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 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 ± 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

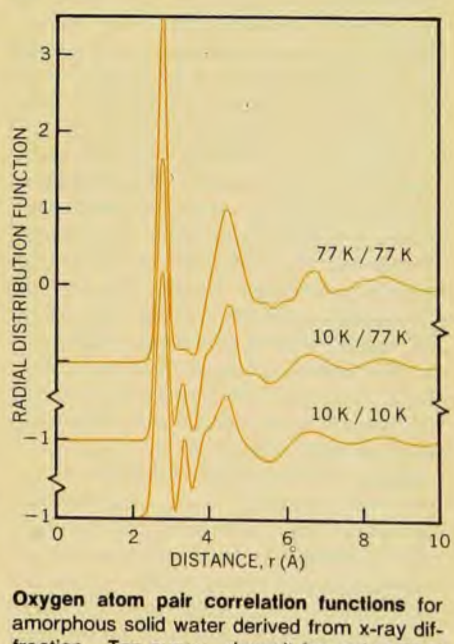
The structure of solid water has intrigued physicists and chemists since the nineteenth century. By now it is known that solid water has at least eight crystalline forms. In 1935 E. F. Burton and W. F. Oliver (University of Toronto) reported seeing an amorphous form of solid water, and since then a few 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[1] 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[2] 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[3] 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^3—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^3, almost the same as that of ordinary ice, which is 0.935 g/cm^3. 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_2O, 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 network 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[4] 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[5] the Raman spectrum of the low-temperature, high-density form using pure H_2O, pure D_2O 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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by the 3.1-GeV state decaying into two muons. Thus, from this evidence one can only say that the mass of the P_c 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_c 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 ±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