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The Antiproton

A quarter-century ago physical theory pointed to the existence of a fundamental particle of matter with the mass of the proton but the opposite charge. An account of its discovery last year

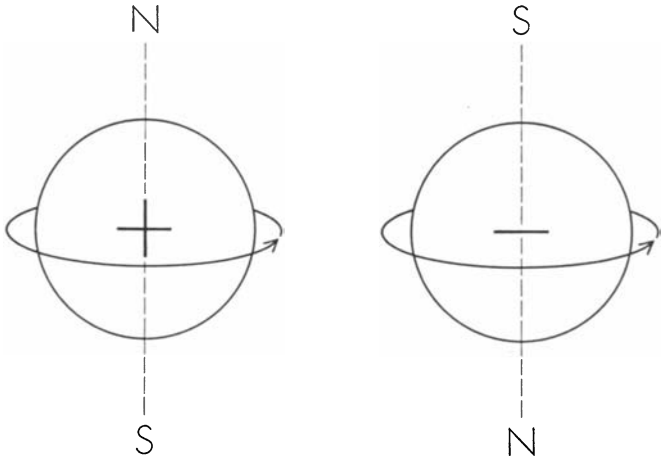
by Emilio Segrè and Clyde E. Wiegand

In the past 10 years physicists have discovered many "elementary" particles (though we must frankly admit that we do not really know how to define an "elementary particle"). Not all of these discoveries have come unheralded. One might suppose that the only way to discover a particle should be by experiment, but this is not so, although of course experiment is the judge of last resort. Sometimes theoretical physicists, from hypothetical equations and calculations with pencil and paper, have predicted the existence of particles that had never been seen. These predictions, however strange some of them may seem, arise from a necessity to preserve basic principles which form the foundation of our present understanding of the physical universe. When necessary, physicists have been willing to entertain the existence of something never seen rather than to imperil these firmly established foundations. This article is the story of how such a prediction was verified.

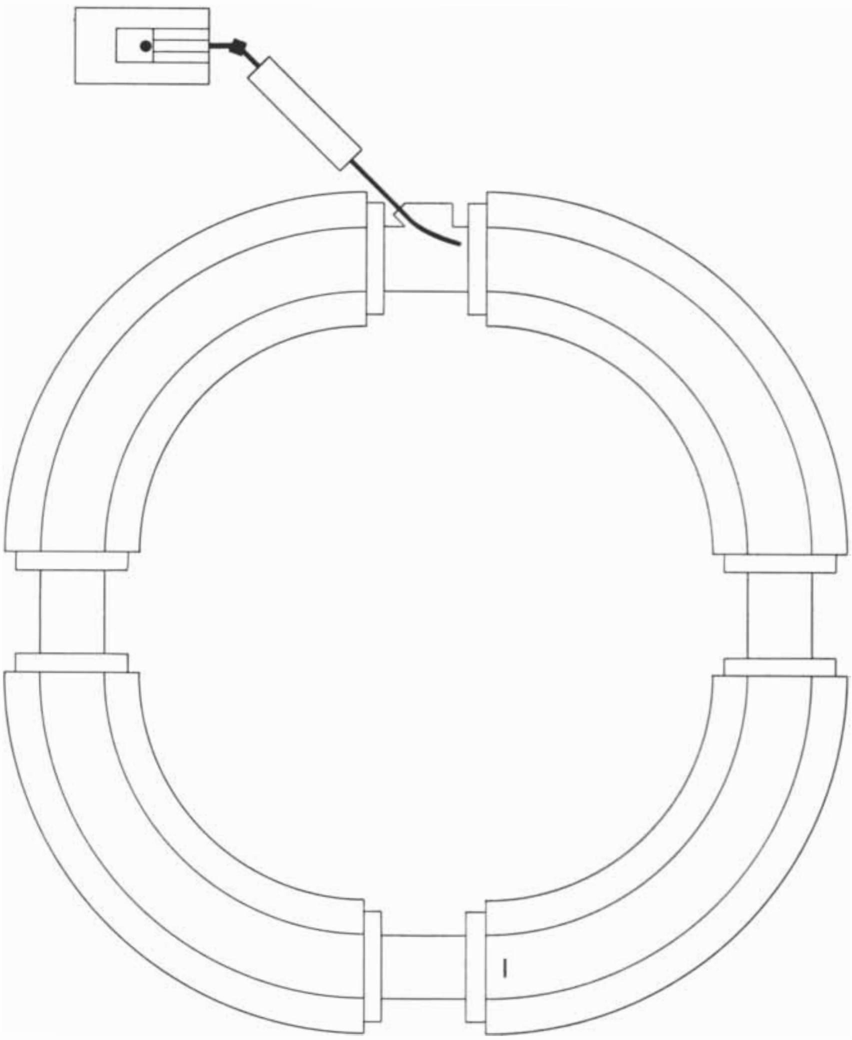
A quarter of a century ago P. A. M. Dirac of the University of Cambridge developed an equation, based on the most general principles of relativity and quantum mechanics, which described in a quantitative way various properties of the electron. He had to put in only the charge and mass of the electron—and then its spin, its associated magnetic moment and its behavior in the hydrogen atom followed with mathematical necessity. The fact that all this could be obtained automatically from one equation without *ad hoc* assumptions for each property was such a spectacular success that great faith was put in Dirac's equation and the theory on which it was based. Its discoverer found, however, that the equation required the existence of both positive and negative electrons: that is, it described not only the known negative electron but also an exactly symmetrical particle which was identical with the electron in every way except that its charge was positive instead of negative. It proved impossible to prevent Dirac's theory from giving both types of solutions. This meant that either Dirac's theory was wrong or there must be a positive electron which no physicist had ever detected or even suspected up to that time.

A few years after Dirac's prediction, Carl D. Anderson of the California Institute of Technology found positive electrons (positrons) among the particles produced by cosmic rays in a cloud chamber. This discovery not only was a triumph for Dirac's theory but also set physicists off on a new and more formidable search for another hypothetical particle—a search which was to take some 25 years and which was finally rewarded only a few months ago.

Dirac's general equation, slightly modified, should be applicable to the proton as well as to the electron. In this instance too it predicts the existence of an anti-particle—an antiproton identical to the proton but with a negative instead of a positive charge. The unknown particle's symmetry to the proton clearly



PROTON (*left*) may be regarded as a spinning sphere weighing 1.6724 x 10^{-24} grams. It has positive electric charge and, as a consequence of its rotation, north and south magnetic poles. The antiproton (*right*) has the same spin and mass. It has the same amount of electric charge, but of the opposite sign. Its north and south magnetic poles are similarly reversed.



BEVATRON at the University of California produced antiprotons by accelerating protons to 6.2 billion electron volts. This schematic plan view shows the four magnet-enclosed segments in which the protons are accelerated. The radius of each segment is 50 feet. The protons are injected into the machine by two accelerators at the top. The copper target in which the antiprotons are produced is represented by the heavy vertical line at the bottom right.

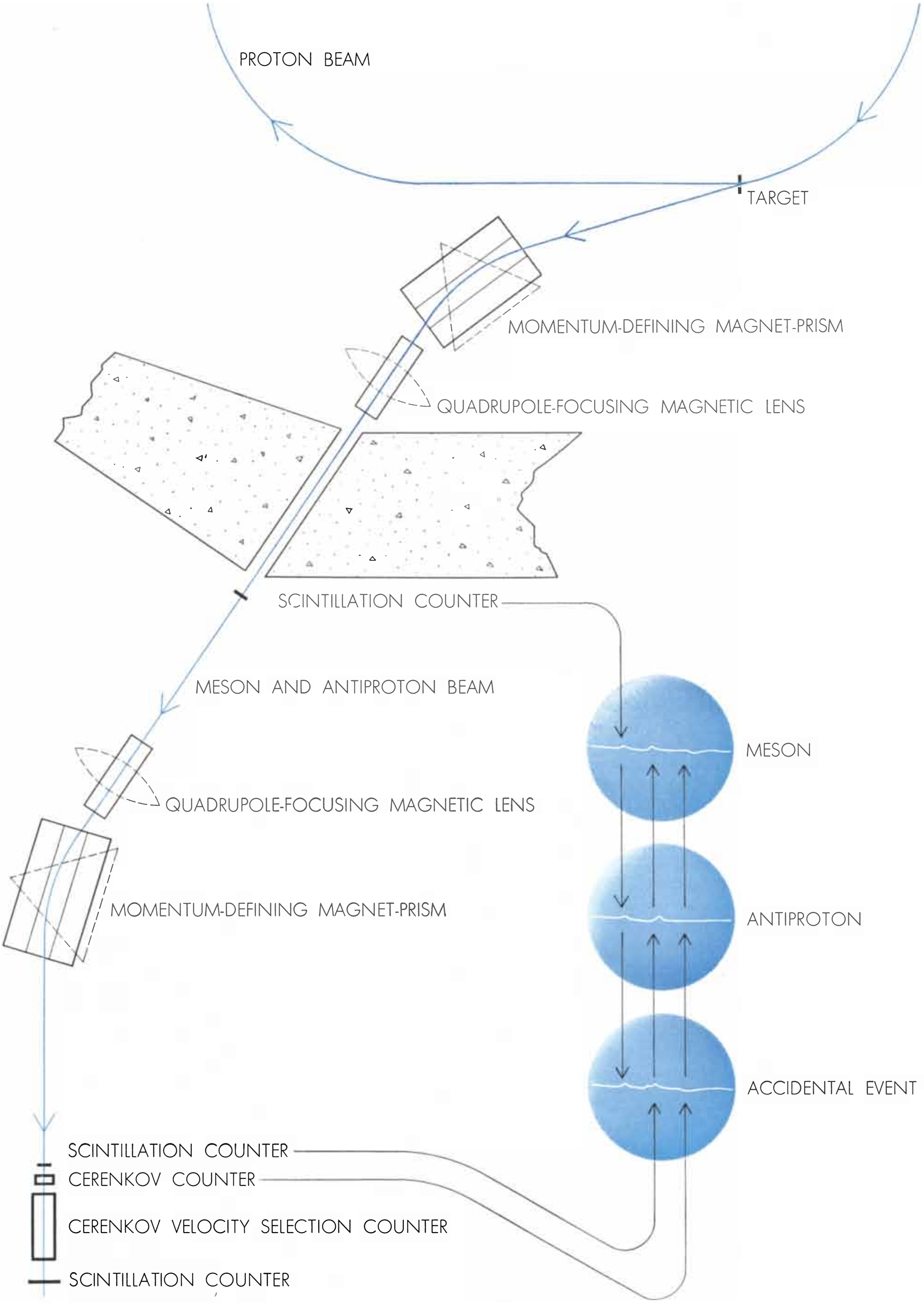
defines some of its properties. A particle in order to have the right to be called an antiproton: (1) must have the same mass as a proton (1.6724×10^{-24} grams); (2) must have an equal charge of opposite sign (4.8028×10^{-10} electrostatic units); (3) must be stable, in the sense that it will not decay spontaneously into a different particle and will last forever in a vacuum; (4) must disappear in a mutual annihilation when it encounters a proton or a neutron, liberating energy equivalent to the mass of the two particles; (5) is never generated separately but only in a pair with a proton or neutron; and (6) must have an angular momentum (spin) equal to that of the proton. Like the proton, an antiproton must also have a magnetic moment (*i.e.*, behave like a little magnet), and when it spins in the same direction as a proton its magnetic moment is equal in magnitude but of opposite sign to that of the proton; that is, the "north and south" poles are reversed.

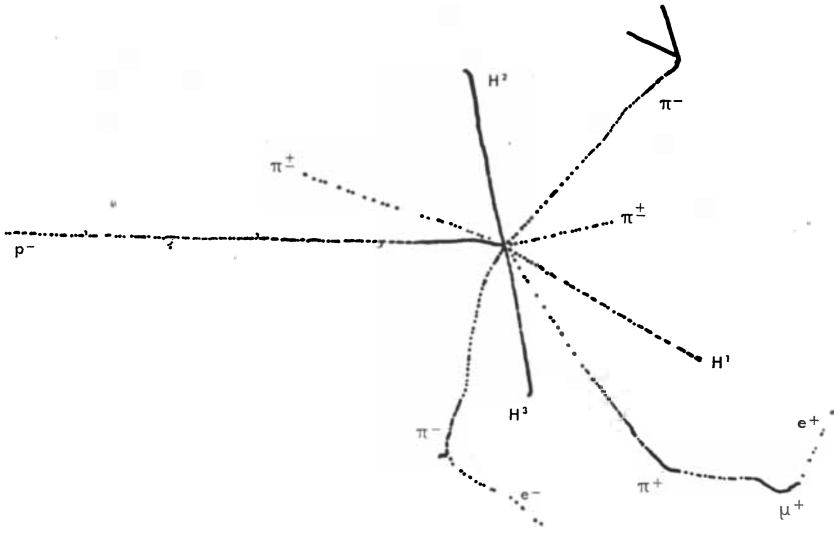
With all these clues, physicists naturally began an intensive search for the antiproton. Since it was apparent that creation of the particle required tremendous energy, the most likely place to look for it was in cosmic rays. On a few occasions investigators found events which seemed to signal the generation of an antiproton, but there was never sufficient information to identify it with certainty. The question then arose as to how much energy would be needed to create antiprotons in the laboratory with an accelerator.

Because an antiproton can be created only in a pair with a proton, we need at least the energy equivalent to the mass of two protons. Albert Einstein's theorem, $E=mc^2$, tells us that this amounts to 2×938, or 1,876 million electron volts (*i.e.*, about two billion electron volts). However, we need much more than two Bev in the proposed laboratory experiment. To convert energy into particles we must concentrate the energy at a point; this is best accomplished by hurling a high-energy particle at a target—*e.g.*, a proton against a proton. After the collision we shall have four particles: the two original protons plus the newly created proton-antiproton pair. Each of the four will emerge from the collision with a kinetic energy amounting to about one Bev. Thus the generation of an antiproton by this method takes two Bev (creation of the proton-antiproton pair) plus four Bev (the kinetic energy of the four emerging particles). It was with these numbers in mind that the Bevatron at the University of California was designed. It was built to accelerate protons to a kinetic energy of more than six Bev, with the hope of producing antiprotons.

When the Bevatron began to bombard a target made of copper with six-Bev protons, the next problem was to detect and identify any antiprotons created. A plan for the search was devised by Owen Chamberlain, Thomas Ypsilantis and the authors of this article. The plan was based on three properties which could conveniently be determined. First, the stability of the particle meant that it should live long enough to pass through a long apparatus. Second, its negative charge could be identified by the direction of deflection of the particle by an applied magnetic field, and the magnitude of its charge could be gauged by the amount of ionization it produced along its path. Third, its mass could be calculated from the curve of its

EXPERIMENTAL SETUP which demonstrated the existence of the antiproton is depicted on opposite page. The colored line at the top is the orbit of the protons in the Bevatron. The path of the antiprotons and other particles produced in the target is traced by the colored line from upper right to lower left. From the target to the last scintillation counter the particles travel 80 feet. At the lower right the various events of the experiment are represented by their characteristic cathode ray traces. Above the center of the diagram is the concrete shield of the Bevatron. The prisms and lenses superimposed with broken lines on the four magnets symbolize their function. The experiment is described in detail by the text of this article.


PROTON BEAM
TARGET
MOMENTUM-DEFINING MAGNET-PRISM
QUADRUPOLE-FOCUSING MAGNETIC LENS
SCINTILLATION COUNTER
MESON AND ANTIPROTON BEAM
MESON
QUADRUPOLE-FOCUSING MAGNETIC LENS
ANTIPROTON
MOMENTUM-DEFINING MAGNET-PRISM
ACCIDENTAL EVENT
SCINTILLATION COUNTER
CERENKOV COUNTER
CERENKOV VELOCITY SELECTION COUNTER
SCINTILLATION COUNTER



NUCLEAR EMULSION PHOTOGRAPH reproduced by tracing shows the death of an antiproton (p^-) in a "star" of pi mesons (π) and hydrogen nuclei (H). One of the pi mesons has decayed into an electron (e); another into a mu meson (μ) and an electron.

trajectory in a given magnetic field if its velocity was known.

The trajectory of a charged particle in a magnetic field depends on its momentum: once the trajectory is known, the momentum can be calculated. Now if we also measure the velocity of the particle (say by timing its travel between two given points in the apparatus), we can compute the mass from the momentum and velocity, using the relativistic equation which connects momentum, rest mass and velocity.

All this sounds very simple, but the main difficulty in the experiment arises from a complication which we have thus far neglected to mention. When the beam of 6.2-Bev protons hits the target, it generates a great many other particles which have the same momentum as the antiprotons. Most of them are mesons, the particles supposed to represent the cement that holds the nucleons together in the nucleus. It turned out that there were about 40,000 mesons for each rare antiproton in the stream of emerging particles focused by our magnets. The mesons follow exactly the same trajectory as the antiprotons, but they are lighter and travel with a velocity practically identical to that of light, whereas the heavier antiproton moves with 78 per cent of the velocity of light. The problem was to pick out of the stream the occasional heavy particle (one in 40,000) moving with the right velocity to be an antiproton.

An extensive array of bending magnets, magnetic focusing lenses and detectors was set up to comb out the antiprotons [*see diagram on page* 39]. From the spray of charged particles emerging from the copper target a bending magnet first sorted out the negatively charged particles of the desired momentum, bending them in a particular trajectory. This stream was then focused by a magnetic lens. The focused beam now encountered a detector—a disk of plastic material which scintillates when charged particles pass through. The main purpose of the detector was to serve as a "stop watch" for timing the passage of particles so as to measure their velocity: precisely 40 feet farther on they hit a second scintillating detector, and the velocity was reckoned from the time taken to travel the distance between the two "stop watches." The flashes of light from each scintillator were translated by photosensitive tubes into pulses of electric current, and these pulses were recorded as pips on a cathode ray screen. This timing system could measure differences of one billionth of a second in the travel time of particles over the 40-foot interval. In our experiment the antiprotons cross the 40-foot distance in 51 billionths of a second, whereas the mesons take only 40 billionths of a second.

However, we found that we needed an independent measurement of the particles' velocities as a check against accidental coincidences. So many mesons were streaming through our "speed trap" that sometimes one meson triggered the first stop watch and another triggered the second after an interval that corresponded to the travel time of an antiproton. We therefore placed a velocity-selecting counter just beyond the second scintillator. This unique selector makes use of the Cerenkov effect, discovered many years ago by the Russian physicist Pavel Cerenkov. He found that when a charged particle passes through a medium such as glass or quartz with a velocity greater than the velocity of light in that medium, it emits light—an effect analogous to the shock waves produced in air by a jet aircraft exceeding the speed of sound. Now the angle at which the Cerenkov light radiation is emitted, with respect to the path of the particle, depends upon the velocity of the particle. An analogy is the wake of a boat: the faster the boat travels, the narrower is the angle of its wake. Taking advantage of this fact, we put a piece of quartz in the path of the beam and arranged a system of mirrors and light shields so that Cerenkov radiation was recorded only from particles traveling at 75 to 78 per cent of the velocity of light—the speed of the antiproton. We took two other precautions against spurious identification. To make sure of weeding out mesons and other unwanted particles we placed in front of the velocity selector a "guard" detector of the Cerenkov type which gave a warning signal of the arrival of any particle exceeding 78 per cent of the velocity of light, and to exclude particles that might come from outside the system we used a final scintillation counter which recorded only particles traveling in the direction of the beam.

Thus a particle would be identified as an antiproton only when all the following conditions were fulfilled: the "stop watch" counters indicated that a particle had passed through with the correct velocity (crossing the 40 feet in 51 billionths of a second); the guard counter gave no warning signal; the velocity selector registered a particle with velocity between 75 and 78 per cent of the velocity of light; and the final scintillation counter showed that the particle had coursed through the length of the selector. When all these things happened, a characteristic sweep was traced on the oscilloscope [*see page* 39]. Many more tests were made to confirm that this type of sweep really meant that an antiproton had passed through the system.

When the discovery of the antiproton was announced last October, 60 of them had been recorded, at an average rate of about four to each hour of operation of the Bevatron. They had passed all the tests which we had preordained before the start of the experiment. We were quite gratified by the comment of a highly esteemed colleague who was visiting from another university where he had just finished an important and difficult experiment on mesons. After examining our tests, he said, "I wish that my own experiments on mu mesons were as convincing as this." At this time several long-standing bets on the existence of the antiproton started to be paid. The largest we know of was for $500. (We were not personally involved.)

It was still highly desirable to have some information on the process of annihilation of the antiproton when it encountered a proton. The first experiment along this line was performed by a group consisting of J. Brabant, B. Cork, N. Horowitz, B. Moyer, J. Murray, R. Wallace and W. Wenzel. They arranged to trap an antiproton from our apparatus in a piece of glass. On being stopped, the antiproton, and the proton which presumably was annihilated with it, emitted charged particles which moved fast enough to release considerable light by Cerenkov radiation. A study of this light confirmed that the particle selected as an antiproton was definitely not a meson.

While all this was going on, another experiment for detection of the antiproton was started by the authors, Chamberlain, W. Chupp and G. Goldhaber, in collaboration with a team of physicists in Italy: E. Amaldi (a former fellow student with Segrè of the late Enrico Fermi), G. Baroni, C. Castagnoli, C. Franzinetti and A. Manfredini. It was decided to try to find the tracks of antiprotons in photographic emulsions. If we could detect them there, we could get direct information about the antiproton's destruction.

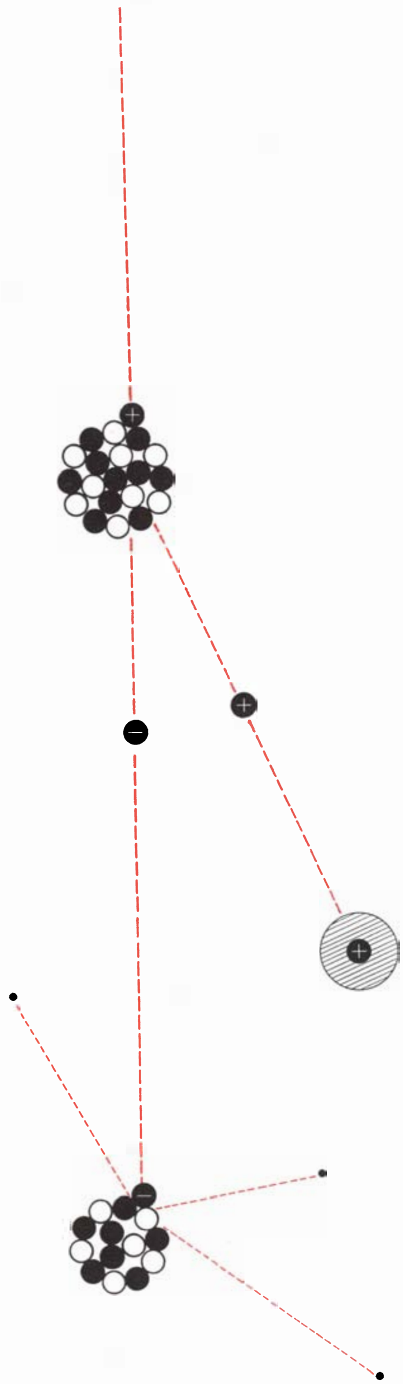
We exposed photographic plates in a beam which should yield antiprotons and then sent some of the plates to Rome and examined some ourselves in Berkeley. In spite of strenuous efforts by both groups, only one star that might represent a proton-antiproton annihilation was found—by the scanners in Rome. Later experiments by our group (including D. Keller and H. Steiner) indicated that absorbers which we had used to slow down the antiprotons before they entered the photographic plates had unexpectedly destroyed many of the antiprotons. The absorbers were then removed and new plates were exposed, with the result that tracks of about 20 antiprotons have now been detected in emulsions by observers in Berkeley.

A star of annihilation is pictured at the top of the opposite page. The track of the incoming antiproton has the range predicted for it. The particle lost its kinetic energy by collisions and ionization and came to rest in the emulsion. It was then captured by a nucleus in the emulsion and promptly annihilated itself with another nucleon. Many of the charged fragments into which it broke down can be identified by their tracks; others cannot be named with certainty; still others were neutral particles which made no tracks in the plate. At all events, we know for certain that the total energy released in the annihilation was greater than the mass equivalent of the antiproton—proof that another nucleon was annihilated along with it.

As usual with all discoveries, the advent of the antiproton has launched a host of new questions, on which work is progressing. For the time being only Berkeley has an accelerator powerful enough to produce antiprotons. The next to enter the picture, according to reports at the Geneva conference of last summer, should be a U.S.S.R. machine, now in an advanced stage of construction.

An interesting subject for contemplation is the possible existence of an "anti-world." This would be a world in which all particles are opposite in charge to our own: the hydrogen atom, for instance, would have an antiproton as its nucleus and a positron in place of the electron. We know of no method by which we could recognize the existence of such a universe by astronomical observation. But if antimatter exists and if it should come into contact somewhere with ordinary matter as we know it, the two forms of matter would annihilate each other with a huge release of energy, mostly as mesons. Whether we would see this event would depend on the density of the matter colliding. If it were spread out as thinly as the average density of matter in the galaxies, the effect might not be very conspicuous. It is also possible that a collision even between concentrated masses of matter and antimatter would not be very spectacular astronomically, for they probably would repel each other, by radiation pressure, as soon as they came into contact.

If the universe originated from the transformation of pure energy into nucleons and electrons, we must suppose, in order to preserve the principle of the constancy of the number of these particles, that somewhere there are antinucleons and antielectrons equal in number to those of our world. It is a speculation which gives a highly satisfying symmetry to creation.



LIFE CYCLE of an antiproton is schematically depicted. A high-energy proton (*black ball with plus sign at the top*) collides with another proton in the target nucleus. This gives rise to a new proton (*black ball with plus sign at right center*) and an antiproton (*black ball with minus sign*). The new proton travels until it comes to rest as the nucleus of a hydrogen atom (*right*). The antiproton continues until it encounters another nucleus (*bottom*). The antiproton and a proton or a neutron are then both annihilated in a shower of various particles.