

# search & discovery

## Sequel to the psi: DESY, SLAC see intermediate states

After the first rush of discovery last fall in which the  $J$  or  $\psi$  particle, with mass of 3.1 GeV was discovered, almost immediately followed by the  $\psi'$  prime, with mass of 3.7 GeV, there has been no new obviously related particle discovered. That is, until now, when an intermediate state, dubbed the " $P_c$  particle" was observed at the DESY electron-positron storage ring, DORIS. The particle apparently has a mass of either 3.5 or 3.3 GeV, but the experimenters cannot tell which.

Since then experimenters at the Stanford electron-positron storage ring, SPEAR, say they have observed two separate intermediate states, one at 3.41 GeV and one at 3.53 GeV.

The observation of an intermediate state offers a lot of support for picturing the 3.1-GeV particle and the 3.7-GeV particle as bound states of a quark and an antiquark. In particular, the new results are encouraging to those who think of the two particles as bound states of a charmed quark and a charmed antiquark. Several groups

had predicted the existence of an intermediate state or states, with mass between 3.7 and 3.1 GeV, which would decay by photon emission. But when the states were not discovered after several months, gloom settled over many high-energy physicists.

The DESY experiment was done by a collaboration between the University of Aachen, DESY, University of Hamburg, Max Planck Institute for Physics and Astrophysics in Munich, and the University of Tokyo.

The 3.7-GeV particle, produced in electron-positron collisions in DORIS, was observed to decay in two different ways. In one mode, it produces two gamma rays plus the 3.1-GeV particle, which in turn decays into two muons. In the second mode, it produces two gamma rays plus the 3.1-GeV particle, which in turn decays into two electrons. In both cases it is presumed that the 3.7-GeV particle decays into one gamma plus an intermediate state, the  $P_c$  particle, which then decays by photon emission into the 3.1-GeV particle.

The double-arm spectrometer, DASP, is used. It has two magnetic spectrometers, each with a solid angle of about  $\frac{1}{20}$  of a sphere. In the middle of the device, covering a much larger fraction of the solid angle, is the so-called "inner detector," which consists of shower counters, scintillators and proportional tube chambers. The latter ones are crucial in determining the directions of the photons.

In the decay in which muons are produced, the DASP experimenters found five events. One muon is seen in each of the spectrometer arms, and two of the shower counters light up. From the measured directions of the photons and the measured angles and momenta of the muons, the experimenters do a two-constraint fit to determine the photon energies. The energies of the gamma rays are roughly 160 and 420 MeV with a resolution of  $\pm 20$  MeV. The result is consistent with the 3.7-GeV particle decaying into a gamma plus  $P_c$  particle, the new particle then decaying into the 3.1-GeV state plus a photon, followed

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## Two forms of amorphous solid water reported

The structure of solid water has intrigued physicists and chemists since the nineteenth century. By now it is known that solid water has at least eight crystalline forms. In 1935 E. F. Burton and W. F. Oliver (University of Toronto) reported seeing an amorphous form of solid water, and since then a few other experimenters have said they had observed it. Now Stuart Rice (University of Chicago) and his collaborators have done careful, quantitative x-ray diffraction, neutron diffraction and Raman-scattering studies of water prepared in two different ways, and they believe they have observed two distinct forms of amorphous solid water.

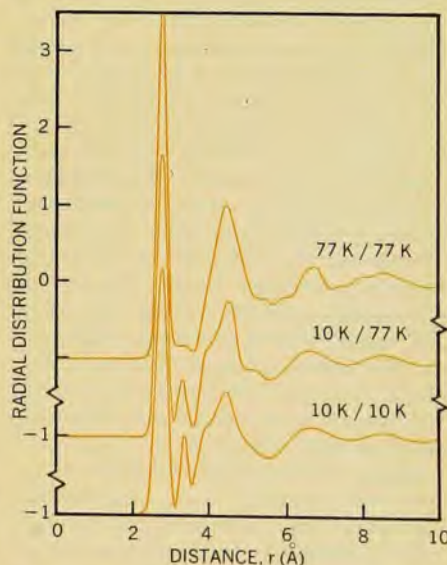
At the same time Richard Alben (Yale University) and Pierre Boutron (Magnetism Laboratory, Grenoble) have produced a continuous random network model that agrees quite well with the observations of Rice and his collaborators for one of the two amorphous phases.

There is hope that work on the amorphous phase of solid water will lead to a better understanding of liquid water,

still far from well understood.

**The observations.** Although Rice has been interested in liquids for a long time, he told us that, obeying W. C. Fields's dictum, he had stayed away from water. Then about 1969 he and David Olander (Chicago) started studying the literature on amorphous solid water and concluded that none of the previous experiments had been completely free of contamination by crystalline material. The following year they found<sup>1</sup> a way to make uncontaminated samples, by condensing water vapor onto a substrate very slowly (a few milligrams per hour) and at lower temperatures than previously used—lower than 55 K. (Earlier measurements, for example by L. G. Dowell and A. P. Rinfret of Linde Co., showed that above about 120 K, amorphous solid water transforms to a form of crystalline ice.)

To study the amorphous material, Rice and Jack Wenzel (University of Chicago and Research Establishment Risø) did<sup>2</sup> neutron-diffraction studies at Risø, using  $D_2O$  instead of  $H_2O$ .



**Oxygen atom pair correlation functions** for amorphous solid water derived from x-ray diffraction. Top curve: deposit formed at 77 K and studied at 77 K. Middle curve: deposit formed at 10 K and studied at 77 K. Bottom curve: deposit formed at 10 K and studied at 10 K. (Figure supplied by Stuart Rice.)



Heavy water is used because deuterons are better coherent scatterers than protons. In addition, C. G. Venkatesh (Chicago), Rice and A. H. Narton (Oak Ridge National Laboratory), did<sup>3</sup> x-ray diffraction studies at Oak Ridge. By combining the results one obtains the orientational distribution. Just as in liquid water, correlation between molecular orientations is limited to first neighbors, Rice says. Correlation between the positions of molecular sensors extends further than in the liquid.

The experimenters found by depositing the sample very slowly and at very low temperatures they produced a form of the amorphous solid with a high density—1.1 g/cm<sup>3</sup>—and the following characteristic diffraction pattern: It has a first-neighbor peak that corresponds to close to four neighbors at a distance of 2.76 Å. This O-O distance is the same that exists for the three simplest phases of crystalline ice—ice I, II and III. The rms deviation of the O-O-O angle is about 8 deg. (In ice I, the O-O-O angle is exactly 109.5 deg, the tetrahedral value.) They obtained a next-nearest neighbor peak at 3.3 Å, which corresponds to about 1.4 neighbors. And there is more blurred structure further out. There is no trace of crystallinity. When the temperature is raised to 77 K, all that happens is a small broadening of the second-neighbor peak.

If the material is instead deposited more rapidly and at 77 K, a different kind of amorphous deposit is obtained, Rice told us, with a density of only 0.94 g/cm<sup>3</sup>, almost the same as that of ordinary ice, which is 0.935 g/cm<sup>3</sup>. The amorphous material has a first-neighbor distance of 2.76 Å, just like the amorphous deposits. A central molecule again has about four nearest neighbors, but the extra little peak at 3.3 Å is missing. And the rms angular deviation of O-O-O angles is about 8 deg.

When the experimenters did neutron-diffraction studies of amorphous solid D<sub>2</sub>O, the molecule in the amorphous solid had the same O-D bond length and the same D-O-D angle as the molecule in the vapor. For each of the experiments a different deposition was made. For the neutron-diffraction studies, the solid was of the low-density form. The data are consistent with the undistorted water molecule having local tetrahedral coordination.

**Model.** While Rice and his collaborators were working, Alben and Boutron met each other in France. Alben had been working on models of amorphous germanium and silicon, and Boutron on cryobiology. They decided to combine efforts to develop a model of amorphous solid water, as a first stage in understanding water-rich amorphous phases of interest to cryobiologists.

The idea of a continuous random net-

work model dates back to 1932 when W. H. Zachariasen (University of Chicago) used it for silicon dioxide glass. Since then others have used the idea of constructing models for the structure of amorphous materials, for example David Turnbull at Harvard, J. D. Bernal (Birkbeck College, University of London), his student there, John Finney, and Turnbull's student, Donald Polk. Alben and Boutron took the Polk model for germanium, scaled the distances so that they became appropriate to the oxygen-oxygen separation and then added hydrogen according to the so-called "ice rules." These require that each oxygen has two hydrogens near to it and two far away from it.

Alben and Boutron built up their model<sup>4</sup> according to various criteria such as compactness, the absence of broken bonds and the absence of large angular distortions. Alben explained to us that by introducing five- and seven-membered rings of bonds (ordinary crystalline ice is made only of six-membered rings), you can make the model appear to be quite random. The point of the model, he says, is to show that you can make a very low-energy structure without long-range order. "You sort of pretend you're an individual atom, wondering where to sit." Alben and Boutron do find correlations at a longer range than one might expect, but these show up in the real material as well. They see correlations that go beyond fourth, fifth and sixth neighbors.

Alben told us that their model fit very well various older x-ray data and also the neutron data supplied by Wenzel, which were for the low-density phase, the phase that satisfies the local rules of ordinary water.

**In a third experiment,** Rice, John Bates (Oak Ridge), and Venkatesh studied<sup>5</sup> the Raman spectrum of the low-temperature, high-density form using pure H<sub>2</sub>O, pure D<sub>2</sub>O and a mixture of the two from 30 to 120 K. They made a Gaussian deconvolution of the spectrum and found four components. To explain their results they postulate that the high-density, low-temperature amorphous solid is a randomized version of either a mixture of ice II and ice III; of ice I, ice II and ice III, or just ice II, or just ice III. Rice says that the Raman spectra are consistent with the higher-density form being a randomized version of a higher density ice.

In trying to connect amorphous solid water to liquid water, Rice cites work by C. A. Angell (Purdue University), who has studied the supercooled state. Angell speculates, on the basis of his measurements of heat capacity and the thermal and volumetric measurements of D. H. Rasmussen and A. P. MacKenzie (Cryobiology Research Institute) that as the temperature is lowered, water molecules organize themselves

into the tetrahedrally coordinated continuous random-network structure in a cooperative process that gives rise to a preliminary higher-order thermodynamic transition in the liquid.

Rice conjectures that the potential surface in the liquid has minima in directions that are related to the directions in which those minima occur in ice I, II and III. If this is correct, he says, it suggests that as you supercool water, you preferentially populate configurations that are like the high-temperature, low-density amorphous solid.

—GBL

## References

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## Sequel to psi

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by the 3.1-GeV state decaying into two muons. Thus, from this evidence one can only say that the mass of the P<sub>c</sub> is either 3.5 or 3.3 GeV.

In studying the second mode, the experimenters, using only the inner detector, look for two charged particles plus signals in two shower counters. From the pulse height in their shower counters, they identify the two charged particles as electrons. Next they do a zero-constraint fit, just from the angles of all the particles, assuming they come from the 3.7-GeV particle, and solve for the masses of all the particles. Then they calculate the invariant mass of the two charged particles, examine the spectrum and observe a peak at 3.1 GeV. The 3.1-GeV particle then decays into a positron and electron. The reaction, they conclude, is a 3.7-GeV particle going to one gamma ray plus a P<sub>c</sub> particle, which then produces a gamma plus the 3.1-GeV particle, which then decays to an electron and positron.

The experimenters find 71 events, 25 of which have an electron-positron pair at a mass of 3.1 GeV. Then, using the zero-constraint fit they calculate the photon energies—one is about 200 and the other about 400 MeV. The resolution on the photons, is, however, not as good as for the first mode, namely  $\pm 70$ –100 MeV. And of the 25 events, the experimenters estimate that nine of them could be from the 3.7-GeV particle going to the 3.1-GeV particle plus two neutral pions.

Thus, the DESY experimenters believe they are seeing a gamma-ray line



spectrum with evidence for an intermediate state. The best evidence is presumably from the muon decay, where the resolution is better. The electron decay, on the other hand, gives better statistics and allows a crude branching fraction to be calculated. The DESY team estimates that the branching fraction for the 3.7-GeV particle to produce two gamma rays and a 3.1-GeV particle is 2-12% of the total decays of the 3.7-GeV particle.

The SPEAR experimenters led by Burton Richter and Martin Perl (SLAC), William Chinowski, Gerson Goldhaber and George Trilling (Lawrence Berkeley Laboratory), looked at the 3.7-GeV particle decaying into a gamma plus an intermediate state, which then decays into hadrons.

They find two peaks in the mass distribution, at 3.53 and at 3.41 GeV. Presumably the 3.53-GeV state corresponds to the possible 3.5-GeV particle reported by the DESY group. But the 3.41-GeV state seen by the SPEAR experimenters was apparently not seen by the DESY team.

Richter told us that their 3.53-GeV state seems broader than their experimental resolution; hence it is either wide or there is more than one state near that mass value. In addition, the SPEAR experimenters looked at branching fractions. They find that the 3.41-GeV particle does not decay into the 3.1-GeV particle plus a gamma as readily as the 3.53-GeV particle does.

**Related experiments.** An earlier experiment looking for the intermediate state was done by a Stanford University-University of Pennsylvania group at SPEAR using sodium iodide detectors. The experimenters reported their results at the Washington meeting of the American Physical Society in April. They find no compelling evidence for monochromatic photon emission in the energy interval 50-1000 MeV with a branching ratio larger than 5-6%.

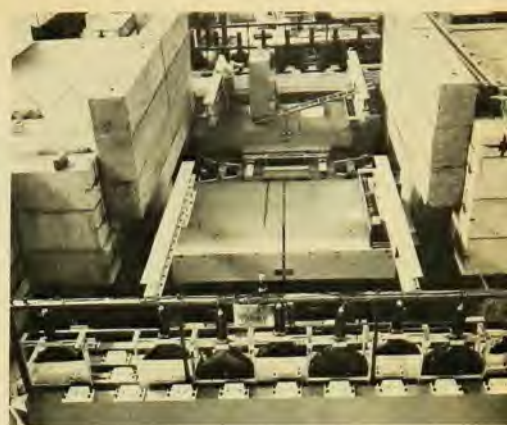
In a different search for the intermediate state, Samuel C. C. Ting, Ulrich Becker, Min Chen and their collaborators at MIT and Brookhaven, using the Brookhaven AGS, have looked for the reaction proton plus proton produces a  $P_c$  particle. They reported at the Palermo International Conference on Nuclear Physics late in June that the reaction has a cross section less than 1 nanobarn. In the same experiment they looked for the decay of a charmed meson into a positive kaon and a negative pion and the decay of a charmed baryon into a negative kaon and a proton. Within the range 1.8-5 GeV they found a cross section of less than 0.1 nanobarn.

**Theory.** What does the existence of the intermediate state suggest? We discussed the discovery with Sheldon Glashow (Harvard University), who to-

gether with J. D. Bjorken of SLAC suggested the existence of charmed quarks in 1964. Subsequently he, John Illiopoulos (Ecole Normale Supérieure) and Luciano Maiani (Istituto di Sanita, Rome) used the charm concept in a theory of weak interactions. Glashow feels that the  $P_c$  is convincing evidence that the 3.1-GeV particle is made up of some new quark and its antiquark, so that more than three quarks are certainly needed. If the charm hypothesis is correct, the new quark should bind to ordinary quarks to form charmed particles. The discovery of these new particles with predicted decay properties remains the ultimate test of charm. Actually one charmed particle may have been observed at Brookhaven National Laboratory by Nicholas Samios and his collaborators. As always, Glashow says, with the observation of one unique event, confirmation via the accumulation of one or more similar events is clearly necessary.

Harvard theorists Thomas Appelquist, Glashow, Alvaro De Rujula and H. David Politzer, have proposed that the 3.1-GeV particle is a bound state of a charmed quark-antiquark pair, called "orthocharmonium," and the 3.7-GeV particle is a radially excited state of it. There two states have spin one. They also predict the existence of parachocharmonium with spin zero; these states would lie slightly below each of the orthocharmonium states, several dozens of MeV below, the group believes. In addition one would expect several P-wave states, the group says, in which there is of course one unit of orbital angular momentum. The 2S state of orthocharmonium is expected to decay into the 2P state by photon emission and then the 2P state would decay into the 1S state by emitting a photon. The argument is analogous to that of positronium, which was always expected to have excited states. However, it took many years to find the positronium excited states (recently reported by Stephen Berko and his collaborators at Brandeis University), whereas it has only taken a few months to do it for charmonium.

Glashow explains that a naive calculation using a Coulomb potential gives the first P-wave state an energy of 3.7 GeV. A harmonic-oscillator potential gives an energy of 3.4 GeV. The Harvard group believes the correct energy lies between the two values. Other groups have made similar predictions of where the P-wave states would lie. These have been done by Curtis G. Callen, R. L. Kingsley, Sam B. Treiman, Frank Wilczek and Anthony Zee (Princeton University), by E. Eichten, Kurt Gottfried, Toichiro Kinoshita, John Kogut, K. Lane and Tung Mow Yan (Cornell University), by Kogut and Leonard Susskind (Tel Aviv University)



**DASP detector at DESY** used to detect  $P_c$  particle. From front to rear are: iron absorber plus range counters, space for spark chambers, magnet, inner detector (centered around interaction point) plus two spectrometer arms on other side of interaction point.

and by Barry Harrington and Asim Yildiz (Harvard). Most of the theorists predicted a larger branching ratio than actually observed by the DESY experimenters.

Commenting on the DESY discovery, theorist Treiman says, "I was a firm believer in the qualitative idea of a charm-anticharm pair and that intermediate states would exist. But I was getting depressed that intermediate states weren't being found. Now those who had faith seem to have been proved right."

—GBL

## Do solar variations affect Earth's weather?

As far back as biblical times, Man has searched for correlations between events in the heavens and events on Earth. In more recent times, scientists have looked for a connection between solar phenomena and the weather on Earth. Over the past twenty years evidence has been growing that variations in solar magnetic activity correlate with low-pressure troughs in the Northern Hemisphere. The work has been pioneered by Walter Orr Roberts (University of Colorado and the National Center for Atmospheric Research, Boulder). In recent years others have collaborated with Roberts, for instance John M. Wilcox, Philip Scherrer and Leif Svalgaard at Stanford University, Roger H. Olson (University of Colorado) and Roy L. Jenne (National Center for Atmospheric Research).

In 1972 Roberts and Olson<sup>1</sup> studied the development of 300-millibar (a height of about 9 km) low-pressure trough systems in the north Pacific and North American region. They reported that troughs that enter or are formed in the Gulf of Alaska two to four days after a sharp rise of geomagnetic activity tend to be bigger than average size.