ground sufficiently with its surface array of photomultipliers, by ignoring events whose vertices lie in the outer two meters of water. This leaves them with a fiducial volume of about 5 kilotons of water. Information about vertex location comes from the size of the cone of Cerenkov light, which spreads as the light travels toward the detectors, and from the arrival time of the light.

Both groups have calculated that they can keep the unresolvable muon-induced background below 0.1 events per year. Their Monte-Carlo simulations further show that the ultimately irreducible background in detectors of this kind comes from the rare—but nonetheless unavoidable—interaction of cosmic-ray neutrinos with nucleons in the detector.

A random nucleon anywhere on or in the Earth interacts with a neutrino about once every 10^{31} years. And so it is with the water in the detectors. Most of the time the products of these weak interactions come out in configurations that are easily distinguished from nucleon decay. But Monte-Carlo simulations have led both groups to conclude that about one percent of the neutrino interactions that produce a Δ (1236) nucleon resonance end up in a back-to-back lepton-pion configuration that cannot be distinguished from a nucleon decay with the resolution of these detectors.

This then is the irredicible background that sets the practical upper limit on the size and sensitivity of detectors of this kind. For every 3×10^{33} nucleons (5 kilotons) one expects about one indistinguishable background event per year, generated by the ubiquitous flux of cosmic-ray neutrinos. The sensitivity of detectors with much fewer than 3×10^{33} nucleons is size-limited; the sensitivity increases linearly with volume. Above this size, the sensitivity is background limited and hence grows only as the square root of the volume.

On these grounds the I–M–B group has concluded that 5 kilotons is the optimal active-volume size for water-Cerenkov detectors. So that's what they have decided to build. In a detector of this size one would see about 150 decays a year (against a background of one event) if the proton lifetime were 10^{31} years and half of all decays were recognized. For a lifetime greater than 10^{33} years, the signal begins to fade into the background.

The H-W-P group, led by Cline, Carlo Rubbia (Harvard) and James Gaidos (Purdue), is proposing a smaller detector (one kiloton of water plus a kiloton of active shield), in hopes of building their device faster and at half the cost. Their silver-mine site in Utah would require no excavation for the smaller detector, which they believe they could construct in one year.

The group has studied the merits of various photomultiplier deployments by Monte-Carlo simulations. Assuming only a 16-meter attenuation length, they conclude that their photomultipliers should be arrayed throughout the detector volume, about a meter apart. With the tubes thus closer to the decay events, they believe they should be able to analyze in detail decay modes that produce less Cerenkov light than does the $e^+ \pi^0$ mode—for example, $p \rightarrow e^+ \rho^0$ or $\mu^+ K^0$. They also propose to line their detectors with mirrors, and to run part of the time with a wavelength-shifting ingredient in the water.

Kenneth Lande and Richard Steinberg of the University of Pennsylvania are also looking for proton decays, with a 200-ton, segmented water-Cerenkov detector a mile under ground in the Homestake gold mine in South Dakota. Their detector, which surrounds Ray Davis's famous solar-neutrino detector (see PHYSICS TODAY, December 1978, page 19), was built to look for neutrino bursts from supernovas as well as proton decays. They have recently received DOE funding to enlarge their detector to 800 tons. With its segmented construction the detector's pattern-recognition capability is limited to stopping muons. But with cells of $2 \times 2 \times 1$ meters, Lande believes they will be able to distinguish decay muons from stopping background muons by the total Cerenkov light generated in a single cell.

In December, Marvin Marshak and his colleagues at the University of Minnesota submitted to the DOE a proposal for a "dense" proton-decay detector, to be placed in a Minnesota iron mine. It would consist of an array of proportional gas tubes, with ironized concrete in the interstices. Its compactness and nonliquid character would facilitate shielding and modular construction. —BMS

References

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Linear electron–positron collider

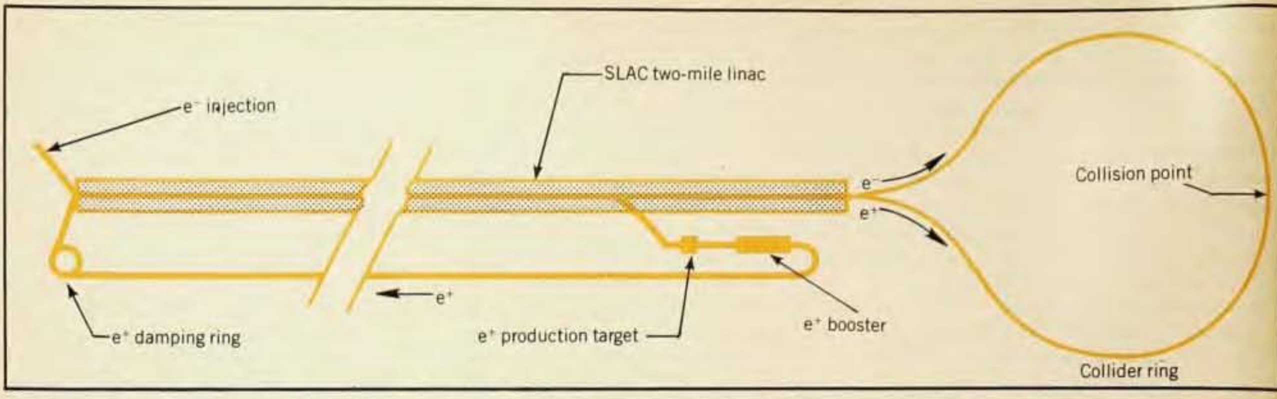
When the first beams begin circulating in PEP at the Stanford Linear Accelerator Center in March, both sides of the Atlantic will have storage rings producing electron–positron collisions at center-of-mass energies up to 36 GeV. If the rich history of the previous generation of e^+e^- colliding-beam storage rings is any guide, this new energy regime should provide an abundance of interesting physics. But PEP and its Germany cousin PETRA (at DESY, Hamburg) still fall short of the energy range 90–150 GeV that particularly intrigues particle physicists. The European high-energy community hopes to have a storage ring (LEP) of gargantuan size and price tag, capable of achieving these energies by about 1988.

Because the size and cost of storage-ring e^+e^- colliders grow as the square of the center-of-mass energy, various people have argued in recent years that beyond LEP energies one must go to linear rather than ever-larger circular colliding beams. For the past year a group at SLAC has been studying the feasibility of using the existing SLAC two-mile linear accelerator as part of a first-generation linear collider that could achieve 100 GeV several years before LEP. At last October's meeting of HEPAP (High-Energy-Physics Advisory Panel), Burton Richter of SLAC presented their results and their conceptual design for a one-armed "quasi-linear" collider, which would accelerate both positrons and electrons in the one linac, and then bring them together in a collider ring.

While Richter's group is seeking design and preliminary engineering funds from DOE, a group at Novosibirsk, led by Alexander Skrinsky, is urging upon the Soviet government its conception of a two-armed "true" linear collider that might achieve 300 GeV in e^+e^- collisions.

The quadratic growth of cost and size with energy in storage-ring colliders is a consequence of the synchrotron-radiation losses of the circulating electron (and positron) beams. A linear collider eliminates the offending circular motion by having two linear accelerators fire beams at each other more-or-less head on. In such a configuration the cost should grow only linearly with collision energy, for a given luminosity (event rate per unit scattering cross section). It follows therefore that at some energy there must be a cross-over between the costs of linear and storage-ring colliders. Richter believes that given its cost and the quadratic scaling, LEP will be the last and largest e^+e^- storage ring to see the light of day. For higher energies, he feels, only linear colliders will be economically feasible.

There appears to be another limit to the energy one can achieve with e^+e^- (or e^-e^-) storage-ring colliders. With increasing energy, each charge bunch generates ever stronger magnetic fields, which perturb the colliding charge bunch coming in the opposite direction. The strong fields generate synchrotron radiation and nonradiative perturbations in the oncoming beam, which tend to disperse it in energy and direction. The radiation resulting from the beam–beam deflections, which is negligible in present-day machines, has been given in name "beamstrahlung." Although charge bunches in linear colliders also suffer these beam–beam disturbances, they can tolerate larger perturbations



Proposed SLAC quasi-linear e^+–e^- collider, not to scale. Electron and positron bunches are accelerated to 50 GeV in the existing SLAC two-mile linac and then meet in a collider ring. Extra bunches of electrons are diverted to a positron-production target. After being boosted, the positron bunch is cooled in a damping ring before injection into the linear accelerator, just behind the electron bunch with which it will collide.

because the bunches are "disposable." Whereas in a storage ring the beam must survive in reasonable shape to travel around the ring many times, the bunches fired at each other in linear colliders never meet again.

The problem of beam–beam interactions only becomes serious in linear colliders when one pushes charge densities so high in the bunches that severe perturbations take place within a single pass. But the need for very high charge densities arises from a problem peculiar to linear colliders. The luminosity of a colliding-beam machine is of course proportional to the frequency with which bunches of charge collide. For a single pair of counterrotating bunches in a large storage ring like LEP, this frequency is about 10^4 per second, the speed of light divided by the 30-km (*sic*) circumference of the ring. By contrast, in linear colliders with disposable bunches the frequency is governed by the maximum repetition rate of the linac, which with present technology is only of the order of 100 per second. These low rates are compensated to some extent by the linear collider's greater tolerance for beam–beam disturbance.

In order to achieve a reasonable luminosity in linear colliders, one must go to very high charge densities in the colliding bunches, and hence very small bunch cross sections. But even with a bunch radius of 2 microns at the collision point, the proposed SLAC linear collider has a design luminosity of only 10^{30} cm^{-2} sec^{-1}, two orders of magnitude below that of LEP. Richter told us that to get up to a luminosity of 10^{32} would require an rf power of 10 megawatts in the beam of the linear accelerator. But the original SLAC linac, which was designed for long beam pulses (1.5 microseconds), cannot be modified to provide the short pulses (10 picosec) necessary for such power.

The SLAC quasi-linear collider. Though ultimately the full benefit of a linear collider can be realized only with two linacs colliding head-on, Richter has proposed that one take advantage of the existing SLAC linac to build a one-linac device quickly and inexpensively. Such a machine would serve a twofold purpose, as Richter sees it. First of all it would be the first experimental test of the linear-collider concept, which has been developing on paper since it was first suggested in print by Maury Tigner of Cornell in 1965. The experience gained with this first-generation device would facilitate the later construction of two-linac colliders at higher energy.

In the second place, high-energy physicists are anxious to achieve e^+e^- (and hadronic) collisions at center-of-mass energies around 100 GeV as soon as they possibly can. Current gauge theories predict that the Z^0, the vector boson that is supposed to mediate neutral-current weak interactions, has a mass between 90 and 93 GeV ("with 99% confidence," the theorists tell Richter). Unlike its charged partners, W^+ and W^-, the Z^0 need not be produced in pairs in e^+e^- collisions. Furthermore, independently of the details of the gauge theories, one expects the weak interaction to begin to dominate the electromagnetic interaction in the energy region between 100 and 150 GeV.

Richter's idea is to accelerate a single bunch of electrons to 50 GeV in the two-mile linear accelerator, followed closely by a bunch of positrons, which are accelerated by the opposite phase of the rf cycle. The linac would deposit the two bunches in opposite senses into a collider ring, where they would collide after a single half circuit, having been focused down to 2-micron bunch radii. Although the collider rings would be similar in size to PEP (radius about 300 meters), one could not make use of the PEP tunnel without evicting the experiments going on there. Therefore Richter envisions the building of a new collider ring and tunnel.

The SLAC scheme requires yet another ring, only about 3 meters in radius, which would serve as a radiation-damping or "cooling" ring for the positrons before they are injected into the linac. Having been generated by the collision of extra bunches of 50-GeV electrons with a tungsten target, the positron beam has far too much random motion perpendicular to the beam direction to permit direct injection into the linac. In the cooling ring this random perpendicular momentum is reduced by synchrotron-radiation damping, so that the positron beam can be focused down to a 700-micron radius for injection into the accelerator.

Feasibility experiments. In conventional use of the SLAC two-mile linac one has never in the past had to worry about stability at the level of microns. But with a bunch radius of two microns at the moment of collision, pulse-to-pulse stability at this level becomes crucial. During the past year Rae Stiening and Roger Miller have been testing this stability at the SLAC linac. With bunches of a few times 10^9 electrons they have satisfied themselves that the pulse-to-pulse operation of the linac is stable to a small fraction of what's needed.

They have also looked at the problem of the perturbation of the positron bunch by the "wake field" left by the electron bunch leading it through the linac. Experimenting with closely spaced bunches of a few times 10^9 electrons coasting down the linac, they have concluded that these wake fields will present no problem, unless things scale in an unexpected way when one goes to the 5×10^{10} electron (and positron) bunches called for in the SLAC collider design.

Computer simulations of nonradiative beam–beam interactions, done by Robert Hollebeek at SLAC, have yielded the somewhat surprising but pleasing preliminary result that the oppositely charged colliding bunches would improve the luminosity by about a factor of three, by reciprocally shrinking one another. A calculation of the beamstrahlung effect gives a 1% energy dispersion in the SLAC design at 100 GeV when the colliding bunches have 2-micron radii. Since the Z^0 is expected to have a width of about 3 GeV, one could tolerate an even greater energy spread due to beamstrahlung.

The SLAC quasi-linear collider would cost "very roughly" $50 million, Richter told us, and would take less than three years to build. LEP would cost an order of magnitude more, but it offers a hundred times greater luminosity and many more facilities for the experimenter. Because he is "by nature a suspicious type," Richter has designed the linear collider to be able to go up to 70 on 70 = 140 GeV by doubling the number of klystrons in the linac, just in case the theorists are wrong and the Z^0 is not to be found below 100 GeV.

Considerable worldwide interest in linear e^+e^- colliders was generated by the 1978 ICFA (International Committee for Future Accelerators) Workshop. Tigner told us that at this workshop, held at Fermilab, he, Richter, and Skrinsky discovered that all three had been thinking along very similar lines. Together with others at the workshop they formed a working group that studied limitations on the performance of future linear e^+e^- colliders. This group was the first to look closely at the "beamstrahlung" phenomenon. They must also take credit for the coinage.

Skrinsky's group at Novosibirsk is proposing to build a 200 or 300-GeV linear collider (VLEPP), consisting of two linacs, each at least a kilometer long. They hope to achieve a luminosity of 10^{32} cm^{-2} sec^{-1} by going to significantly higher charge densities than does the SLAC design. Tigner fears that at such high densities plasma instabilities would be generated in the colliding bunches. Skrinsky's computer simulations convince him (but not Tigner) that one can operate at these very high densities.

The collider designs under active consideration at Novosibirsk and SLAC both contemplate only one bunch collision per linac cycle. The luminosity could be increased by accelerating numerous bunches of electrons and positrons per cycle, but this involves more rf power than can be fed into the linacs with present-day techniques. Tigner in 1965 and Ugo Amaldi (CERN) in 1976 suggested that one go to superconducting colliding linacs. Tigner's group at Cornell has been working on superconducting rf acceleration. A superconducting linac could operate in a continuous mode, with repetition rates in the megaherz region. The Russians are approaching the multi-bunch problem from the nonsuperconducting direction—looking into the production of 5-gigawatt rf tubes. SLAC is also working on superconducting linacs, as well as "warm" linacs optimized to accelerate extremely short charge bunches. —BMS

Have galactic antiprotons been found in cosmic rays?

Nearly a quarter-century after the first production of antiprotons in the laboratory, a group of experimenters using a balloon-borne superconducting-magnet spectrometer believes they have detected a statistically significant number of these particles in cosmic rays entering the Earth's upper atmosphere. The observation of cosmic-ray antiprotons—believed to be secondary particles, not primordial antimatter from the Big Bang or from antistars—has confirmed theorists' predictions of the ratio of antiprotons to protons in the interstellar medium and has greatly extended the antiproton's measured lifetime. The observation is expected to furnish new information about the amount of matter traversed by the cosmic rays and the mechanism of their acceleration.

The experimenters from New Mexico State University and Johnson Space Flight Center in Houston used a 5000-lb superconducting magnet and particle counters, flown at an altitude of 120 000 feet, to search for cosmic-ray antiprotons. In the 15 October issue of *Phys. Rev. Letters*, they reported[1] the detection of at least 28 such particles on 21–22 June 1979.

As Maurice Shapiro (Naval Research Laboratory) told us, "While antiprotons are produced with high-energy laboratory beams, their occurrence in Nature, though fully anticipated, has hitherto been made only plausible, but not absolutely certain by observations. Upper limits on its presence had been set, but we had no actual measure of the antiproton flux in cosmic rays." The new result, he noted, is consistent with calculations of this flux.

The group consisted of Robert L. Golden, Stephen Horan and Bradley G. Mauger (New Mexico State), Gautam D. Badhwar and Jeffrey L. Lacy (Johnson Space Center), S. Alfred Stephens and Roy R. Daniel (Tata Institute for Fundamental Studies, Bombay) and John E. Zipse (Computer Sciences Corp, Greenbelt, Maryland).

Finding the particles. Negative, singly charged particles present in the upper atmosphere include pions and muons, electrons (both atmospherically produced and cosmic), and the sought-after antiprotons. Golden and his collaborators used a gas Cerenkov detector (called a "G-counter") at the top of the instrument payload to distinguish π^- and $\mu-$ particles from antiprotons.

"The G-counter," Golden told us, "is a kind of velocity-threshold mass-discriminator: If you have muons and antiprotons passing through with the same momentum, the muons—being lighter—will have higher velocities and emit Cerenkov light." The cosmic-ray events accompanied by G-counter pulses are mostly muons; events for which no G-counter pulses are recorded are not muons, but are chiefly the antiproton residue.

Below the G-counter are two scintillators for charge determination and eight multiwire proportional counters. These counters were used to reconstruct the flight trajectories of particles passing through the payload. A superconducting magnet produces a 10–40-kG field in the vicinity of the proportional counters, bending the paths of incoming particles of like mass but opposite charge in opposite directions.

After passing through the region of the multiwire proportional counters, particles traverse a sequence of seven scintillators or shower counters, which distinguish electrons from antiprotons by the cascading of the electrons.

In previous flights, the apparatus had measured the flux of normal matter (protons and electrons) in cosmic rays and searched for antihelium nuclei. This was the first time, Horan told us, that the experiment was flown "tailor-made" to look for antiprotons.

Tallying the results. The experimenters found a total of 46 antiproton candidates in the rigidity interval 5.6–12.5 GV/c. (The rigidity or momentum per unit charge is proportional to the energy per nucleon for relativistic particles and provides a measure of resistance to bending in a magnetic field.) Further analysis of the data showed that, in the interval of interest [corresponding to a magnetic deflection of -0.18 to -0.08 $(\mathrm{GV}/c)^{-1}$], 5.0 events could be attributed to negative pions and muons; albedo protons (in the overlap region between upward- and downward-moving particles) provided 2.5 events; spillover of normal-proton events into the negative-deflection region accounted for 0.2 events, and another 3.4 spurious events resulted from nuclear interactions in the G-counter's mirror. Atmospheric (non-cosmic) antiprotons, it was determined, produced another 6.5 events in this rigidity range.

After all these corrections are made, 28.4 events (a statistical average) remain and are interpreted as evidence of galactic antiprotons formed in secondary interactions that take place when high-energy cosmic-ray protons collide with atomic nuclei in the interstellar medium.

Golden and his collaborators have calculated from their data that the ratio of antiprotons to protons in cosmic rays (for rigidities of 5.6–12.5 GV/c) is $(5.2 \pm 1.5) \times 10^{-4}$. This value is consistent with Badhwar's earlier calculations, based on antiproton cross-section data from accelerator experiments, and with similar