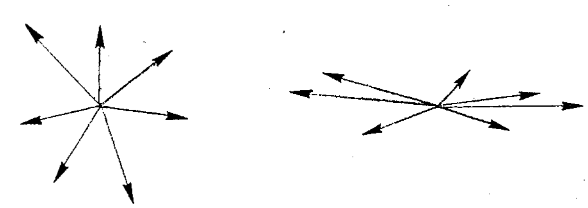
## 3. OBSERVATION OF "JETS" AT SPEAR

The earlier SPEAR experimental data was taken at combined beam energies ranging from about 2.4 to 4.8 GeV. In this energy region the $e^+e^-$ annihilation process gave rise to the creation of new particles in what might be called a "spherically symmetric" manner. That is, the process could be thought of as, first, the creation of a kind of virtual photon "fireball," which then "boiled off" new particles with equal probability in all directions. (There are some actual theoretical models which are based on a "thermodynamic" principle of this kind.) In this kind of a picture, all the energy from the annihilation process is concentrated in a single spot of very high "temperature," and when the spot or fireball radiates away its heat in the form of new particles it does so uniformly (on the average) in all directions.

With the advent of SPEAR II and the higher energies that became possible, this picture of spherical symmetry began to change. At an energy of 6.2 GeV, and even more so at 7.4 GeV, it was observed that the new particles emerged from the annihilation process in patterns that had a preferred direction (or rather two such directions back-to-back, so that an axis was formed). Such a clustering of particles around a certain direction, like this



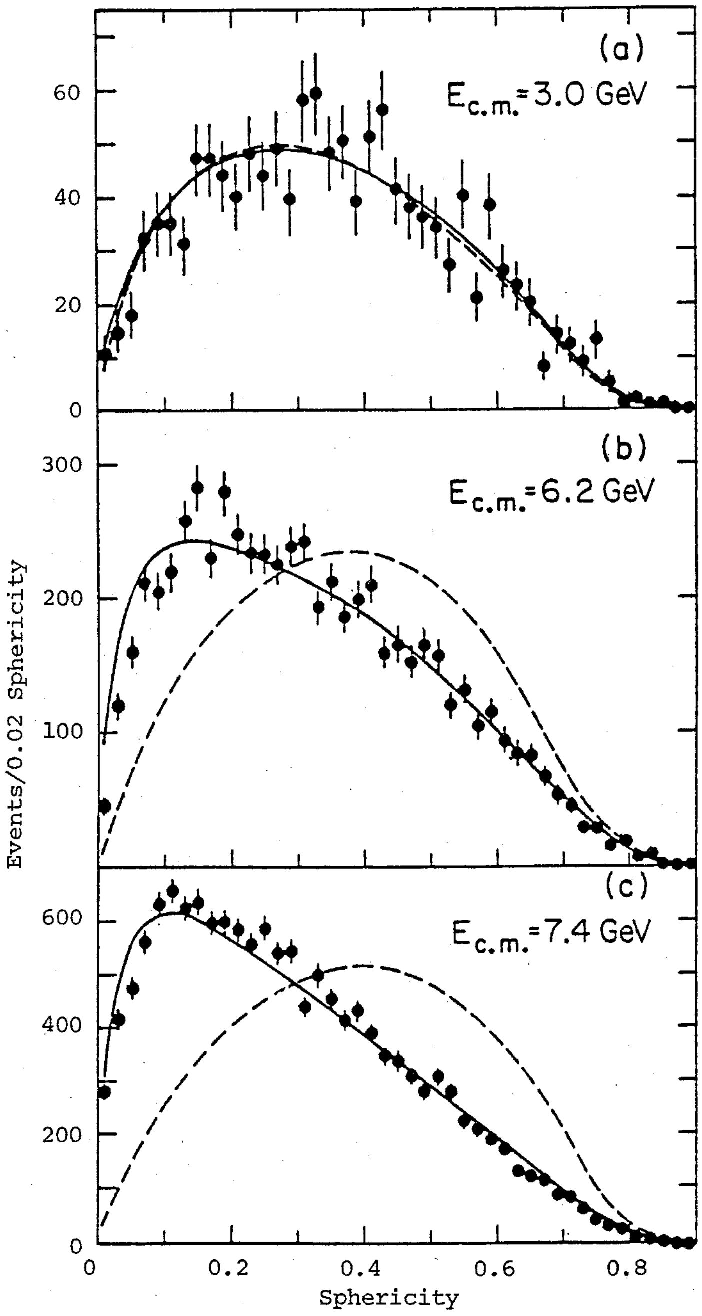

is called a *jet*, and two such clusterings back-to-back form a *jet axis*. The experimenters who study these things have invented a way to describe just how "jetty" a particular interaction is by measuring its "sphericity." A sketch can illustrate the general idea without worrying about a lot of details:



High Sphericity Low Sphericity

How this sphericity measurement applies to the SPEAR data is illustrated in the three-part figure on this page. The precise information conveyed by the figure is not particularly important for our purposes. The general idea is that the "shape" of the particle distributions changes from that of, say, a basketball at 3.0 GeV to a football at 6.2 GeV and then to a cigar at 7.4 GeV.

*So what?* This evidence for jets at SPEAR is actually very important, for reasons which we'll now discuss. Although there is no generally accepted theory that describes exactly what is happening when jets are produced, the existence




Observed sphericity distributions for 3 or more prong hadron events at SPEAR at energies of 3.0, 6.2 and 7.4 GeV. See text for details.

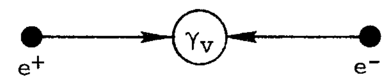
of jets is assumed to lend general support to the idea that hadrons are composed of simpler, more fundamental constituents such as quarks. There is a further bit of evidence from the SPEAR data that makes this possible interpretation even more persuasive, namely that the directional properties observed in the two processes

$$e^+e^- \to \text{hadrons} \quad \text{and} \quad e^+e^- \to \mu^+\mu^-$$

appear to be similar. The significance of this similarity is that muons are point-like, spin-½ elementary objects that would be expected to produce a jet-distribution pattern that is the same as that produced by the point-like, spin-½ elementary objects that quarks are also assumed to be.

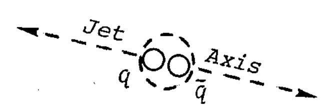
What the jet structure in hadron production at SPEAR seems to imply, then, is a sequential, three-step process that proceeds as follows:

(1)



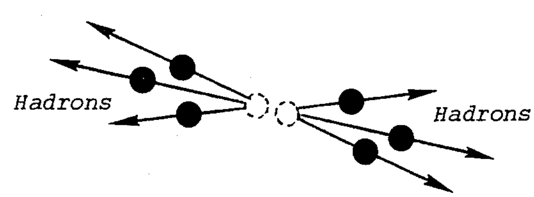

In Step (1), $e^+e^-$ annihilate to form a virtual photon ($\gamma_V$). This virtual photon intermediate state itself has no preferred "jettiness" or directionality.

(2)




In Step (2), the virtual photon forms a quark-antiquark pair ($q\bar{q}$), and it is this pair which determines the direction that will become the jet axis for this particular event. Both the $q\bar{q}$ pair and the virtual photon are shown as open circles to indicate that neither can be directly observed--that is, their existence must be inferred from indirect evidence.

(3)




In Step (3), the $q\bar{q}$ pair interact with each other to produce the various combinations of hadrons that finally materialize and are detected by the experimental apparatus. The hadrons produced in this process tend to retain the direction established by the initial $q\bar{q}$ pair--they emerge, that is, along the jet axis. The jet structure established in this process becomes more pronounced as the $e^+e^-$ collision energy is increased.

# D. Psi(3.1) & Psi(3.7)

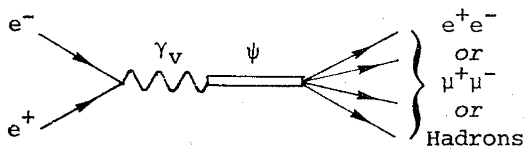
In this section we focus specifically on the properties of the $\psi(3.1)$ and $\psi(3.7)$ resonances--which we'll sometimes refer to by their fuller names: $\psi(3095)$ and $\psi(3684)$. We divide the description into the following parts:

1. The nature of the psi resonances.
2. Where the psi particles fit in.
3. Figuring out some psi properties.

This section will end with the summary tables of psi properties that appear in Detour 2.

## 1. THE NATURE OF THE PSI RESONANCES

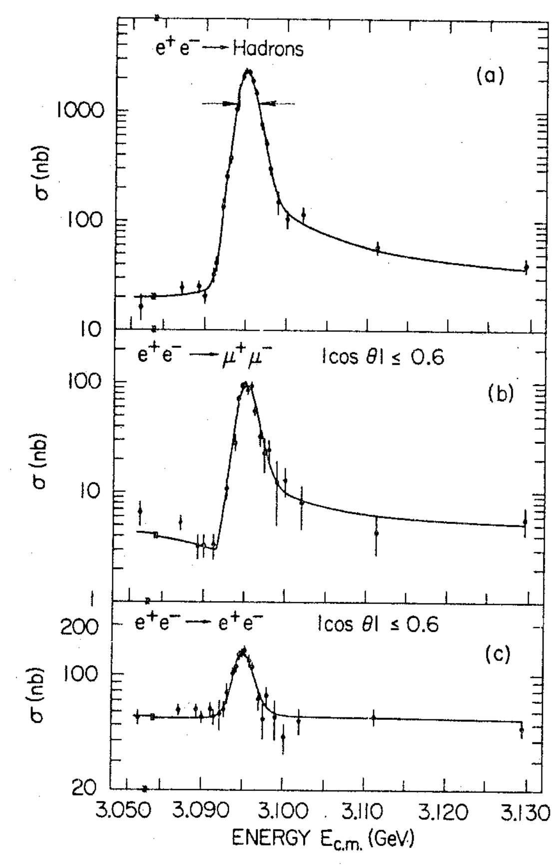
Psi particles are created at SPEAR in an $e^+e^-$ annihilation process that can be pictured in the following way:




In words, this process would read: *$e^+e^-$ annihilate to form a virtual gamma ray, which then creates a psi particle, which then decays into $e^+e^-$ or $\mu^+\mu^-$ or any of a large number of possible combinations of hadrons.* (In about 20% of the cases, the created psi particle is converted back into a second virtual gamma ray, and *it* then produces the final observed particles.)

Psi particles are created at SPEAR most copiously when the combined energy of the two SPEAR beams is exactly equal to either of the psi masses: 3.095 GeV or 3.684 GeV. The figure on this page illustrates how sharply the cross section (or rate of particle production) rises in the case of the $\psi(3095)$ when the SPEAR energy is dead solid perfect on 3.095 GeV. From the shapes of the production curves in the figure it isn't too difficult to get a feeling for why processes of this kind are called *resonant* production, or equivalently why the created particles are also known as *resonances*. This resonant behavior is in many ways similar to what happens with tuning forks, microwave cavities, tank circuits, wine glasses, large speakers in small rooms, and many etceteras.

Although the resonant peaks in the figure appear to quite sharp, there are two different effects at work at SPEAR that cause the curves to be very substantially broadened or smeared out: (1) synchrotron radiation emitted by the circulating beams causes the particles within the beam bunches to have somewhat different energies. (2) Sometimes the particles that annihilate each other first spit out some of their energy in the form of a gamma ray. To see how strongly these two effects operate, let's look for a moment at the tallest peak shown in the figure. The two small arrows on the sides of the peak enclose an energy width of about 2.5 MeV. But if we were able to subtract out the smearing effects of the synchrotron and gamma radiation, the true width of the peak would emerge as only 0.05 MeV, or about 50 times narrower than what is shown. The fact that the peaks shown in the figure are asymmetric, with a fairly abrupt rise on the left and a long slow fall-off on the right, is attributable to the gamma radiation we just talked about. This slow fall-off is called the *radiative tail* of the resonance, and it is characteristic of all high-energy processes in which electrons or positrons participate.




These three curves show the cross sections or production probabilities for $e^+e^-$ annihilation into $e^+e^-$, $\mu^+\mu^-$, and hadrons in the region of the $\psi(3095)$ resonance. As described in the text, the measured curves shown here are roughly 50 times broader than the intrinsic resonant behavior because of certain radiation effects. Note that the vertical scale is logarithmic. The upper curve is particularly remarkable for the roughly 100-fold increase in cross section that occurs at 3.095 GeV SPEAR center-of-mass energy.

## 2. WHERE THE PSI PARTICLES FIT IN

The $\psi(3.1)$ and $\psi(3.7)$ resonances have now been studied in enough detail so that it is possible to start giving some fairly confident answers about them. On perhaps the most fundamental level, it seems pretty clear that the psi particles are *hadrons*, and more specifically that they belong to the particular class of hadrons that are called *vector mesons*.

(As we go through this section, sounding pretty much like we know what we're doing, it would be wise to keep the following fact in mind. There is a rather common particle known as the mu-meson or muon whose properties are very well known and whose behavior can be predicted to a fare-thee-well. That is, we understand practically all there is to understand about muons except for one thing: Why are they there? What role do they play in making the world tick? Muons have been members in good standing of the elementary particle zoo for about 30 years, and no one has yet figured out what they are *for*. So as we blow up a storm of information about the properties of the psi particles, etc., let's reflect that the kind of knowing that goes with name, rank and serial number may not produce much understanding.)

The vector mesons are a somewhat special class of particles because they have many of the same characteristics ("quantum numbers") as the very special particle, the photon, that is the "carrier" of the electromagnetic force. Back at the beginning we discussed the fact that the elementary particles could be grouped into two major families--the small family of leptons such as the electron, and the very large family of hadrons such as the proton. But the photon has the unique distinction of being neither one; it's in a category all by itself.

Before we discuss the photon's relation to the vector mesons, let's first list the particles we're talking about, along with some of their characteristics, in the following table.

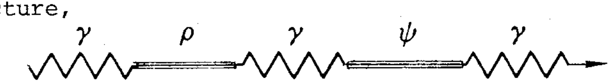
| Vector Mesons | Mass in GeV | Total Decay Width in MeV | Decay Width To Electrons in keV |
|---|---|---|---|
| Rho ($\rho$) | 0.770 | 150 | 6.5 |
| Omega ($\omega$) | 0.783 | 10 | 0.8 |
| Phi ($\phi$) | 1.020 | 4 | 1.3 |
| $\psi$(3095) | 3.095 | 0.07 | 4.8 |
| $\psi'$(3684) | 3.684 | 0.23 | 2.1 |
| ?(4100) | 4.150 | ~ 275 | 4.0 |

As we talked about earlier, decay widths are related to the lifetime of a particle--the wide resonances are short-lived. Widths are also related to "branching ratios," that is, to the likelihood that one particular decay process out of all possible decays will occur. In the table, for example, we can figure out that the $\psi'$(3684) decays into electrons about 1% of the time:

$$\frac{\text{Decay into electrons}}{\text{Decay into anything}} = \frac{2.1\ \text{keV}}{230\ \text{keV}}$$

The decay widths into electrons shown in the table are characteristic of vector mesons. The obvious striking discrepancies in the table are the extremely narrow total decay widths for the two psi particles. Where a rho meson, for example, will go $\rho \to \pi^+\pi^-$ quick as a flash, the psi's dawdle around forever before undergoing a similar hadronic decay. This sort of $10^3$ procrastination has several possible explanations which we'll discuss eventually. For our present purpose we now want to see what the connection is between the vector mesons and the photon.

A useful but peculiar-seeming way or expressing the photon-vector meson relationship is to say that the photon actually spends a certain fraction of its time *being* vector mesons. In a picture,




Another way of stating the same idea is to say that the photon (even though it is not a hadron) *contains* or has mixed in with it a small percentage of all the vector mesons. And when the photon happens to be wearing its rho or omega or phi or psi hat, then it also *acts* like a hadron by responding to the strong force.

This hadronic aspect of the not-hadron photon was first discovered about 10 years ago, and it came as a great surprise to physicists who imagined that the fundamental forces--weak, strong, and electromagnetic--were entirely distinct from each other. A major development of the last decade, however, has been an increasing realization that there are connections and similarities --perhaps even an underlying sameness that will eventually make it possible to understand the three forces as simply different manifestations of a single ubiquitous force. The search for such an underlying identity--for what is called a "unified" theory--is presently arousing great interest and attention in particle physics research.

## 3. FIGURING OUT SOME PSI PROPERTIES

To arrive at the conclusion that the psi particles are hadrons and in fact vector mesons requires some work that was not evident in the previous section. In this section we try to rectify that oversight by describing a couple of examples of how such information is obtained. To begin with, mesons are chiefly characterized by three particular quantum numbers or attributes which we will very briefly define:

J is a particle's spin angular momentum, or just *spin*, and is a measure of how rapidly the particle spins on its axis. In the microscopic world of the particles things don't work the same way as they do in the large. A top, for example, can spin at any old speed, but for the elementary particles spin is *quantized* in certain discrete amounts. Baryons can have 1/2 unit of spin, or 3/2, or 5/2, etc., while mesons must have spin in integer amounts: 0, 1, 2, etc.

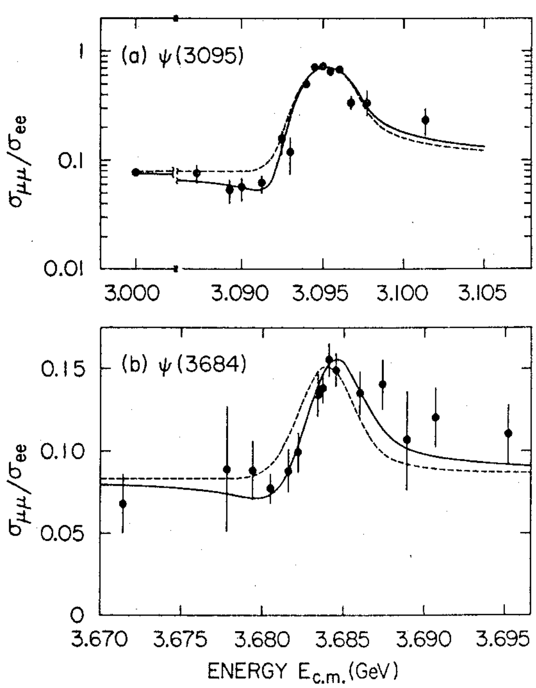
P is a thing called *intrinsic parity*. Whatever it is, it is not easy to visualize, but it is related to the fact that nature does not distinguish between left and right in the strong or electromagnetic interactions (not true for the weak interactions). P is also connected with J in a complicated way that we will ignore here.

C is an intrinsic property called *charge conjugation*. Again it is not easily to visualize but is connected with the fact that particles and antiparticles are interchangeable for the strong and electromagnetic interactions.

These three quantum numbers for mesons are usually written together like this:

$$J^{PC}$$

For the vector mesons the values of $J^{PC}$ are $1^{--}$ (which is spoken "one-minus-minus"). The photon is also $1^{--}$.




This figure illustrates the production of muons in the regions of the two psi resonances. The direct production process $e^+e^- \to \mu^+\mu^-$ will interfere destructively with the resonant process $e^+e^- \to \psi \to \mu^+\mu^-$ in the energy region below the peak if the psi particles have the same quantum numbers as the photon, $J^{PC} = 1^{--}$. The dashed curve gives the expected result for no interference, while the solid curve is the prediction for maximum interference. The data are consistent with maxiumum interference, confirming the vector meson nature of the psi's.

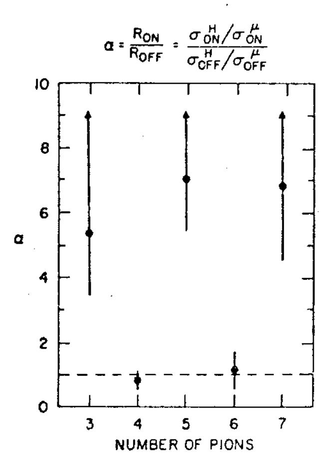
Now let's see how the $J^{PC}$ assignments for the psi particles were arrived at.

<u>Interference effect</u>. We consider two processes that occur at SPEAR:

$$e^+e^- \to \gamma_V \to \mu^+\mu^-$$
$$e^+e^- \to \gamma_V \to \psi \to \mu^+\mu^-$$

The first reaction is the direct production of muon pairs, and the second reaction is the production of muon pairs via the $\psi$ resonances. Now if the photon and the psi have the same quantum numbers, then there should be an interference between the two reactions in the energy region near resonance. By an "interference" we mean that the two processes should compete with each other destructively at a certain energy and thus reduce the total production of muons at that energy. The figure on the left shows what happened when this test was carried out. The interference effect was in fact observed, and this established the fact that the psi's quantum numbers were $1^{--}$ like the photon. (This assumes the expected circumstance that P and C are conserved in this interaction.) Confirmation for the assignment of J = 1 was also obtained by observing the angular distribution pattern made by the decay muons; this distribution was consistent with possible spin assignments of J = 1, 2 or 3, but 2 and 3 were eliminated by certain other tests.

<u>Decay modes</u>. Two other quantum numbers (G parity and Isospin--which we won't define) were inferred by observing the decay modes of the psi particles. The key fact in this inference was whether the psi's decayed into both odd and even numbers of pions. This was tested by making the comparison that is illustrated in the figure.




This figure compares the ratio of pion production to muon-pair production at two different energies: 3.095 GeV, which is "on" the lower psi resonance; and 3.000 GeV, which is "off" resonance. The results indicate that the $\psi(3.1)$ decays with a strong preference for an odd number of pions. In fact all the decays with an even number of pions can be identified with the "second-order" decay mode:

$$e^+e^- \to \gamma \to \psi \to \gamma \to \text{even \# pions}$$

This result establishes the quantum number assignments I = even, G = minus.

# Detour 2: Psi Properties

In this second Detour we gather together in Tables some of the more important experimental information that has been learned about the psi particles. In the "Decay Modes" Tables, the "branching ratio" refers to the fraction of the time a psi particle will decay into the particular particles listed. For example, the $\psi(3095)$ decays to an $e^+e^-$ pair 6.9% of the time. This branching ratio number is directly related to the "decay widths" shown in the other Table: note that the $\psi(3684)$ decays into $e^+e^-$ 1% of the time and also that its decay width to $e^+e^-$ is 2.2 KeV, or 1% of the total decay width of 225 KeV.

There are some interesting patterns in the psi decay modes. The $\psi(3095)$ decays readily into 3, 5 or 7 pions ($\pi$), but much less so into 2, 4 or 6 pions. (In fact the even-pion decays probably all come from the "second-order" decay process $\psi \to \gamma \to 2,4,6\ \pi$.) The $\psi(3684)$ decays 57% of the time into $\psi(3095)$ + anything, 2% of the time into either $e^+e^-$ or $\mu^+\mu^-$, and the remaining 41% of the time into →(things we haven't yet figured out).

Most theories of the elementary particles make extensive and detailed predictions of how particles with a certain set of properties should decay, and the painstaking experimental work that is carried out to determine all these decay modes and other properties provides the most stringent tests of theory and is in fact the bread-and-butter business of high energy physics.

| *Some Psi Properties* | $\psi(3095)$ | $\psi(3684)$ |
|---|---|---|
| $J^{PC}$ | $1^{--}$ | $1^{--}$ |
| Mass | 3095 ± 0.004 GeV | 3864 ± 0.005 GeV |
| **Decay Widths** | | |
| $\psi \to e^+e^-$ / $\psi \to \mu^+\mu^-$ | 4.8 ± 0.6 KeV | 2.2 ± 0.3 KeV |
| $\psi \to$ Hadrons | 59 ± 14 KeV | 220 ± 56 KeV |
| $\psi \to$ All | 69 ± 15 KeV | 225 ± 56 KeV |
| $\frac{\psi \to \text{Hadrons}}{\psi \to \text{All}}$ | 0.86 ± 0.02 | 0.981 ± 0.003 |
| $\frac{\psi \to e^+e^-}{\psi \to \text{All}}$ | 0.069 ± 0.009 | 0.0097 ± 0.0016 |
| **Cross Sections** (peak) | | |
| $\psi \to e^+e^-$ | 130 nb | 40 nb |
| $\psi \to \mu^+\mu^-$ | 100 nb | 6 nb |
| $\psi \to$ Hadrons | 2300 nb | 560 nb |

DECAY MODES OF THE $\psi(3095)$

| Mode | Branching Ratio (%) | # Events Observed |
|---|---|---|
| $e^+e^-$ | 6.9 | 2000 |
| $\mu^+\mu^-$ | 6.9 | 2000 |
| $\rho\pi$ | 1.3 | 153 |
| $2\pi^+2\pi^-$ | 0.4 | 76 |
| $2\pi^+2\pi^-\pi^0$ | 4.0 | 675 |
| $3\pi^+3\pi^-$ | 0.4 | 32 |
| $3\pi^+3\pi^-\pi^0$ | 2.9 | 181 |
| $4\pi^+4\pi^-\pi^0$ | 0.9 | 13 |
| $\pi^+\pi^-K^+K^-$ | 0.4 | 83 |
| $2\pi^+2\pi^-K^+K^-$ | 0.3 | |
| $K_SK_L$ | – | ≤ 1 |
| $K^0K^{0*}(892)$ | 0.2 | 57 |
| $K^{\pm}K^{\mp*}(892)$ | 0.3 | 87 |
| $K^{0*}(892)K^{0*}(1420)$ | 0.4 | 30 |
| $K\ K^*(1420)$ | – | ≤ 3 |
| $K^*(892)K^*(892)$ | – | ≤ 3 |
| $K^*(1420)K^*(1420)$ | – | < 3 |
| $K^*(892)K^*(1420)$ | – | ≤ 3 |
| $p\bar{p}$ | 0.2 | 105 |
| $\Lambda\bar{\Lambda}$ | 0.2 | 19 |
| $p\bar{p}\pi^0$, $\bar{n}p\pi^-$, $\bar{p}n\pi^+$ | 0.4 | 87 |

DECAY MODES OF THE $\psi(3684)$

| Mode | Branching Ratio (%) |
|---|---|
| $e^+e^-$ | 1.0 % |
| $\mu^+\mu^-$ | 1.0 |
| $\psi(3095)$ anything | 57 |
| $\psi(3095)\pi^+\pi^-$ | 32 |
| $\psi(3095)\eta$ | 4 |
| $\psi(3095)\gamma\gamma$ | ≤ 6.6 |
| $\rho^0\pi^0$ | ≤ 0.1 |
| $2\pi^+2\pi^-\pi^0$ | ≤ 0.7 |
| $p\bar{p}$ | ≤ 0.03 |