A Crystal Ball Looks at Charm and Beauty

by Frank C. Porter and Charles W. Peck

SINCE THE beginnings of modern science, one of its most important and exciting goals in the quest to understand nature has been to identify and describe the fundamental forces. Over the years, four such forces have been established. Three of these have long been "understood," at least at a working level, in terms of well-defined theoretical structures: the gravitational force (17th century), the electromagnetic force (19th century), and the weak force (1930s). In the late 1960s, a great advance in our understanding was made when the theoretical descriptions of the electromagnetic and weak forces were unified into a single theory. And even more recently — in the 1970s — a likely candidate for a theory of the fourth fundamental force, the strong interaction, has finally arisen. The long time between the realization in the 1930s that such a strong force existed and the recent development of a theory to describe it was certainly not because this force is of little consequence in nature. In fact, the strong force is responsible for holding the neutrons and protons together inside the atomic nucleus, and so, in some sense at least, it governs the basic structure of all ordinary matter. A group of people from Caltech (the authors, Research Fellow Peter Ratoff, and graduate students Richard Partridge and Charles Edwards), together with collaborators from other universities, are working to increase our understanding of the strong force by doing experiments with an apparatus called the "Crystal Ball."

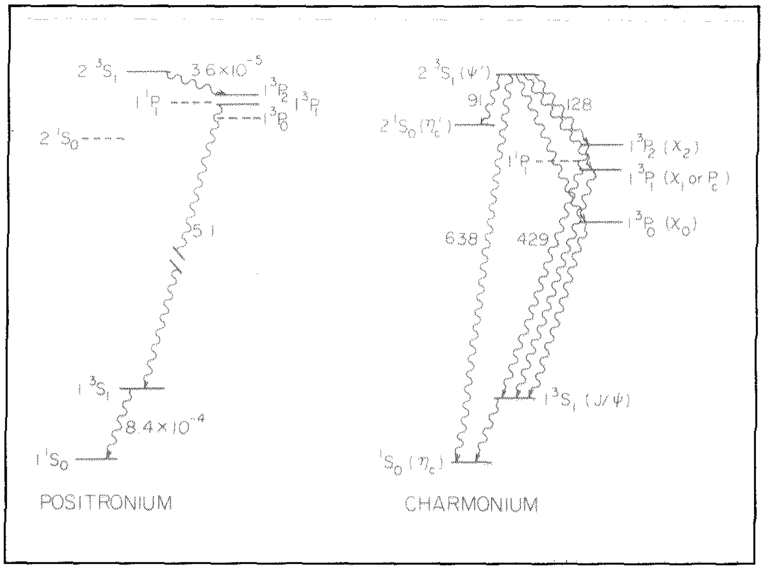
Given its fundamental character, you might reasonably ask why an understanding of the strong force has been so elusive. Perhaps the chief reason has been the difficulty of probing the interaction experimentally in clear-cut ways. Efforts to investigate the short-range phenomena of the strong force by ever higher energy probes simply yielded a bewildering array of new particles. The idea invented by theoretical physicists Murray Gell-Mann and George Zweig of Caltech that strongly interacting particles (called hadrons) are made of more fundamental particles (called quarks) is now well accepted, and it has been found possible to interpret much of the experimental data by assuming that all particles observed before 1974 are composed of various combinations of just three types of quarks (and the corresponding antiquarks). An attractive way to study the strong force is thus to examine how it holds the quarks together inside the hadrons. Until 1974, however, the only hadrons we knew about were made of these three types of quarks only, and it turns out that these three quarks have relatively low masses. Because of this, they typically move about inside a hadron at relativistic speeds (that is, approaching the speed of light) and, to complicate matters even more, they are bound with energies comparable to their own masses. The resulting complexities tended to obscure the underlying fundamental physics, although it was possible to make a few very powerful observations, such as the apparent impossibility of separating two quarks very far without creating new quarks in between.

It was thus a cause for great excitement when, in November of 1974 (the "November revolution"), a new kind of quark (the fourth) was discovered. This new quark was dubbed "charmed," and deemed to carry a new attribute called "charm" in the often fanciful nomenclature of high energy particle physics. One of the things that make this new quark so special is that it is heavy — with an apparent mass of about one and a half times the mass of a hydrogen atom. In fact, what was discovered was not quite the quark itself but rather a particle (called J/ψ) made of the charmed quark bound together by the strong force with its antiparticle, the charmed antiquark. Because these quarks are so heavy, their motion inside the J/ψ is relatively slow, and the binding energy is reasonably small compared to the quark mass. Hence, it was immediately clear that we here had a chance to study the strong force, which holds the two quarks together, in a setting that avoided many of the overwhelming complexities of the earlier known particles.

This nonrelativistic bound system of a charmed quark and its antiparticle was quickly dubbed "charmonium," in analogy with "positronium," the bound system made of a positron and its antiparticle, the electron. The analogy can actually be carried much further; just as in positronium, a whole set of energy levels of charmonium bound states should exist, according to the different possible orientations of the quark spins, their relative angular momentum, and their average separation. Because the quark and the electron have the same spin, the smallest nonzero amount allowed by quantum mechanics, there is a one-to-one correspondence between the energy levels expected in the two systems.

There is, however, a fundamental difference between positronium and charmonium, and this difference is one of the reasons charmonium is so interesting. In positronium, the positron and the electron are bound together by the well-known electromagnetic force, whereas charmonium is held together by the quite different and poorly known strong force. It is of profound significance that the same rules of angular momentum seem to apply to both systems, giving them analogous energy levels. Nonetheless, positronium and charmonium are very different systems — an "atom" of positronium has a size comparable to that of ordinary atoms (also bound by the electromagnetic force), roughly one angstrom, while a charmonium "atom" is approximately a hundred thousand times smaller. Most of this difference can be understood as a consequence of the fact that the charmed quark is 3000 times more massive than the electron, but a factor of perhaps 50 remains on account of the different strengths of the forces.

This is, of course, not the whole story — the strong and electromagnetic forces differ not only in strength but, as one might guess, in form as well. Thus, the popular new theory of the strong interaction — called Quantum Chromodynamics, or just QCD — predicts a different dependence of the force on the distance between two quarks than that which the theory of the electromagnetic interaction — Quantum Electrodynamics, or QED — predicts for two electrons. This difference manifests itself very nicely in a comparison of the energy levels (masses) of the excited states of the charmonium and positronium systems, since the relative positions of the energy levels depend on the details of the binding force. For example, in positronium the lowest state with one unit of orbital angular momentum (1P state) has very nearly the same mass as the 2S state, which has no orbital angular momentum, but is excited from the ground state by virtue of having a larger average size.



In this comparison of the energy level structure in positronium, an electron-antielectron "atom," and charmonium, a quark-antiquark "atom," each observed energy state is shown as a solid horizontal line with more massive states shown higher in the diagram. States that are thought to exist but have so far never been observed are shown as dashed lines. For charmonium, the various states have been given conventional names (J/ψ, ψ′, η_c, and so on), but that practice was never adopted by people studying positronium or atomic systems; they used only the "spectroscopic" notation, such as 1^3S_1, which is also applicable to charmonium. The wiggly lines connecting states show the photon transitions that have been experimentally observed, and the number beside the transition line gives the photon's energy. For positronium, the energy units are in electron-volts and for charmonium, in millions of electron-volts. The astonishing structural similarity of these two energy level diagrams is strong qualitative evidence for the quark-antiquark interpretation of the several charmonium particles.

On the other hand, comparison of the corresponding states in charmonium shows a much larger splitting between the 1P and 2S levels. Qualitatively, the difference can be understood in terms of the fact that the strong force becomes relatively stronger at large distance than the corresponding QED force law. For electromagnetism, the dominant part of the force was discovered by Coulomb, and it is well known to decrease as the square of the distance, r, between two charged particles. However, for the strong force under these circumstances, the main part seems to be approximately, $F_{\text{strong}} = A + B/r^2$, where A and B are constants. The two terms are equal at a distance of about 0.5×10^{-13} cm, and the position-independent part, A, has a value of about 10 tons. The strong force is strong indeed. Thus, since the 2S state is larger than the 1P state, the 2S state will have correspondingly higher mass (that is, energy) than the 1P state in charmonium. More quantitative predictions must include the fact that the quarks in charmonium are in fact moving rather quickly (about 45 percent of the speed of light), and hence there are significant relativistic corrections. The details of the level spacings also depend on the nature of the spin-dependent and orbital angular momentum-dependent components of the force. Thus, studying the level spacings (that is, the mass spectrum) in the charmonium system serves as a very convenient probe into the nature of the strong force.

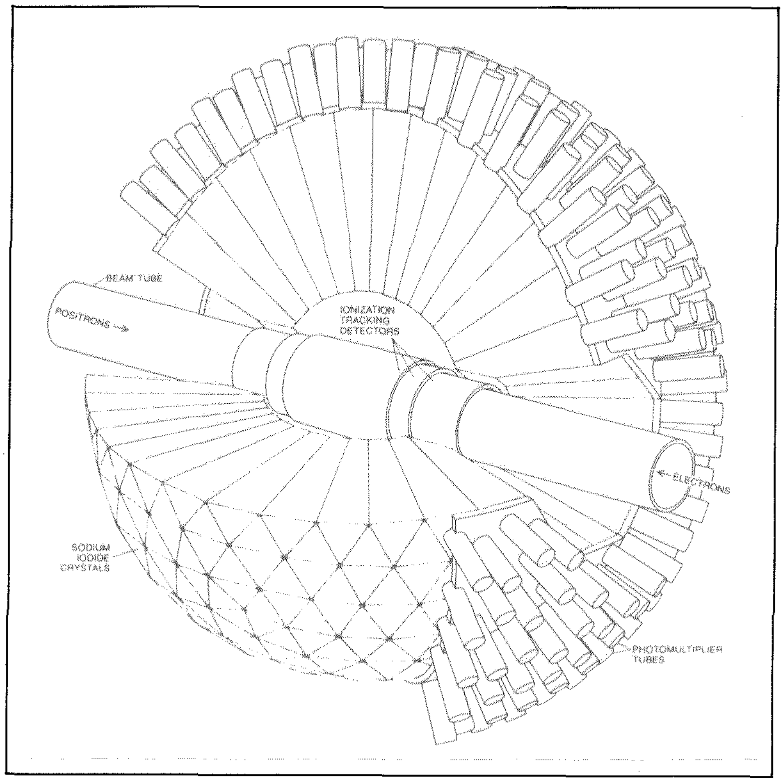
It turns out that we can study the charmonium energy levels experimentally in a way reminiscent of atomic (and positronium) spectroscopy. First, make an excited state of the system, or "atom," under study. Then, watch it decay into a less excited state via the emission of a photon (a quantum of electromagnetic radiation, or "light"). Finally, measure the energy of the photon (that is, its "color"), and this gives the spacing between the energy levels.

In atomic spectroscopy, we might create the excited states with an electric discharre in a gas of the atoms under study. The ubiquitous neon lights, mercury vapor lamps, and sodium vapor street lights are common examples of this. Typically, the decay photons in atomic systems have energies in the visible light region, and thus, their energies can be measured with an ordinary prism. For charmonium spectroscopy, the idea is similar, but the technique is quite different. First, an "atom" of charmonium lives much too short a life (roughly 10^{-20} seconds) for anyone to be able to collect many of them as a gas. We can, however, create certain of the charmonium states (such as the 1S J/ψ and the 2S ψ') one at a time by colliding an electron and a position together at just the right energy. When the e^+ and e^- annihilate at just this right energy, there is a high probability that a charmed quark and a charmed antiquark will be created in a charmonium state. Second, the energy levels in charmonium are separated by many millions of electron volts, instead of the one or two electron volts typical of ordinary atoms. Thus, a simple prism is no longer a suitable device for measuring the energy of the decay photons from charmonium. And this brings us to the Crystal Ball apparatus.

By design, the Crystal Ball detector is a device uniquely suited to the detection and measurement of photons from the decays of charmonium states. It is basically a spherical shell of crystalline sodium iodide (hence, the name) used to measure a high-energy photon's energy and direction. When a high-energy photon enters such a crystal, it interacts with an atomic nucleus in the crystal, typically producing an electron-positron pair. This pair then interacts with further atoms to produce, after a few successive generations of such processes, an elaborate "shower" of electrons, positrons, and photons. Ultimately, the particles in the shower lose their energy to the crystal atoms by ionizing or otherwise exciting them. Finally, some of the atoms de-excite by the emission of light in the visible region. Since the crystal is transparent to this visible light, it can be collected and the amount measured by a photomultiplier tube attached to the crystal. Surprisingly, this involved process is actually a very efficient means of measuring the energy of the initial high-energy photon. At the time this detector was conceived, sodium iodide was the optimal material for this purpose.

Developed by a collaboration of physicists from Caltech, Harvard, Princeton, Stanford (High Energy Physics Laboratory), and the Stanford Linear Accelerator Center (SLAC), the Crystal Ball consists of an array of 672 sodium iodide crystals. Each crystal has the shape of a truncated, triangular pyramid arranged with its small end pointing toward the center of the sphere. A photomultiplier tube views its large end, one per crystal. In general, the "shower" from a single photon spreads out into several of these pyramids. Thus the energy of a photon is determined by the sizes of the signals from the several photomultipliers involved, and its direction, by the location of the struck crystals. An electron beam and a positron beam enter the sphere from opposite directions through regions cut out for this purpose and collide at the center. Occasionally, an electron and a positron will annihilate to form, say, a

High energy electrons and positrons collide and annihilate each other at the center of the Crystal Ball, as can be seen in this schematic cutaway diagram of its principal components. The products of the annihilation fly off in all directions. Those that are charged leave tracks in the three cylindrical ionization detectors surrounding the collision point. From the electrical signals produced by the ionization detector, the path of the charged particles can be deduced. The Ball itself consists of a close packing of truncated prisms of sodium iodide with a triangular cross section. When a high energy photon, such as from charmonium decay, hits the Ball, it deposits most of its energy in one or two prisms, but a significant amount spills out into about twelve adjacent ones. A constant fraction of this deposited energy is converted to visible light, which is detected and the amount measured by the photomultiplier tubes.



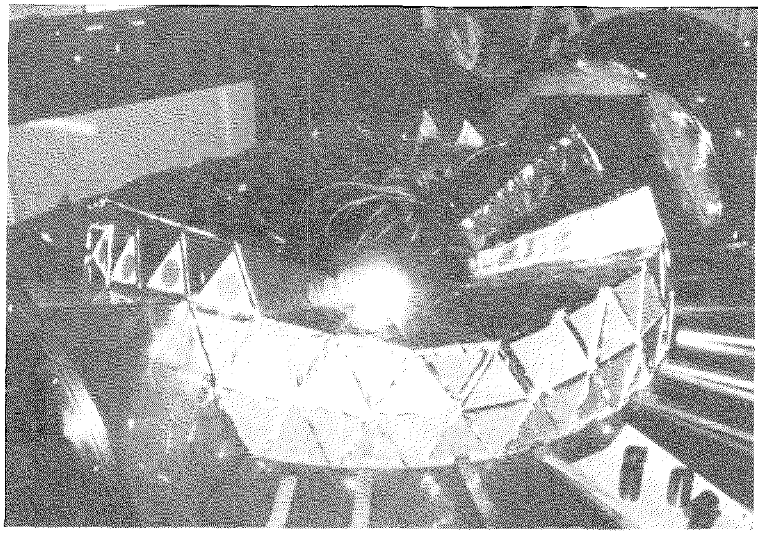
ψ′ (2S charmonium state). The ψ′ decays almost immediately, and the decay products are then detected in the Crystal Ball.

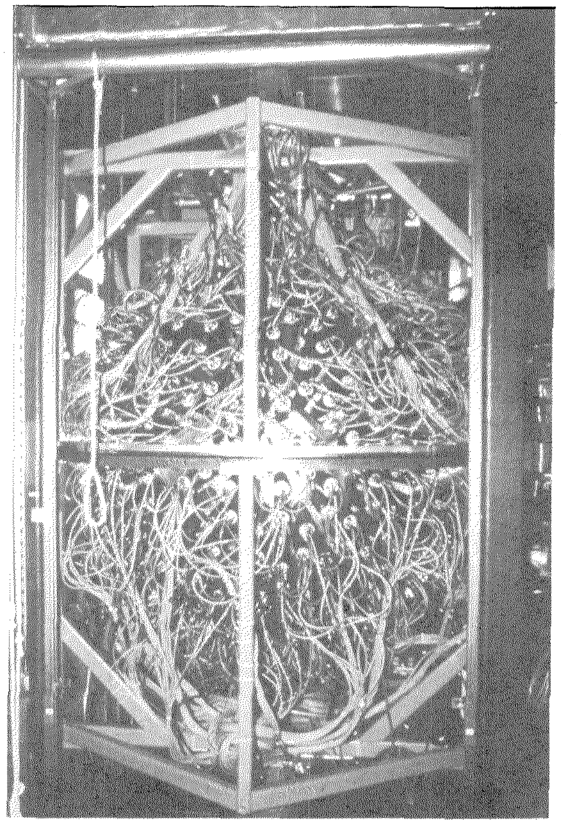
Although simple in concept, the construction of the Crystal Ball was actually a rather delicate and time-consuming enterprise. It was fabricated at the Harshaw Chemical Company in Cleveland, where each of the 16″-long crystals had to be precisely machined to the proper geometric shape from Harshaw's special, mechanically rugged brand of sodium iodide. An annoying complication is that sodium iodide is extremely hygroscopic, and a crystal of it is quickly ruined by even the smallest amount of water in ordinary air. Thus, the crystals must be continuously protected from the atmosphere, and after a certain point in their manufacture, all of the work on them had to be done in special, extremely dry rooms. Following machining, and further adjustments to tune optical properties, each crystal was wrapped with reflective material and carefully positioned in a hemispherical array. Once completely stacked, each of the two hemispherical arrays was hermetically sealed inside an aluminum and stainless steel container for mechanical support and protection from the atmosphere. At the large end of each crystal, a glass window was cemented over a hole in the container to allow the light to get to a photomultiplier mounted outside the shell. This part of the project, the construction of the Ball itself, cost about one million dollars.

Two trips by truck brought the hemispheres to the Stanford Linear Accelerator Center, one in the fall of 1977, and the other in the spring of 1978. The trucks were specially equipped to ensure that no ordinary wet air could get near the hemisphere, so that, even if its hermetic seal happened to be broken by vibration or bumpy roads, the sodium iodide would not be damaged. Needless to say, a physicist was in nervous attendance at monitoring equipment during the whole of both trips. The summer of 1978 saw much feverish activity by an excited group of physicists, students, engineers, and technicians as the Crystal Ball experiment was installed at the SPEAR (for Stanford Positron Electron Asymmetric Ring) e^+e^- colliding beam accelerator ring at SLAC. In the fall of 1978, the accelerator was turned on, and we began to take our first data with the new detector which had been three years in the building.

Before information collected with an apparatus — the raw data — can be converted into interesting results about nature — the "physics" — there is still a lot that must be done. The raw data, which are collected onto magnetic tapes, are processed through sophisticated computer programs to interpret the electrical signals measured by the apparatus as energies and directions of photons and other particles. The results of this analysis are written on additional tapes, which are then studied in great detail to extract the physically interesting quantities. To set the scale of this effort, since 1978 we have written a few thousand tapes and have used many hundreds of hours of time on large, fast computers.

Our first goal in the study of charmonium spectroscopy was to actually find all the various states that were predicted to exist. Some of these had





The photograph above shows the Crystal Ball at an early stage of its stacking before encapsulation. The small end of each triangular prism rests against a thin metal spherical dome of 20″ diameter to which thin cables are fixed, as can be seen. The large triangular end of most of the crystals has not yet been covered with the endpiece containing a circular hole, which is visible on a few of them. When the outer spherical shell was finally installed, the thin cables were fixed to it and radially tensioned. They function mechanically like the spokes of a bicycle wheel, giving the completed structure rigidity and stability. The outside diameter of the outer shell is about 56″.

At left the two hemispheres of the Crystal Ball are closed over the beam pipe, fully instrumented with its phototubes and a powerful lot of cables.

already been found in other experiments (with relatively crude photon-detection capabilities) before the existence of the Crystal Ball. But the situation when the Crystal Ball experiment began was actually very confused. Evidence had been reported in the literature for three states that fit very badly with the expectations of the theory. If these observations were correct, something was very wrong with our understanding of charmonium. The first triumph of the Crystal Ball was to rescue the theory from this dilemma by showing that all three of these earlier observations were incorrect.

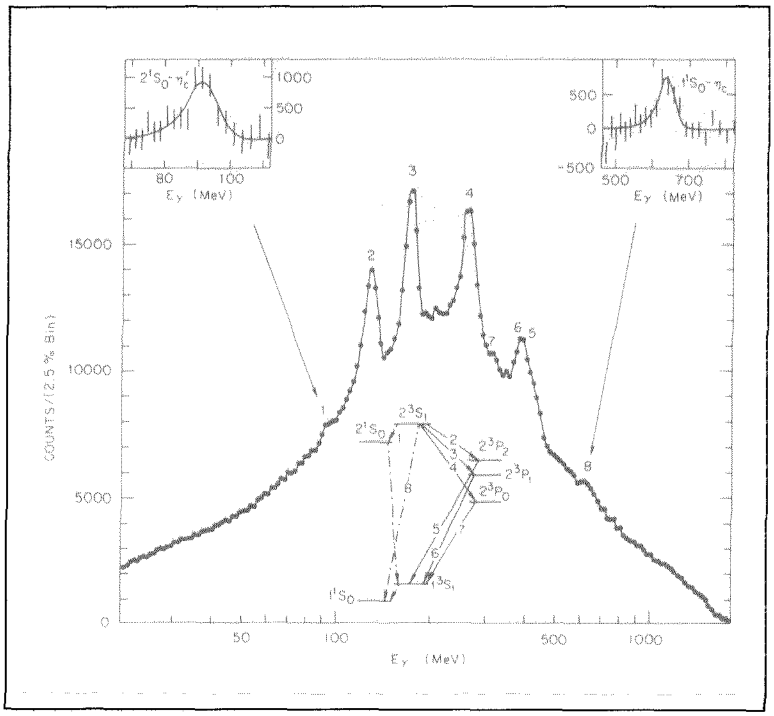
Having eliminated the early contenders, we set about to find some of the as-yet-unobserved states, notably the 1^1S_0 and 2^1S_0 states. These differ from the corresponding $^3S_1$ states by having the quark spins aligned so as to cancel, rather than to add. The most fruitful approach for this turned out to be the one suggested earlier by analogy with atomic spectroscopy: simply looking at the energy distribution of the photons emitted in decays of an excited charmonium state (the 2^3S_1, or ψ' state). Most of these photons result from secondary decays of hadrons, which come from the primary charmonium decay, and no particular photon energy is especially favored. Direct radiative transitions to other charmonium states, however, yield photons of a unique energy (they are monochromatic), and these should appear as peaks, or "lines," in this spectrum. Indeed, we do observe several such lines. The most prominent are due to transitions involving the previously discovered 1^3P_0, 1^3P_1, and 1^3P_2 states; but careful analysis revealed two other signals in this spectrum, corresponding to transitions from the ψ' to the 2^1S_0 and 1^1S_0 states of charmonium. Note that the $^1S_0$ state is actually the ground state of charmonium — we knew a lot about several excited states before we had even proved the ground state really existed.

The predictions of the QCD theory of the strong force, with some assumptions for things that no one yet knows how to calculate in the theory, agree rather nicely with the experimental observations of charmonium. All of the expected states exist at the expected places and have the expected properties. All, that is, except for one state that has not been observed yet. It is thought, however, that this is only an experimental difficulty. The missing state is the 1^1P_1, which, because of its quantum numbers, cannot be reached from the ψ' via a single photon transition. We have searched for this state by looking for transitions involving the emission of *two* photons, which is allowed, but so far we have been unsuccessful.

So, in less than a decade since its discovery, charmonium has provided us with an important laboratory for the study of the strong force. So far, the favorite theory for the force, QCD, has come through unscathed. Where do we go from here? Certainly, the study of charmonium is far from over, but it does have its limitations. Corrections for the fact that the quark motion is not really very slow complicates comparison with theory at a detailed level. Further complications arise from the size of the charmonium "atom"; it is just too big. QCD calculations get easier for smaller systems, and, although it is useful to have systems of all sizes so that the force may be probed over different distances, the smaller the size of a system, the more reliable the QCD prediction.

It just so happens that a new kind of quark-antiquark system was discovered in 1977. For no particular reason except whimsy, the new quark, the fifth known, is called "beauty" or, with only slightly more motivation, "bottom." (To the more prosaic, it is simply the b-quark.) The beauty quark is roughly three times heavier than the charmed quark, so the corresponding "beautiful atom" should be less relativistic and even smaller in size than charmonium. Naturally, having a device well suited to studying such systems, the Crystal Ball experimenters were eager to take data on beauty in addition to charm, and serious preparation for this option began in 1981.

Because the beauty quark is three times more massive than the charmed quark, an accelerator



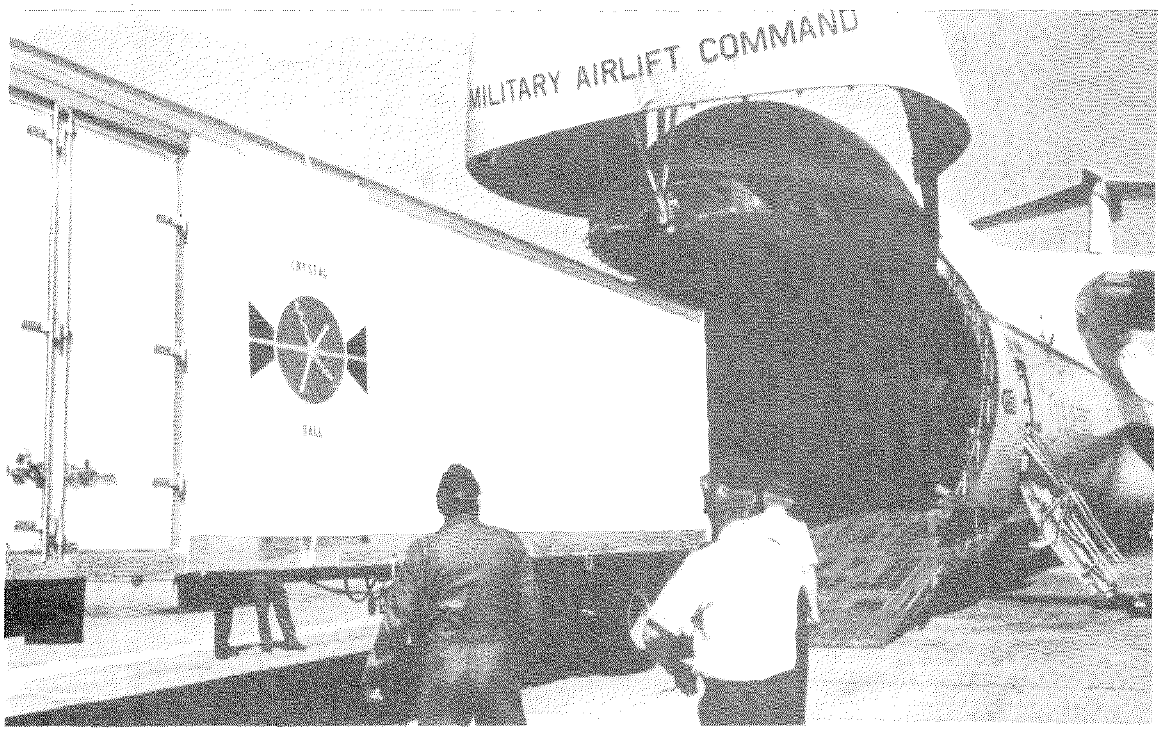
This diagram shows the spectrum of energy E_γ of photons resulting from the decay of the ψ' particle, the 2^3S_1 state of charmonium. Most of the photons in this distribution come from the secondary decays of hadrons produced in the primary decay of the ψ', and, in particular, from the sequence $\psi' \to \pi^0 + ... \to \gamma\gamma + ...$ Monochromatic photons arising from a decay like $\psi' \to \gamma + X$, where X has a definite mass, appear in this spectrum as an accumulation of events near a particular energy. Examples are numbered 1, 2, 3, 4, 8, and these refer to the correspondingly numbered transitions in the inset energy level diagram. The single peak labeled 5, 6 actually arises from two overlapping transitions; we see only inconclusive evidence for the transition labeled 7 in this spectrum. The Crystal Ball experiment was the first to see the lines numbered 1 and 8 and this observation constituted the discovery of the two states 2^1S_0 and 1^1S_0. The insets show the data near these two energies with superimposed curves showing what the instrumental response would be to monochromatic photons. The agreement of the data with these curves is important evidence that the accumulation of events near these energies is not just a statistical accident.

with three times the energy is needed to produce it. Unfortunately, the SPEAR accelerator at SLAC cannot attain the required energy, and so we had to look elsewhere. When an opportunity presented itself to do the experiment at the higher energy DORIS accelerator at the Deutsches Elektronen-Synchrotron (DESY) in Hamburg, Germany, we enthusiastically pursued it.

Needless to say, moving a complex and delicate apparatus halfway around the world required a substantial effort. The roomful of electronics presented no serious problems — we just put it in a trailer, drove it to the dock, and put it on a boat. But moving a large array of crystals — without cracking them or getting them even very slightly wet — was another matter. Considerable research and discussion went into choosing among various options — including assorted combinations of land, sea, and air delivery (submarines were mentioned only in jest). Finally, the decision was made to fly the array aboard an Air Force C5A cargo transport. This aircraft could easily handle the size and weight of our Crystal Ball, could maintain controlled pressure and temperature in the cargo hold, and could land softly. Thus, in April of 1982, the Crystal Ball was entrusted to the flying skill of the U.S. Air Force who took it uneventfully (except for a scheduled in-flight refueling) to a base near Frankfurt, Germany. A small band of physicists, including Caltech graduate student Charles Edwards, went along for the ride as babysitters to the apparatus.

While the trip from California to Germany went like clockwork, the drive from Frankfurt to the accelerator in Hamburg did not. There are some pretty steep hills on the Autobahn between these cities, and the truck tractor turned out not to be up to the challenge; its engine blew up along the route. After some anxious and extended discussion in a mixture of broken German, English, and arm-waving, a new tractor was acquired, which finally took the experiment the rest of the way. Once again, a large group of people, now including collaborators from not only Germany but also the Netherlands, Italy, South Africa, and Poland, in addition to the United States, engaged in feverish activity to prepare the apparatus for the turn-on of the accelerator. We took our first "beautiful" data in August 1982, and are now busily working with our computers to analyze that data and produce "beautiful" physics.

Many things about the spectrum of energy levels of beautonium particles are now known, but we expect that many other things are yet to be discovered. Of course, fairly reliable predictions of many of these have been made by theorists using ideas from QCD. But physics is an *experimental* science, and experimental physicists are always on the lookout for new phenomena. We are always hopeful that the careful exploration of new ground with proven techniques will reward us with unexpected discoveries. The new ground is the energy range populated by beauty; the proven technique is the Crystal Ball. Together, we hope that they may lead to new insights into the nature of the strongest known force in the universe! □



As the trip to Hamburg, Germany, begins, the two hemispheres of the Crystal Ball sit carefully cushioned in a temperature-controlled, extremely low humidity compartment inside the trailer. The trailer was simply rolled into the gaping maw of the C5A and flown to Frankfurt, courtesy of the U.S. Air Force. Except for a mechanical breakdown on the Autobahn from Frankfurt to Hamburg, the trip was, happily, uneventful. After arrival in Hamburg in mid-April 1982, the fully operational Crystal Ball was again taking physics data three and a half months later.