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 values obtained[2] by Thomas K. Gaisser (Bartol Research Foundation).

Gaisser says that his and Badhwar's calculations of the cosmic-ray antiproton–proton ratio differ mostly in the region where the value of the antiproton-production cross section (which is energy dependent, in contrast to the energy-insensitive cross sections of the heavier nuclei) changes rapidly. "The job now is for us to go back and review accelerator data on antiproton production," says Gaisser, "to resolve the discrepancies between the values we get for the ratio."

But are they what they seem? Not everyone is satisfied that Golden and his collaborators have found secondary antiprotons. Andrew Buffington (Caltech), who has also studied cosmic-ray particle flux by balloon-borne experiments, has suggested that faulty calibration of the Golden apparatus could account for some or even all of the alleged galactic antiprotons.

"The problem is that Golden cannot identify his particles on a single-event basis; his approach is necessarily statistical, with some number of the events attributed to mirror interactions, atmospheric antiprotons, or what-have-you, and the rest regarded as the real thing," Buffington said. "In calculating the proton spillover, he used muon data taken on the ground with the magnet off. The trouble is, there is a fundamental difference between muons and protons—the latter can experience the strong interactions. If strong interactions took place with incoming protons near the magnet, the products might have been counted as antiprotons."

Buffington has estimated that about 100 of every 10^5 incoming protons would interact strongly, in a simple elastic-scattering mode, and that approximately 15 of the product particles would pass through the region where Golden and his collaborators found antiparticles. If Buffington's figure were doubled, he could account for all 28 "antiproton events."

Golden told us he is using Monte Carlo techniques (making up data to see if the experiment, as programmed, would have rejected the fake events) to check out Buffington's suggestion. Even if the statistical significance of the experimental results were greatly reduced, however, the value obtained for the antiproton–proton ratio would remain consistent with calculations.

Antiproton lifetime. If the particles detected are in fact galactic antiprotons, they establish a new lower limit on the order of 10^7 years, for the antiproton's lifetime. (This period is the residence time estimated for cosmic rays to remain in our galaxy, according to the widely accepted "leaky-box" model of cosmic-ray propagation.) Such a result is hardly surprising—if the lifetime of the antiproton were not the same as that of the extremely stable proton (greater than 10^{30} years), the CPT conservation theorem would be violated—but it is encouraging that the results of Golden and his collaborators tend to confirm the theorists.

Luis Alvarez (Golden's onetime teacher and collaborator at Berkeley) calls the measurement of the antiproton's lifetime the major result of the experiment. A recent experiment at CERN, in which no evidence of antiproton decay was found over a ten-day period, had provided[3] a lower limit on the antiproton's lifetime of 1700 hours times the branching ratio for the decay.

Some theorists had postulated that if antiprotons were unstable, their decay would explain the apparent asymmetry between matter and antimatter in the macroscopic world. Now it appears that antiprotons might be stable for long periods, in which case cosmologists must account for the asymmetry by other means.

Astrophysical implications. The observed flux of cosmic-ray antiprotons suggests that most of the matter encountered by cosmic rays in their circulation through the galaxy is met after their initial acceleration. Cosmic-ray investigators want to know how much matter the cosmic-ray particles traverse before they acquire their relativistic energy, and whether these energies are attained all at once or in small increments.

Gaisser notes that the detection of galactic antiprotons has already ruled out at least one oversimplified picture of cosmic-ray acceleration, but that much more complicated problems remain. "From the energy dependence of antiproton production," Gaisser said, "we can learn about the differences between environments encountered by the low-energy cosmic rays and environments seen by the higher-energy particles."

A serious limitation on the usefulness of antiprotons as probes for astrophysical investigations is that the experimenters cannot determine where the observed antiprotons (or their parent cosmic-ray particles) come from. The experimental data also do not permit discrimination between secondary and primary particles, a distinction Gary Steigman (Bartol Research Foundation) says must be made if the antiprotons are to indicate the presence of antimatter in bulk in the galaxy. "To learn about antimatter in our galaxy," he went on, we need heavier antinuclei, something that can't be a secondary. A single anticarbon nucleus in the cosmic rays would tell us that somewhere there are antistars in which antihydrogen and antihelium are processed to make anticarbon."

History of the search. The existence of antimatter was predicted in 1928 by P. A. M. Dirac's theory of the electron. In 1954, Bruno Rossi and his collaborators at MIT reported[4] an unusual cosmic-ray event photographed in the MIT multiplate cloud chamber, and later analysis made it "virtually certain that the MIT event was actually the annihilation of an antiproton. . .with an ordinary nucleon."[5] Rossi told us that the 1954 event could have been produced in the material above the cloud chamber, but it was definitely a secondary antiproton associated with the cosmic rays. Meanwhile, in 1955, at the Berkeley Bevatron, Owen Chamberlain, Emilio Segre, Clyde Wiegand and Thomas Ypsilantis had produced and observed[6] antiprotons.

In 1963, Alvarez had the idea of doing antimatter research by means of superconducting-magnet spectrometers lofted in balloons, rather than by ground-based accelerators. Golden became interested in the associated astrophysical problems. In April of 1969, Golden and his colleagues at Houston launched their first balloon flight, carrying a 12-inch magnet. "We had great hopes," Golden recalls. "The number of particles detected was small, but for all I knew there might be a 50–50 split between matter and antimatter. When we found 35 iron nuclei, with 15 bent one way and 20 the other, we were really excited. But it was only a bug in the program."

Future plans. Golden says the team hopes to fly a longer antiproton experiment this fall, to acquire better particle statistics for studying the antiproton energy distribution in cosmic radiation. The group also plan to compare their earlier data on cosmic-ray positrons with the antiproton results to obtain a more precise measure of the amount of material traversed by the cosmic rays on their way to the Earth.

Golden's New Mexico State team, together with Buffington and his collaborators (who lost their magnet-spectrometer payload in an accidental freefall two years ago) and researchers at the University of Arizona, Goddard Space Flight Center and the Danish Space Research Institute, have proposed an antiproton experiment for NASA's Space Shuttle.

If the experiment goes aboard the Shuttle, Golden notes, the background of atmospheric antiprotons would be eliminated, and a 100-hr data-acquisition period would make possible very much improved antiproton statistics.

—*Floyd Carse Bennett*

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