PETRA and PEP: Two Machines Race to Probe the New Physics

Electron-positron colliding beam storage rings have been by far the most successful examples of a new philosophy in accelerator design: crashing two beams of elementary particles head-on into one

This is the first of two Research News articles on electron-positron storage rings and elementary particle physics.

another rather than bombarding a fixed target. They have been so fruitful, in fact, that two new machines, enlarged versions of the storage rings that ushered in the era of the "new physics" of quarks (the supposed constitutents of particles such as the proton, neutron, and pi meson) and leptons (including the electron, the muon, and the neutrinos), are, or soon will be, open for business.

The apparent winner in a "friendly" race to explore higher energies than heretofore available in storage rings is a 98-million-deutschmark ($52-million) machine named PETRA, which started operation last July at the Deutsches Elektronen-Synchrotron (DESY) laboratory in Hamburg. The second machine is a joint project of the Stanford Linear Accelerator Center (SLAC) and the Lawrence Berkeley Laboratory (LBL) called PEP, which is under construction at Stanford at a comparable cost and is planned to be operating by October of next year. DESY physicists are, however, in the midst of debugging their new machine, a process common to big new accelerators, and may not operate their machine at maximum performance for several more months.

The obvious way to find out what makes something tick is to break it apart into its constituent pieces. In the barest of terms, this is what high-energy physicists do when they slam protons and electrons into nuclei in accelerators. At the energies of today's machines, a complication arises due to the huge momentum of a particle accelerated to nearly the speed of light. Because the relativistic momentum must be conserved, most of the bombarding particle's energy is not effective in the collision but simply goes to accelerating the stationary target. To curb this inefficiency, physicists have increasingly gone to a new type of machine, the colliding beam storage ring. When two particles of equal mass and velocity crash head-on, all their energy is available for breaking them apart.

Electron-positron storage rings have an additional advantage over other accelerators in this endeavor. Because the electron and positron are antiparticles of each other, they are annihilated in the collision, creating, as physicists graphically describe it, a miniature fireball of pure energy. In the now conventional wisdom, after the shortest of instants, the fireball materializes into either a pair of quarks or a pair of leptons. Because of quantum mechanical selection rules, the pair must consist of a particle and its antiparticle, such as a negatively and a positively charged muon. The wisdom further dictates that "free" quarks do not exist; therefore, if a pair of quarks forms from the fireball, after another exceptionally brief moment, they transform into protons, neutrons, pi mesons, and other particles of the same class called hadrons. In every case, Einstein's famous $E = mc^2$ is obeyed, so that the sum of the rest masses of all particles created must not exceed the sum of the electron and positron energies in the storage ring. Electron-positron storage rings are thus an efficient way of creating new elementary particles from high-energy collisons. And because of the simple quark-antiquark starting state, the particles are not embedded in the confusing array of debris that accompanies events in other types of accelerators.

How to Make a Particle

New particles manifest themselves in two ways. The first is called a resonance and occurs when the electron and positron energies exactly match the mass of the new entity. When this match is achieved, the probability of the fireball materializing into the new particle in preference to any other combination of particles dramatically increases. The signal that the new particle was produced is a much increased rate of production of lower mass particles that form when the new entity decays. It was in this way that the J/psi particle, an exceptionally massive and long-lived meson whose discovery was such a turning point in the new physics that its discoverers received Nobel prizes, was found at SLAC. (The J/psi was simultaneously found by researchers at Brookhaven National Laboratory in a different type of experiment.)

The second method of producing new particles is called a threshold process. If a resonance is somewhat analogous to the transition induced between two quantum states of an atom by the absorption of light, then a threshold corresponds to ionizing the atom. At any energy above the threshold, new particles appear in pairs, and these can carry away, as kinetic energy, the energy beyond that needed to create them. The signal for a threshold process is an increase in the number of ordinary particles detected when the new ones decay, but the effect is generally less dramatic than a resonance.

Physicists can precisely tune the energy of the storage ring and in this way study in detail the properties of the new particles created. A disadvantage is that electrons and positrons, being pointlike particles with no spatial extent, do not collide very often, and it is a slow, painstaking business to scan the energy range of the storage ring. These machines are thus most useful when experimenters have some notion of which energies to tune to, a point well illustrated by the J/psi particle. SLAC's electron-positron storage ring SPEAR was completed in April 1972, but the particle discovery came in November 1974.

SPEAR was the brainchild of Burton Richter of SLAC, who first proposed, in 1965, that such a machine be built. Funding was not forthcoming, however, for several years. Eventually a scaled-down version was found acceptable, and a storage ring was built in the remarkably short time of 21 months and at the low cost of $5.3 million.

While Richter was busy looking for a way to get his machine funded, European physicists had previously caught on to the virtues of colliding beam storage rings. The first large electron-positron machine was, in fact, built in Italy. Jumping into the game somewhat later were German physicists from DESY, who were able to construct and put into operation by mid-1974 an electron-positron storage ring similar in complexity to the one Richter had originally proposed. In this way, what has become one of the great rivalries in physics came into being. (Officials at both accelerator centers emphasize, however, that competition does not preclude cooperation. Thus, there is constant sharing of technical information concerning machine operation, although naturally not detailed plans for experiments.)

Although the group at Brookhaven un-

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der Samuel Ting of the Massachusetts Institute of Technology (MIT) found the J/psi particle at the same time as the SLAC collaboration (which included physicists from LBL and a second Stanford group in addition to Richter's team), the majority of further studies of the J/psi and the many subsequently found particles related to it depended on two positron-electron storage rings: SPEAR and the German machine DORIS. The two new storage rings, PEP and PETRA, will continue the competition, but this time it will be DESY that has the head start.

Behind this turnabout lies the differing responses of the German and American governments to the economic recession of 1974, when both projects were initially put forth (*Science*, 19 December 1975, p. 1179). Whereas the West Germans were looking for ways to stimulate a sagging economy with infusions of money, the U.S. administration was retrenching. Thus, the DESY project was approved approximately a year ahead of its American counterpart. Moreover, in starting construction, DESY had an even earlier head start because of different bureaucratic procedures in the two countries.

Writing in the CERN *Courier*, the unofficial news magazine of international particle physics, Gustav-Adolf Voss, director of the PETRA project, noted that completion of the storage ring came 9 months ahead of the original schedule of $3^1/_2$ years with no cost overruns. According to the director of the PEP project, John Rees of SLAC, a similarly rapid construction pace is being experienced there, leaving about a year to go before beam turn-on time.

Both machines will have nearly identical performance specifications, and both are more like SPEAR than like DORIS. A storage ring consists of a circular tube evacuated to better than 10^{-8} torr through which electrically charged particles travel at high velocities approaching the speed of light. Magnets surrounding the tube confine the particles to a circular path (Fig. 1). Radio-frequency power sources (klystrons) replenish energy lost by the particles because of synchrotron radiation and other factors during each cycle (Fig. 2). Since electrons and positrons have identical masses but opposite electrical charges, they can be stored simultaneously in the same ring as counterrotating electron and positron beams. By confining the electrons and positrons to small "bunches" that travel around the ring, physicists can control where collisions take place in the ring. With one electron and one positron bunch, for example, collisions occur twice during each revolution, on opposite sides of the ring. DORIS consists of two separate rings that intersect in two places. (In this way, DESY physicists could, but so far have not, study electron-electron or positron-positron collisions, as well as those between electrons and positrons.) PETRA and PEP are single-ring machines.

The two new storage rings are improvements on SPEAR and DORIS because they will store electron and positron beams at much higher energies, thus permitting the creation of much more massive particles than heretofore possible. Just as important, certain questions that theorists would like answered regarding the forces by which elementary particles interact require the study of higher-energy collisions. Whereas the older storage rings could reach energies of 4 and 5 GeV per beam, respectively, the new rings will be able to stretch to 18

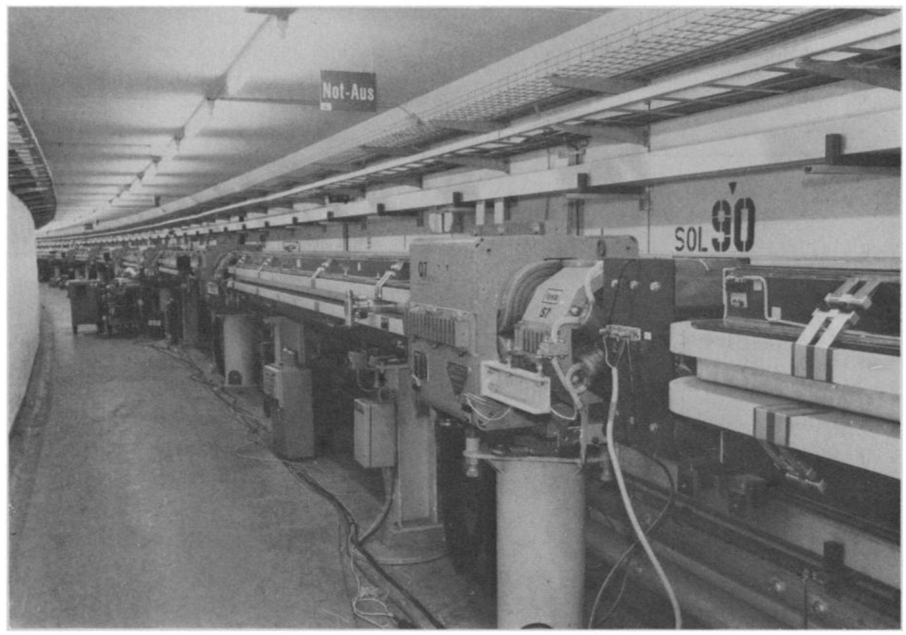

Fig. 1. Portion of the PETRA electron-positron storage ring. Visible are three types of magnets. The long, flat structure in the left-center is a dipole magnet that bends the electrons and positrons into their curved path around the ring. The devices in the right-center labeled Q7 and S7 are quadropole and sextapole magnets that keep the electrons and positrons "focused" in a beam with a small cross section. Altogether there are more than 700 such magnets that consume a total of up to 4 megawatts of power. [Source: DESY]

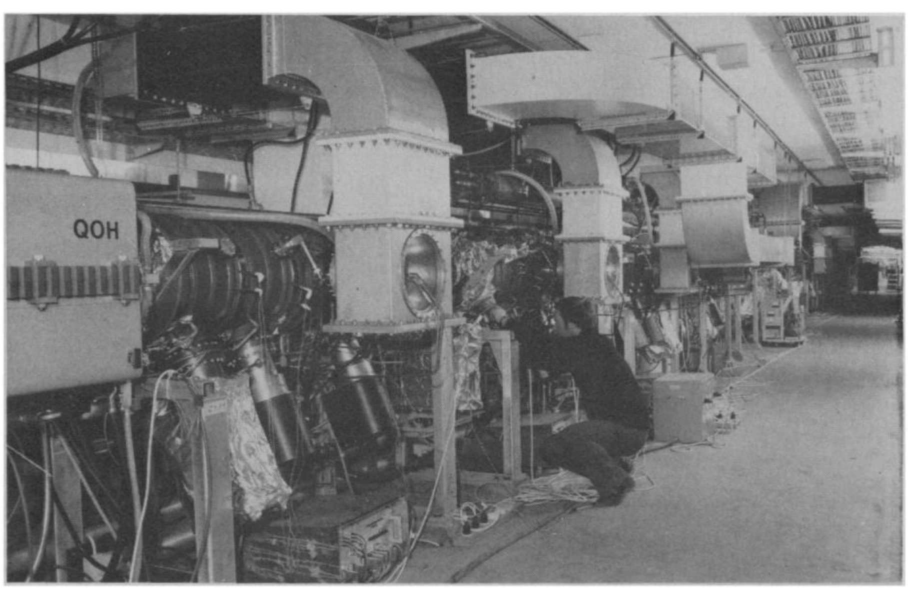

Fig. 2. A straight section of the PETRA storage ring showing the radio-frequency cavities that transmit power generated by the klystrons to the electrons and positrons. The structures resembling furnace ducts are waveguides by which the radio-frequency power reaches the cavities from the klystrons, which are located elsewhere. A total of eight klystrons will provide a maximum of 4 megawatts to the electron and positron beams. [Source: DESY]

and 19 GeV per beam. For perspective, the J/psi particle mass is about 3.1 GeV, requiring 1.55 GeV per beam in a storage ring. A recently discovered particle, the upsilon, is similar to the J/psi but which contains a heavier quark has a mass of almost 9.5 GeV, just reachable by DORIS. And some theorists speculate that a third particle with an even heavier quark in it may have a mass near 30 GeV, accessible by PETRA and PEP.

Among other details, PETRA is octagonal in shape with a circumference of 2.3 kilometers. Although there are eight possible beam intersection regions, only four will be used at first, and two others will be activated if the "physics" looks interesting enough. PEP is hexagonal, with a slightly smaller circumference of 2.2 kilometers. Five of its six intersection regions are scheduled for major experiments. If either machine ever is operated at the maximum beam energy, the total electrical power consumed will be about 15 to 20 megawatts, which is about that needed for a town of 20,000 inhabitants.

Both machines will receive electrons and positrons from accelerators already existing on site, but there is a significant difference in how this is accomplished in the two rings. SLAC has the advantage of its 2-mile-long linear electron accelerator, which is capable of injecting both electrons and positrons into PEP at any energy that the storage ring can handle. DESY has a 7.5-GeV electron synchrotron that, in combination with other machines also located at the laboratory, squirts these particles into PETRA. Thus, PETRA must be able to accelerate both electrons and positrons to the operating energy, as well as to store the particles.

Carrying out the ambitious experimental program planned for the new storage rings is well beyond the capability of the in-house staff of the institutions respon-

Successful Transplant of a Functioning Mammalian Gene

Someday, perhaps, advances in recombinant DNA research will be so commonplace that they are no longer news. That day has not yet arrived, however. The latest development to attract attention in the press is the successful transplant of a rabbit gene into monkey cells, which was achieved by Paul Berg and his colleagues, Richard Mulligan and Bruce Howard, at Stanford University.

The DNA segment they transplanted codes for one of the polypeptide chains (called the β chain) comprising hemoglobin, the oxygen-carrying protein of red blood cells. All mammals (and birds) produce hemoglobin, but the structures of the molecules differ somewhat from species to species. As a result of the gene transfer, the monkey cells began producing the rabbit form of the β chain.

The experiment became public as a result of remarks Berg made in response to reporters' questions at a press conference preceding his address on recombinant DNA research to the clinical congress of the American College of Surgeons on October 18. Berg thought he had made it clear that his comments on the ongoing research in his laboratory were off the record, but they were reported in several newspapers.

Although the investigator is unwilling to describe the details of the gene transfer because they have not yet been published in a scientific journal, he confirms that the transfer was accomplished by inserting the rabbit gene into the DNA of the virus SV-40 to form a recombinant molecule. Berg and his colleagues then infected a cultured line of African green monkey cells with the altered virus, which is able to take over the cell's synthetic machinery to make viral nucleic acids and proteins, including, in this case, the rabbit hemoglobin chain. The monkey cells, which are derived from the kidney, do not ordinarily produce hemoglobin and certainly do not produce rabbit hemoglobin.

Introduction of the functioning rabbit gene into monkey cells is another accomplishment in a series of successful transplants of mammalian genes into cells of other species. For example, within the last year or so, investigators have transferred genes for the mammalian hormones insulin and somatostatin into bacterial cells which consequently acquired the ability to produce the hormones.

But the current development is the first example of the use of recombinant DNA technology to transfer a functioning gene from one mammalian species to another, although it is not the first time this feat ever has been accomplished. About 5 years ago, O. Wesley McBride of the National Cancer Institute and Harvey Ozer, now at the Worcester Foundation for Experimental Biology, showed that mouse cells, when incubated with chromosomes from hamster cells, acquired the ability to synthesize a hamster enzyme. Presumably the hamster gene entered the mouse cells on a piece of chromosome. Several investigators are now using chromosome-mediated gene transfer for genetic studies such as the mapping of gene arrangements on chromosomes. Moreover, formation of hybrids by fusing cells from two different species is a common technique that achieves a form of gene transfer. Recombinant methods have the advantage of being more specific, however; procedures are now available for isolating and copying individual genes for insertion into a suitable transfer vehicle, whereas selection of a particular gene for transfer by the other methods is more difficult.

An obvious implication of the Stanford work is that a similar procedure might one day be used for genetic engineering, such as the replacement of defective or missing genes. Sickle cell anemia, for example, is caused by the gene for the β chain of hemoglobin being defective. Because SV-40 causes tumors in some animals, although not in humans as far as is known, the virus would not be a suitable vehicle for gene replacement therapy. In fact, an early (1973) experiment in Berg's laboratory, which involved the insertion of a bacterial gene into SV-40, helped to alert investigators and ultimately the public to the possibility that production of recombinant DNA molecules might have hazardous as well as beneficial effects. Although no hazards have materialized, the guidelines for recombinant DNA research that were adopted by the National Institutes of Health require that experiments using SV-40 for the introduction of new genes into cultured mammalian cells be carried out in at least P3 laboratories. (P3 is the second highest level of physical containment specified by the guidelines.)

But, in any event, the gene transfer procedure developed at Stanford should greatly facilitate the study of such fundamental problems in molecular biology as the control of gene expression in mammalian cells.—J.L.M.

sible for building and operating the machines. Thus, as has been the case with large accelerators in the past, members of the experimental teams at PETRA and PEP will be drawn from many universities and research laboratories. DESY collaborations, for example, are truly international, being made up of other Europeans, Americans, Japanese, Chinese, and Israelis, in addition to the host Germans.

One role of these large research teams is that of designers and builders of the detectors that identify and measure the properties of the particles emanating from high-energy collisions. These instruments are mighty beasts in themselves, costing in some cases $10 million or more, and weighing, if much use is made of iron, several hundred to a few thousand tons. More than half of the $30 million that will be spent on the five detectors planned or already built for PETRA is coming from outside Germany.

Because electron-positron collisions are so rare (at PETRA and PEP collision energies, perhaps 150 collisions per hour will result in the production of hadrons, and only a few of these may be of interest for a given experiment), detectors are designed to collect as much information as possible for later analysis by computer. In this way of doing things, one group's experiment can consist of computer-searching data gathered by others for events of interest. Alternatively, it may take an experimental team months or years to completely search for new phenomena in data gathered in a short time.

Although the rate of interesting events is relatively low, the peculiarities of those selected for measurement place severe constraints on the design of detectors. At PETRA and PEP energies, physicists estimate, an average of 15 particles will be produced per electron-positron collision, half electrically charged and half neutral. Moreover, these will be distributed mainly in two "jets" that move away from the collision region in opposite directions (except at resonances), so that any detector will have to be able to sort out many closely spaced, rapidly moving particles. Unfortunately, the direction of the jets is different for each event in which they are produced, so the detector must also be sensitive to as much of the total 4π steradian solid angle as possible.*

PETRA and PEP most clearly diverge in the designs of their detectors. Although none of the detectors at DESY, for example, are identical, four of the five are large, powerful detectors that are expected to do a creditable job of identifying and measuring the properties of all particles produced in the storage ring. In part, say observers, this overlap in function may be one result of the very rapid construction pace in Hamburg, which pressured physicists preparing proposals for the competitive process by which experiments were selected to stick with all-inclusive designs.

The detectors at SLAC tend to be more complementary. While one detector is a general purpose instrument, a second is exceptionally good at distinguishing between electrons and charged pi mesons (a perennial problem), a third will track muons (which are difficult to tag because they penetrate through solid material easily), and a fourth will be able to measure particle momenta and masses with a high resolution. According to Pier Oddone of LBL and the PEP facilities coordinator, the diversity was partly the result of a two-stage selection process in which proposals submitted in the second phase tended to avoid duplication of successful first-stage bids. An additional reason for the diversity was an effort to avoid overlapping the PETRA detectors, which had been selected by then.

PETRA has just started operating with three detectors in place. The first, called

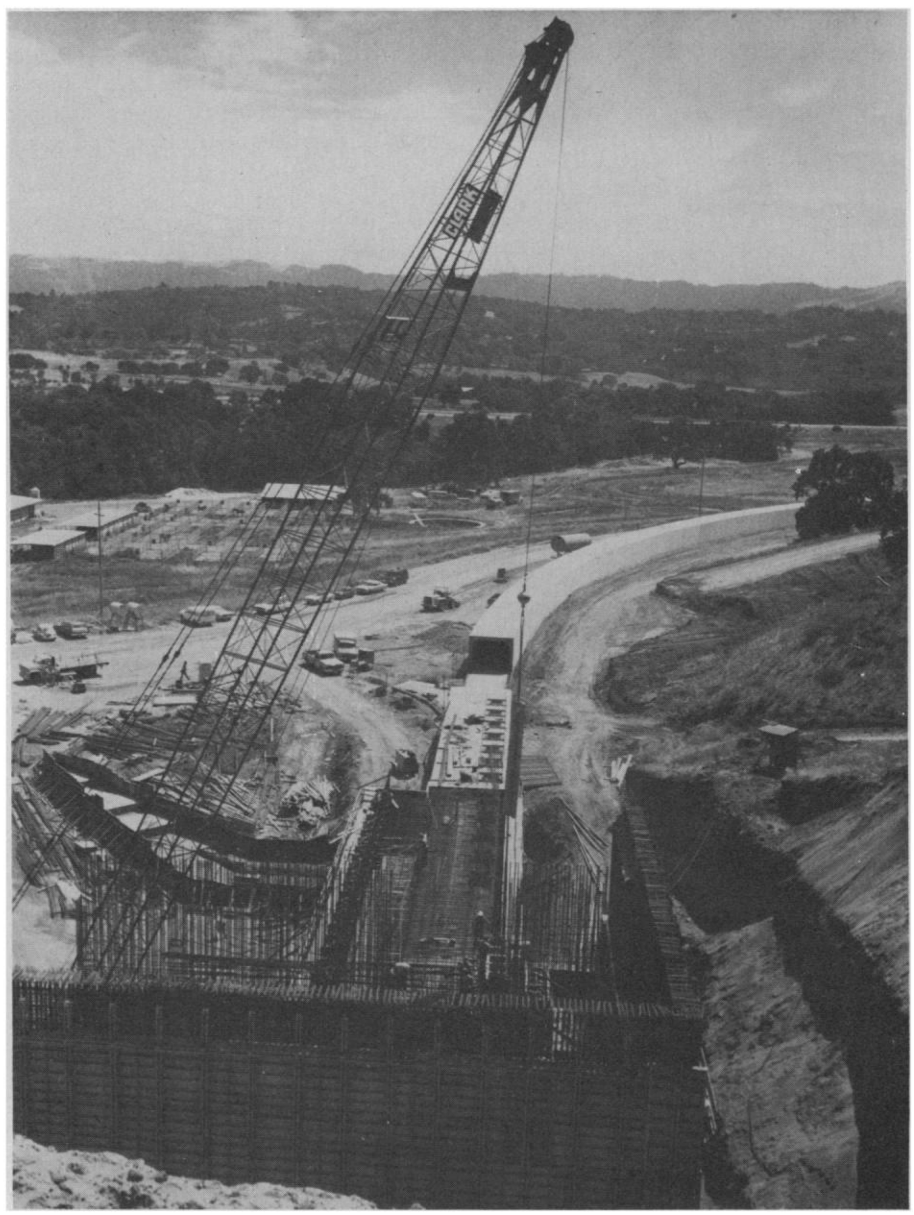

Fig. 3. PEP construction as of July at the Stanford Linear Accelerator Center. In the background is a portion of the concrete tunnel in which the storage ring will reside. In the foreground is one of the six experimental halls which will house the particle detectors. At present, more than 75 percent of the PEP beam tunnel is completed and workers are in the process of burying it under from 5 to 14 meters of dirt for protection from radiation and to restore the terrain to its original grade. The experimental halls will not be covered. [Source: SLAC]

*For a readable description of modern particle detectors, see *Physics Today* (October 1978).

PLUTO, is a thoroughly tested instrument, having been one of two detectors used on the DORIS storage ring. The two others will need several weeks or possibly months of debugging before being ready for full-time data taking. The fourth and fifth detectors are under construction and are expected to be in place by the coming spring.

PEP, coming on line a year behind PETRA, may get scooped on some major new discoveries (Fig. 3). Researchers at SLAC will have two already proven detectors (Mark II and DELCO) in place by the October 1979 opening date in addition to one all-new instrument that will need to be broken in. Three other new detectors will be ready about 6 months later.

A search for new elementary particles containing heavier quarks could be one of the earliest of findings of this type. With the experience of the J/psi in hand, physicists now believe that an increase in the ratio of the probability of producing hadrons to the probability of producing muon pairs is a signal of a new quark. Since an increase in this ratio is a threshold process, even if the resonance should be missed, observation of such an increase would tell experimenters to remeasure at lower, perhaps only cursorily scanned, energies. But, points out Wolfgang Panofsky, director of SLAC, other effects also can contribute to an increase in this ratio, thus requiring precision measurements. Even when a storage ring is operating at full performance, it takes hundreds of hours to gather data for one point on a high-precision energy scan.

Thus, given the necessity of breaking in PETRA and of debugging its new detectors, it could be some time, say observers, before results of experiments requiring such high-precision scans are forthcoming. At present, DESY physicists are experiencing difficulty in packing large numbers of electrons and positrons into their respective bunches, a problem that goes under the general heading of beam instability. Such problems have been encountered and solved in other machines in the past, and DESY's Voss emphasizes that PETRA is well within its planned timetable for storing high electron-position currents at high energies. Nonetheless, until beam instability effects are overcome, many types of experiments will not be possible.

Since beam instabilities are a fact of life in storage rings, physicists operating PEP may well run into similar difficulties in a year's time. If they are lucky and avoid such problems, or if they are able to incorporate directly the solutions that their German counterparts come up with, experimenters using PEP may not find themselves so far behind after all. In any case, all observers agree that there is more than enough "physics" for both machines to lead long and productive lives.—ARTHUR L. ROBINSON

Fields Medals (III): A Broad Attack on Analysis Problems

Charles Louis Fefferman was born on 19 April 1949 in Washington, D.C. His remarkable development was that of a child prodigy. At the age of 14 he entered college at the University of Maryland, where understanding professors guided his education. He went to graduate school at Princeton University, where he received the Ph.D. when he was 20 years old. At the age of 22 he became a full professor at the University of Chicago (the youngest full professor at a U.S. college), and a year later he moved to Princeton University, where he is now working. His outstanding achievements were recognized by a number of awards before he received the Fields Medal. In 1971 he received the Salem Prize and in 1976 the Waterman Award of the National Science Foundation.

Fefferman works on various aspects of analysis, such as harmonic analysis, partial differential equations, and several complex variables. These are relatively old subjects and the problems in these fields are notoriously complicated and difficult. One of Fefferman's major contributions is the solution of a problem in the theory of functions of several complex variables. In this theory, one studies mappings given by holomorphic (complex analytic) functions of several variables and asks which regions in the space of n complex variables can be mapped into each other—that is, are biholomorphically equivalent. In contrast to the situation in the theory of one complex variable, simply connected regions are generally not equivalent in two or more variables. For example, it has been known for a long time that the inside of a sphere $|z_1|^2 + |z_2|^2 < 1$ is not biholomorphically equivalent to a "bicylinder" $|z_1| < 1$, $|z_2| < 1$. In short, regions are much more "rigid" under biholomorphic mappings in two or more variables than they are in one variable. Usually one requires these regions to be "pseudoconvex."

Now it is natural to expect that a biholomorphic mapping that takes one such pseudoconvex region with a smooth boundary into another will also be smooth up to the boundary. This problem of the boundary smoothness is as basic as it is simple to state. Nevertheless, it is a very difficult problem on which several prominent mathematicians worked without success. This difficulty stems from the rigidity mentioned above which makes ineffective methods that are applicable to one complex variable. In 1974 Fefferman succeeded in proving the theorem on boundary smoothness. This makes it now possible to study the mapping on this boundary. His paper was a very difficult one, and various researchers have tried to simplify the proof, thus far without success. A number of papers have appeared in which Fefferman's theorem is used. Without question, this result is important to the theory of several complex variables.

Related to this work is a later discovery about the boundaries of such biholomorphically equivalent regions. By extending these odd-dimensional boundaries by one dimension, he was able to introduce an indefinite metric (Lorentz metric) that changes only by a factor under biholomorphic transformations. In particular, the null geodesics—the analogs of light rays in relativity theory—form an invariant set of curves on the boundary. These curves had been discovered before but by a completely different method. Thus Fefferman unexpectedly introduced the differential geometric concept of an indefinite metric into complex function theory. Many of these concepts are still so new that one cannot predict where they will lead.

Fefferman's earlier studies were with harmonic analysis, a subject that deals with questions related to Fourier integrals and Fourier series. Problems in this area are very delicate and difficult, and progress on them is correspondingly slow. For example, it was known for a very long time that even for continuous functions Fourier series need not converge everywhere. This led to the need for other convergence concepts, and every student of mathematics now learns that the Fourier series of a function which, when squared, is integrable (L^2 function) converges in the space of L^2 functions. This result was proved as early as 1907, but the question of wheth-

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