4

Antibaryons

The discovery of the antiproton and other antimatter, 1955–1959.

While the existence of antiparticles was established with Anderson's discovery of the positron in 1932, it was not clear in 1955 whether the pattern of each fermion having an antiparticle, suggested by the Dirac equation, would hold for baryons, the heavy particles p, n, Λ, Σ, and Ξ. There were two arguments raising doubts about such particles. One was that nucleons had an anomalous magnetic moment that differed markedly from the Dirac moment. Measurements by Otto Stern in 1933, later improved by I. I. Rabi, had shown that the proton had a magnetic moment of 2.79 nuclear magnetons. [One nuclear magneton is $e\hbar/(2M_pc)$, where M_p is the nucleon mass.] The neutron's magnetic moment, which would be zero if the neutron were an ordinary Dirac particle, was measured by L. Alvarez and F. Bloch in 1940 to have a value of -1.91 nuclear magnetons. The second reason was based on a cosmological argument. Where were the antigalaxies one expected if the Universe had baryon–antibaryon symmetry?

One of the motivations for the choice of the energy for the Bevatron was the hope that the antiproton could be found. The momentum chosen, 6.5 GeV/c, was above threshold for antiproton production on free protons, $p + p \rightarrow p + p + p + \overline{p}$, to occur. In 1955, one year after the Bevatron became operational, there were a number of different plans to look for the antiproton, including two within the Segrè group at Berkeley, an experiment using electronic counters and a photographic emulsion experiment.

The detection of the antiproton was first achieved in 1955 by O. Chamberlain, E. Segrè, C. Wiegand, and T. Ypsilantis **(Ref. 4.1)**. The primary obstacle to overcome was the background from the much more copiously produced π^- whose charge was the same as that of the antiproton. To separate the antiprotons, Chamberlain *et al.* measured both the momentum and velocity of the negative particles.

The beam from the Bevatron impinged on a copper target. Negative particles produced with a momentum near 1.19 GeV/c were focused by a quadrupole magnet on a first set of scintillators, which emitted light when charged particles passed through them. A second quadrupole focused the beam on a second set of scintillators 40 feet farther down the line. An antiproton with momentum 1.19 GeV/c and a velocity $v = 0.78\,c$ required 51 ns for the flight, while a π^- of this momentum needed only 40 ns.

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Additional verification was provided by using Cherenkov counters. Cherenkov counters detect the light emitted by charged particles passing through a medium when the velocity of the particle is greater than the velocity of light in the medium. Since that velocity is the usual velocity of light divided by the index of refraction, it is possible to fill the detector with a gas, possibly under pressure, so that the detector will respond only to particles with velocities exceeding some minimum value. To demonstrate the presence of antiprotons, one Cherenkov counter was set to count pions and was used in anticoincidence for the protonic-mass particles, that is, if the particle was determined to be a pion, it was rejected. A second one was a specially designed differential counter that only responded to particles in a narrow velocity band corresponding to the protonic mass. This counter was used in coincidence for the acceptance of the $\overline{p}$ candidates.

Some 60 antiproton candidates had been observed by October 1955. Calibrating the apparatus with ordinary protons allowed a determination of the mass of the negative particle and it was found to be the same as the proton's to within 5%. This was strong circumstantial evidence that this was the antiproton and not some other long-lived, negative particle. Still, the fundamental property of the antiproton, its ability to annihilate with a proton or neutron to produce a final state with no baryons in it, had not been confirmed.

The Bevatron's high energy proton beam provided the opportunity to look for antiprotons in other ways. With emulsions it is possible, in principle, to measure the large energy released when an antiproton annihilates with a proton or neutron, providing direct evidence for the antiparticle character of the annihilating particle.

While the experiment of Chamberlain *et al.* was being set up, an emulsion stack was exposed at the location of the first scintillator in a collaborative experiment between a Berkeley group under G. Goldhaber and E. Segrè and a Rome group under E. Amaldi. This exposure required a 132 g cm^{-2} copper absorber to slow the antiprotons so they would stop in the emulsion. After laborious scanning, both in Berkeley and in Rome, one stopping negative particle of protonic mass was observed by the Rome group (Ref. 4.2). The energy release observed was 850 MeV. (See Figure 4.1.)

In another effort to confirm the antiparticle nature of the new negative particles, Brabant *et al.* placed a lead glass Cherenkov counter at the end of the antiproton beam of the Chamberlain–Segrè team in order to look for evidence of annihilation (Ref. 4.3). While sizeable energy releases were observed, none was greater than the rest mass of the proton.

In December 1955, a second emulsion exposure was carried out at the Bevatron, this time with the momentum selected to be 700 MeV/c. This value was chosen so that the antiprotons entered the emulsion with tracks giving twice minimum ionization, making them readily distinguishable from the more numerous minimum ionizing pion tracks. This procedure turned out to be most effective. The first track of protonic mass that was followed through the emulsion stack until it came to rest released 1350 $\pm$ 50 MeV **(Ref. 4.4)**. This was unequivocal evidence for an antiproton–nucleon annihilation. The complete analysis turned up 35 antiproton annihilations, more than half of which had energy releases greater than the mass of the proton (Ref. 4.5).

The team consisting of Cork, Lambertson, Piccioni, and Wenzel in another experiment at the Bevatron established the existence of the antineutron **(Ref. 4.6)** by observing the

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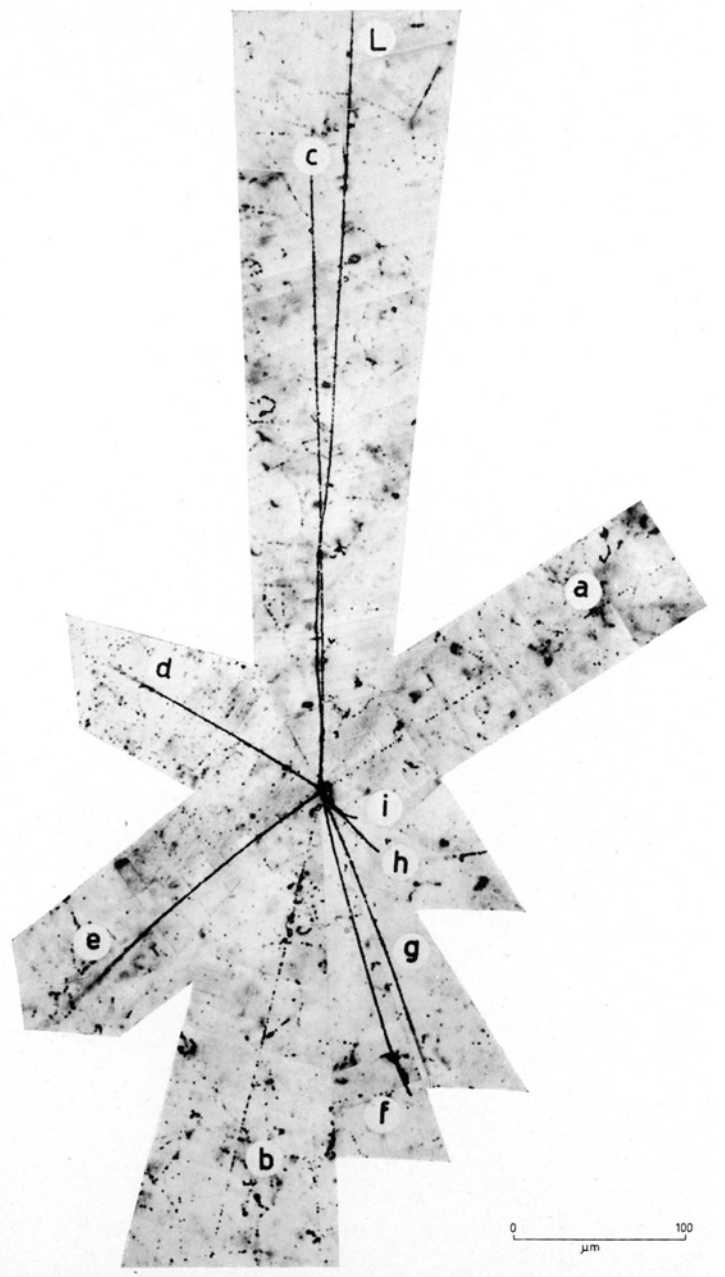


Figure 4.1. The first antiproton star observed in an emulsion. The incident antiproton is track L. The light tracks *a* and *b* are pions. Track *c* is a proton. The remaining tracks are protons or alpha particles. The exposure was made at the Bevatron. (Ref. 4.2)

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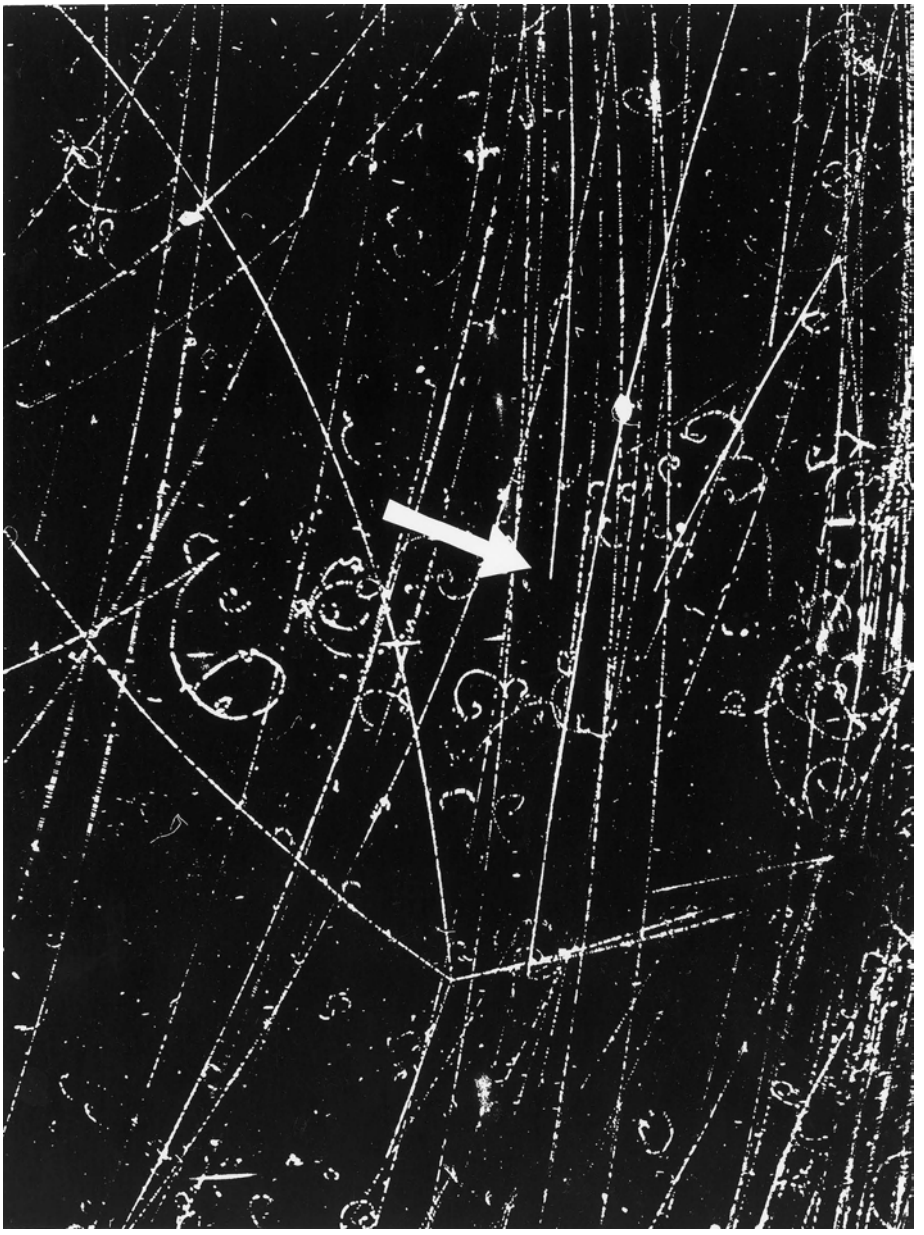


Figure 4.2. An antiproton enters the bubble chamber from the top. Its track disappears at the arrow as it charge exchanges, $p\overline{p} \rightarrow n\overline{n}$. The antineutron produces the star seen in the lower portion of the picture. The energy released in the star was greater than 1500 MeV. (Ref. 4.7)

charge-exchange process, $\overline{p}p \rightarrow \overline{n}n$. This experiment used a highly efficient antiproton beam constructed with the aid of magnets using the principle of strong-focusing, which will be described in Chapter 6.

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The antiproton beam was directed on a cube of liquid scintillator in which the charge-exchange process occurred. The produced antineutron continued forward into a lead glass Cherenkov counter that detected the annihilation of the antineutron. To demonstrate that antineutrons, not antiprotons, were responsible for the annihilation, counters were placed in front of the Cherenkov counter and events with charged particles were rejected. The liquid scintillator was also monitored to make sure that the reaction that took place there was indeed charge exchange rather than annihilation into mesons of the incident antiproton.

The final annihilations occurring in the Cherenkov counter were compared with those produced directly by antiprotons. Their similarity established that antineutrons had been observed.

The bubble chamber contributed as well to the discovery of antibaryons. An experiment by W. Powell and E. Segrè *et al.* using the Berkeley 30-inch propane bubble chamber at the Bevatron found a clear antiproton charge-exchange event showing an antineutron annihilation star. This event is reproduced in Figure 4.2. The anti-lambda ($\overline{\Lambda}$) was first seen in emulsions by D. Prowse and M. Baldo-Ceolin (Ref. 4.8). A classic picture of $\Lambda\overline{\Lambda}$ production observed in an antiproton exposure of the 72-inch hydrogen bubble chamber at the Bevatron is shown in Figure 4.3. The next few years witnessed the discoveries of the $\overline{\Sigma}$ (Refs. 4.10, 4.11), the $\overline{\Xi}$ (Ref. 4.12), and even the $\overline{\Omega}$ (Ref. 4.13). (The discovery of the Ω^- itself is discussed in Chapter 5.) Ultimately, all the stable baryons were shown to have antiparticles.

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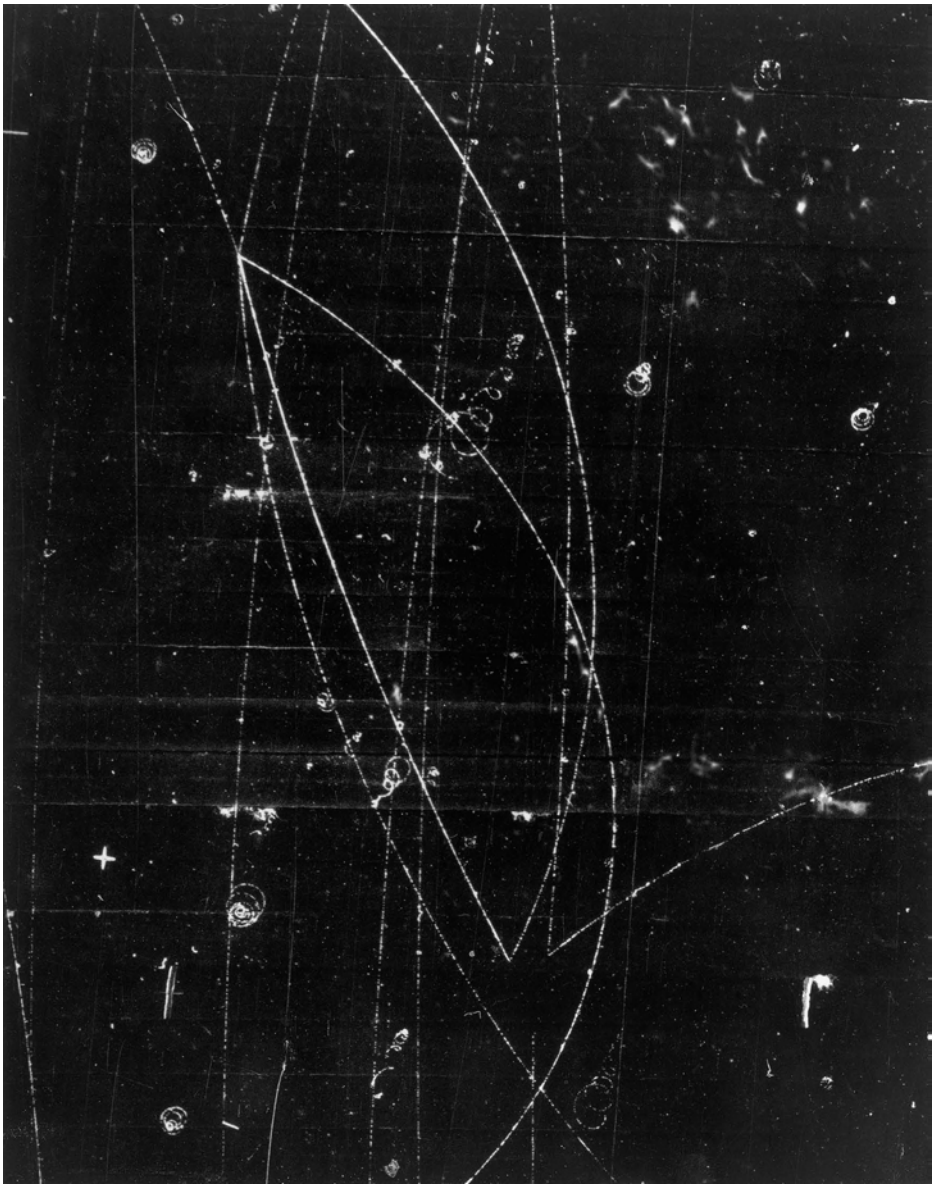


Figure 4.3. Production of a $\Lambda\overline{\Lambda}$ pair by an incident antiproton. The antiproton enters the chamber at the bottom and annihilates with a proton. The Λ and $\overline{\Lambda}$ decay nearby. The antiproton from the antilambda annihilates on the left-hand side of the picture and gives rise to a 4 prong star. The picture is from the 72-inch bubble chamber at the Bevatron. (Ref. 4.9)

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Exercises

4.1 Show that a Fermi energy of 25 MeV lowers the threshold incident kinetic energy for antiproton production by a proton incident on a nucleus to 4.3 GeV.

4.2 Derive the half-angle of the cone into which Cherenkov radiation is projected in terms of the velocity of the radiating particle and the index of refraction of the medium.

4.3 Design a differential Cherenkov counter that can separate π^- and $\overline{p}$ as in Ref. 4.1. See the reference quoted therein.

4.4 Suppose positive and negative kaon beams are available for an exposure of a hydrogen bubble chamber. For which beam is the threshold lowest for the production of $\overline{\Sigma}^-$, $\overline{\Sigma}^0$, $\overline{\Sigma}^+$, $\overline{\Xi}^+$, $\overline{\Xi}^0$, and $\overline{\Omega}^+$? Give the reaction that has the lowest threshold and the incident momentum at threshold.

4.5 How was the magnetic moment of the neutron measured by L. Alvarez and F. Bloch [*Phys. Rev.* **57**, 111 (1940)]?

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Observation of Antiprotons*

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(Received October 24, 1955)

ONE of the striking features of Dirac's theory of the electron was the appearance of solutions to his equations which required the existence of an antiparticle, later identified as the positron.

The extension of the Dirac theory to the proton requires the existence of an antiproton, a particle which bears to the proton the same relationship as the positron to the electron. However, until experimental proof of the existence of the antiproton was obtained, it might be questioned whether a proton is a Dirac particle in the same sense as is the electron. For instance, the anomalous magnetic moment of the proton indicates that the simple Dirac equation does not give a complete description of the proton.

The experimental demonstration of the existence of antiprotons was thus one of the objects considered in the planning of the Bevatron. The minimum laboratory kinetic energy for the formation of an antiproton in a nucleon-nucleon collision is 5.6 Bev. If the target nucleon is in a nucleus and has some momentum, the threshold is lowered. Assuming a Fermi energy of 25 Mev, one may calculate that the threshold for formation of a proton-antiproton pair is approximately 4.3 Bev. Another, two-step process that has been considered by Feldman[1] has an even lower threshold.

TABLE I. Characteristics of components of the apparatus.

$S1$, $S2$	Plastic scintillator counters 2.25 in. diameter by 0.62 in. thick.
$C1$	Čerenkov counter of fluorochemical 0–75, ($C_8F_{16}O$); $\mu_D=1.276$; $\rho=1.76$ g cm^{-3}. Diameter 3 in.; thickness 2 in.
$C2$	Čerenkov counter of fused quartz: $\mu_D=1.458$; $\rho=2.2$ g cm^{-3}. Diameter 2.38 in.; length 2.5 in.
$Q1$, $Q2$	Quadrupole focusing magnets: Focal length 119 in.; aperture 4 in.
$M1$, $M2$	Deflecting magnets 60 in. long. Aperture 12 in. by 4 in. $B\cong 13\,700$ gauss.

There have been several experimental events[2–4] recorded in cosmic-ray investigations which might be due to antiprotons, although no sure conclusion can be drawn from them at present.

With this background of information we have performed an experiment directed to the production and detection of the antiproton. It is based upon the determination of the mass of negative particles originating at the Bevatron target. This determination depends on the simultaneous measurement of their momentum and velocity. Since the antiprotons must be selected from a heavy background of pions it has been necessary to measure the velocity by more than one method. To date, sixty antiprotons have been detected.

Figure 1 shows a schematic diagram of the apparatus. The Bevatron proton beam impinges on a copper target and negative particles scattered in the forward direction with momentum 1.19 Bev/c describe an orbit as shown in the figure. These particles are deflected 21° by the field of the Bevatron, and an additional 32° by magnet $M1$. With the aid of the quadrupole focusing magnet $Q1$ (consisting of 3 consecutive quadrupole magnets) these particles are brought to a focus at counter $S1$, the first scintillation counter. After passing through counter $S1$, the particles are again focused (by $Q2$), and deflected (by $M2$) through an additional angle of 34°, so that they are again brought to a focus at counter $S2$.

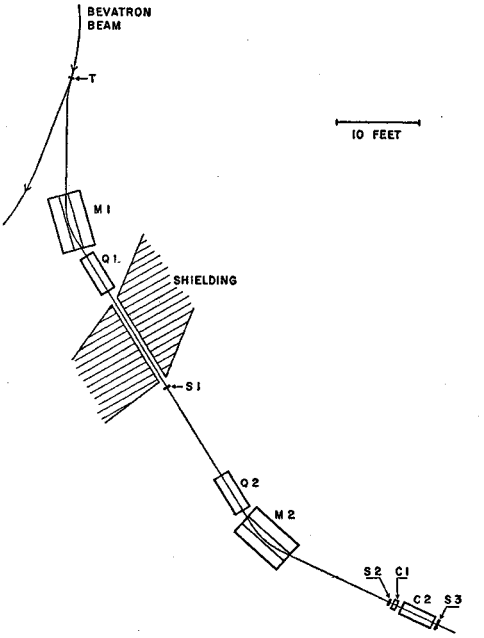


FIG. 1. Diagram of experimental arrangement. For details see Table I.

The particles focused at $S2$ all have the same momentum within 2 percent.

Counters $S1$, $S2$, and $S3$ are ordinary scintillation counters. Counters $C1$ and $C2$ are Čerenkov counters. Proton-mass particles of momentum 1.19 Bev/c incident on counter $S2$ have $v/c=\beta=0.78$. Ionization energy loss in traversing counters $S2$, $C1$, and $C2$ reduces the average velocity of such particles to $\beta=0.765$. Counter $C1$ detects all charged particles for which $\beta>0.79$. $C2$ is a Čerenkov counter of special design that counts only particles in a narrow velocity interval, $0.75<\beta<0.78$. This counter will be described in a separate publication. In principle, it is similar to

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some of the counters described by Marshall.[5] The requirement that a particle be counted in this counter represents one of the determinations of velocity of the particle.

The velocity of the particles counted has also been determined by another method, namely by observing the time of flight between counters $S1$ and $S2$, separated by 40 ft. On the basis of time-of-flight measurement the separation of π mesons from proton-mass particles is quite feasible. Mesons of momentum 1.19 Bev/c have $\beta=0.99$, while for proton-mass particles of the same momentum $\beta=0.78$. Their respective flight times over the 40-ft distance between $S1$ and $S2$ are 40 and 51 millimicroseconds.

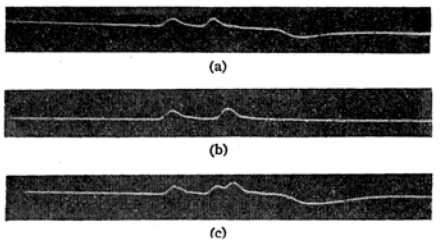


FIG. 2. Oscilloscope traces showing from left to right pulses from $S1$, $S2$, and $C1$. (a) meson, (b) antiproton, (c) accidental event.

The beam that traverses the apparatus consists overwhelmingly of π^- mesons. One of the main difficulties of the experiment has been the selection of a very few antiprotons from the huge pion background. This has been accomplished by requiring counters $S1$, $S2$, $C2$, and $S3$ to count in coincidence. Coincidence counts in $S1$ and $S2$ indicate that a particle of momentum 1.19 Bev/c has traversed the system with a flight time of approximately 51 millimicroseconds. The further requirement of a coincidence in $C2$ establishes that the particle had a velocity in the interval $0.75<\beta<0.78$. The latter requirement of a count in $C2$ represents a measure of the velocity of the particle which is essentially independent of the cruder electronic time-of-flight measurement. Finally, a coincident count in counter $S3$ was required in order to insure that the particle traversed the quartz radiator in $C2$ along the axis and suffered no large-angle scattering.

As outlined thus far, the apparatus has some shortcomings in the determination of velocity. In the first place, accidental coincidences of $S1$ and $S2$ cause some mesons to count, even though a single meson would be completely excluded because its flight time would be too short. Secondly, the Čerenkov counter $C2$ could be actuated by a meson (for which $\beta=0.99$) if the meson suffered a nuclear scattering in the radiator of the counter. About 3 percent of the mesons, which ideally should not be detected in $C2$, are counted in this manner. Both of these deficiencies have been eliminated by the insertion of the guard counter $C1$, which records all particles of $\beta>0.79$. A pulse from $C1$ indicates a particle (meson) moving too fast to be an antiproton of the selected momentum and indicates that this event should be rejected. In Table I, the characteristics of the components of the apparatus are summarized.

The pulses from counters $S1$, $S2$, and $C1$ were displayed on an oscilloscope trace and photographically recorded. From the separation of pulses from $S1$ and $S2$ the flight time of the particle could be measured with an accuracy of 1 millimicrosecond, and the pulse in the guard counter $C1$ could be measured. Figure 2 shows three oscilloscope traces, with the pulses from $S1$, $S2$, and $C1$ appearing in that order. The first trace (a) shows the pulses due to a meson passing through the system. It was recorded while the electronic circuits were adjusted for meson time of flight for calibration purposes. The second trace, Fig. 2(b), shows the pulses resulting from an antiproton. The separation of pulses from $S1$ and $S2$ indicates the correct antiproton time of flight, and the absence of the $C1$ pulse shows that no meson passed through $C1$. The third trace, Fig. 2(c), shows the accidental coincidence of two mesons with a difference of time such as to register in the electronic circuits. Either the presence of a pulse from $C2$ or the presence of multiple pulses from $S1$ or $S2$ would be

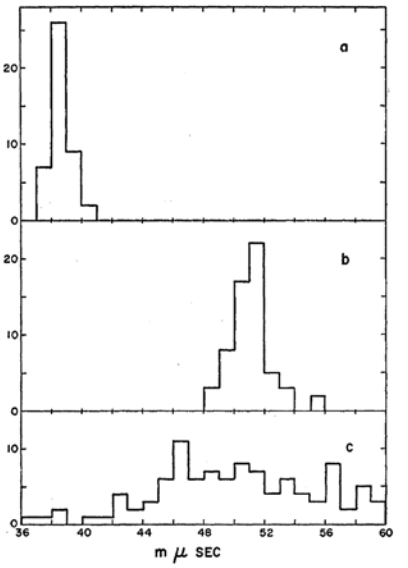


FIG. 3. (a) Histogram of meson flight times used for calibration. (b) Histogram of antiproton flight times. (c) Apparent flight times of a representative group of accidental coincidences. Times of flight are in units of 10^{-9} sec. The ordinates show the number of events in each 10^{-10}-sec intervals.

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sufficient to identify the trace as due to one or more mesons.

An over-all test of the apparatus was obtained by changing the position of the target in the Bevatron, inverting the magnetic fields in $M1$, $M2$, $Q1$, and $Q2$, and detecting positive protons.

Each oscilloscope sweep of the type shown in Fig. 2 can be used to make an approximate mass measurement for *each* particle, since the magnetic fields determine the momentum of the particle and the separation of pulses $S1$ and $S2$ determine the time of flight. For protons of our selected momentum the mass is measured to about 10 percent, using this method only.

The observed times of flight for antiprotons are made more meaningful by the fact that the electronic gate time is considerably longer than the spread of observed antiproton flight times. The electronic equipment accepts events that are within ± 6 millimicroseconds of the right flight time for antiprotons, while the actual antiproton traces recorded show a grouping of flight times to ± 1 or 2 millimicroseconds. Figure 3(a) shows a histogram of meson flight times; Fig. 3(b) shows a similar histogram of antiproton flight times. Accidental coincidences account for many of the sweeps (about $\frac{2}{3}$ of the sweeps) during the runs designed to detect antiprotons. A histogram of the apparent flight times of accidental coincidences is shown in Fig. 3(c). It will be noticed that the accidental coincidences do not show the close grouping of flight times characteristic of the antiproton or meson flight times.

Mass measurement.—A further test of the equipment has been made by adjusting the system for particles of

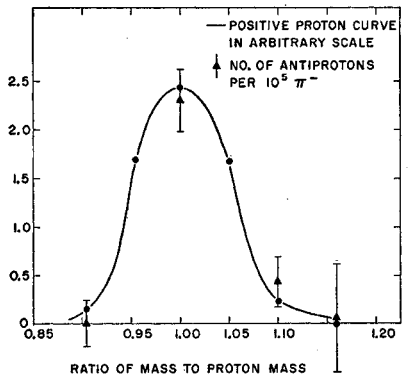


FIG. 4. The solid curve represents the mass resolution of the apparatus as obtained with protons. Also shown are the experimental points obtained with antiprotons.

different mass, in the region of the proton mass. A test for the reality of the newly detected negative particles is that there should be a peak of intensity at the proton mass, with small background at adjacent mass settings. By changing only the magnetic field values of $M1$, $M2$, $Q1$, and $Q2$, particles of different momentum may be chosen. Providing the velocity selection is left completely unchanged, the apparatus is then set for particles of a different mass. These tests have been made for both positive and negative particles in the vicinity of the proton mass. Figure 4 shows the curve obtained using positive protons, which is the mass resolution

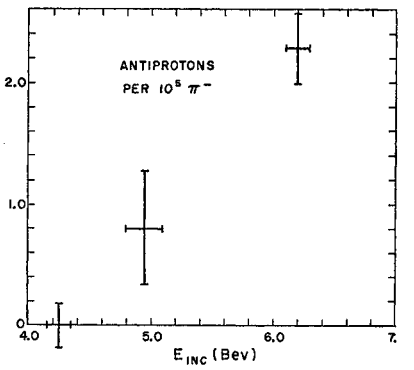


FIG. 5. Excitation curve for the production of antiprotons relative to meson production as a function of Bevatron beam energy.

curve of the instrument. Also shown in Fig. 4 are the experimental points obtained with antiprotons. The observations show the existence of a peak of intensity at the proton mass, with no evidence of background when the instrument is set for masses appreciably greater or smaller than the proton mass. This test is considered one of the most important for the establishment of the reality of these observations, since background, if present, could be expected to appear at any mass setting of the instrument. The peak at proton mass may further be used to say that the new particle has a mass within 5 percent of that of the proton mass. It is mainly on this basis that the new particles have been identified as antiprotons.

Excitation function.—A very rough determination has been made of the dependence of antiproton production cross section on the energy of the Bevatron proton beam. A more exact determination will be attempted in the future, but up to the present it has not been possible to monitor reliably the amount of beam actually striking the target. Furthermore, the solid angle of acceptance of the detection apparatus may not be independent of Bevatron energy since the shape of the orbit on which the antiprotons emerge depends somewhat on the magnetic field strength within the Bevatron magnet. It has, however, been possible to measure the ratio of antiprotons to mesons (both at momentum 1.19 Bev/c) emitted in the forward direction from the target as a function of Bevatron energy. The resulting approximate excitation function is shown in the form of three experimental points in Fig. 5.

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Even at 6.2 Bev, the antiprotons appear only to the extent of one in 44 000 pions. Because of the decay of pions along the trajectory through the detecting apparatus, this number corresponds to one antiproton in 62 000 mesons generated at the target. It will be seen from Fig. 5 that there is no observed antiproton production at the lowest energy. Although the production of antiprotons does not seem to rise as sharply with increasing energy as might at first be expected, the data indicate a reasonable threshold for production of antiprotons. It must again be emphasized that Fig. 5 shows only the excitation function relative to the meson excitation function, hence the true excitation function is not known at this time. If and when detailed meson production excitation functions become known, data of the type shown in Fig. 5 may allow a true antiproton production excitation function to be determined. It should also be mentioned that the angle of emission from the target actually varies slightly with Bevatron energy. At 6.2 Bev, it is 3°, at 5.1 Bev it is 6°, and at 4.2 Bev it is 8° from the forward direction at the Bevatron target.

Possible spurious effects.—The possibility of a negative hydrogen ion being mistaken for an antiproton is ruled out by the following argument: It is extremely improbable that such an ion should pass through all the counters without the stripping of its electrons. It may be added that except for a few feet near the target the whole trajectory through the apparatus is though gas at atmospheric pressure, either in air or, near the magnetic lenses, in helium gas introduced to reduce multiple scattering.

None of the known heavy mesons or hyperons have the proper mass to explain the present observations. Moreover, no such particles are known that have a mean life sufficiently long to pass through the apparatus without a prohibitive amount of decay since the flight time through the apparatus of a particle of proton mass is 10.2×10^{-8} sec. However, this possibility cannot be strictly ruled out. In the description of the new particles as antiprotons, a reservation must be made for the possible existence of previously unknown negative particles of mass very close to 1840 electron masses.

The observation of pulse heights in counters $S1$ and $S2$ indicates that the new particles must be singly charged. No multiply charged particle could explain the experimental results.

Photographic experiments directed toward the detection of the terminal event of an antiproton are in progress in this laboratory and in Rome, Italy, using emulsions irradiated at the Bevatron, but to this date no positive results can be given. An experiment in conjunction with several other physicists to observe the energy release upon the stopping of an antiproton in a large lead-glass Čerenkov counter is in progress and its results will be reported shortly. It is also planned to try to observe the annihilation process of the antiproton in a cloud chamber, using the present apparatus for counter control.

The whole-hearted cooperation of Dr. E. J. Lofgren, under whose direction the Bevatron has been operated, has been of vital importance to this experiment. Mr. Herbert Steiner and Mr. Donald Keller have been very helpful throughout the work. Dr. O. Piccioni has made very useful suggestions in connection with the design of the experiment. Finally, we are indebted to the operating crew of the Bevatron and to our colleagues, who have cheerfully accepted many weeks' postponement of their own work.

* This work was done under the auspices of the U. S. Atomic Energy Commission.

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Corrections supplied by the authors: In Fig. 3a the peak should be located at 40×10^{-9}s. In the caption for Fig. 3 the last sentence should read: "The ordinates show the number of events in each 10^{-9} sec interval."

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expected, assuming a geometric interaction cross section for antiprotons in copper. It has now been found[3] that the cross section in copper is about twice geometric, which explains this low yield.

In view of this result a new irradiation was planned in which (1) no absorbing material preceded the stack,

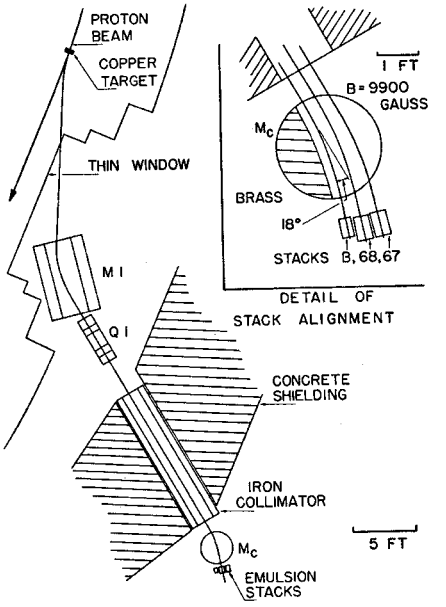


FIG. 1. Plan of the irradiation.

Example of an Antiproton-Nucleon Annihilation

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(Received March 8, 1956)

THE existence of antiprotons has recently been demonstrated at the Berkeley Bevatron by a counter experiment.[1] The antiprotons were found among the momentum-analyzed (1190 Mev/c) negative particles emitted by a copper target bombarded by 6.2-Bev protons. Concurrently with the counter experiment, stacks of nuclear emulsions were exposed in the beam adjusted to accept 1090-Mev/c negative particles in an experiment designed to observe the properties of antiprotons when coming to rest. This required a 132-g/cm^2 copper absorber to slow down the antiprotons sufficiently to stop them in the emulsion stack. Only one antiproton was found[2] in stacks in which seven were (2) the range of the antiprotons ended in the stack, and (3) antiprotons and mesons were easily distinguishable by grain density at the entrance of the stack. In order to achieve these three results it was necessary to select antiprotons of lower momentum, even if these should be admixed with a larger number of π^- than at higher momenta.

In the present experiment we exposed a stack in the same beam used previously, adjusted for a momentum of 700 Mev/c instead of 1090 Mev/c. Since the previous work[2] had indicated that the most troublesome background was due to ordinary protons, the particles were also passed through a clearing magnetic field just prior to their entrance into the emulsion stacks. The clearing magnet (M_c) had $B=9900$ gauss, circular pole faces of diameter 76 cm, and a gap of 18 cm, so particles scattered from the pole faces of the clearing magnet could be ignored on the basis of their large dip angle in the emulsions. With this arrangement we have achieved conditions in which the negative particles enter the emulsions at a well-defined angle, and extremely few positive particles enter the emulsions within the same

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range of angles. For the first time we have obtained an exposure in which more antiprotons than protons enter the stacks with the proper entrance angles. Under these conditions it is relatively easy to find antiprotons in these stacks even though approximately 5×10^5 negative π mesons at minimum ionization accompany one antiproton. The exposure arrangement is shown in Fig. 1. The beam collimation was such that at any given position at the leading edge of the stacks the angular half-width of the pion entrance angles is less than 1° both in dip and in the plane of the emulsions. This very small angular spread allowed us to apply strict angular criteria for picking up antiproton tracks, and thus helped to reduce confusing background tracks to a negligible level. The antiproton tracks were picked up at the leading edge of the emulsions on the basis of a grain count (~twice minimum) and angular criteria (angle between track and average direction of pions less than 5°) and were then followed along the track.

A number of antiproton stars have been observed in these nuclear emulsions.[4] The one we will describe here was found in Berkeley and is of particular interest since it is the first example of a particle of protonic mass ($m/M_p=1.013\pm0.034$) which on coming to rest gave rise to a star with a visible energy release greater than M_pc^2. This example thus constitutes a proof that the particles here observed undergo an annihilation process with a nucleon, a necessary requirement for Dirac's antiproton.

Description of the Event.—The particle marked P^- in Fig. 2 entered the emulsion stack at an angle of less than 1° from the direction defined by the π^- mesons in the beam. It came to rest in the stack and produced an 8-prong star. Its total range was $R=12.13\pm0.14$ cm. Table I gives the results of three independent mass measurements on the incoming particle. The first two methods listed in Table I use measurements made entirely in the emulsion stack. The third combines the range, as measured in the stack, with the momentum as determined by magnetic field measurements. For the position and entrance angle of this particle into the stack the momentum is $p=696$ Mev/c with an estimated 2% error. All three methods are in good agreement and give a mass of $m=1.013\pm0.034$ in proton mass units.

TABLE I. Mass measurements.

Method	Residual range cm of emulsion	Mass M/M_p
Ionization–range	2, 5.5, and 12	0.97 ±0.10
Scattering–range (constant sagitta)	0–1	0.93 ±0.14
Momentum–range	12.13+0.12 (air and helium equivalent)	1.025±0.037
Weighted mean		1.013±0.034

Of the particles forming the star, five came to rest in the emulsion stack, two left the stack (tracks numbered 4 and 8), and one disappeared in flight (track number 3). The tracks numbered 1, 4, and 6 in Fig. 2 were caused by heavy particles. Particle 4 was near the end of its range ($R_{res}=2$ mm) when it left the stack. Tracks 1 and 4 are probably due to protons and track 6 to a triton. However, owing to the large dip angles the assignments for tracks 1, 4, and 6 are not certain. Track 2 has the characteristics of a π meson and on coming to rest gives a 2-prong σ star. It is thus a negative π meson. Particle 5 came to rest and gave the typical π-μ-e decay, and was thus a positive π meson. From the measured range its energy would have been 18 Mev; however, after

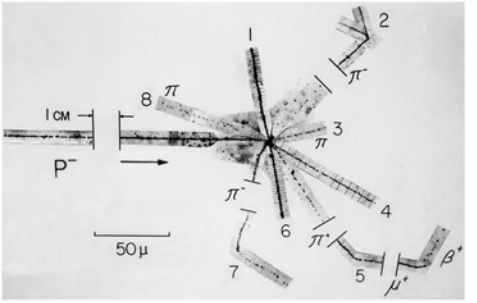


FIG. 2. Reproduction of the P^- star. The description of the prongs is given in Table II. The star was observed by A. G. Ekspong and the photomicrograph was made by D. H. Kouns.

0.22 mm it underwent a 22° scattering that appears to be inelastic. The initial energy as estimated from the grain density change was 30±6 Mev. Track 7 is very steep (dip angle=83.5°). The particle came to rest as a typical light ρ meson after traversing 30 emulsions. At the end of the track there is a blob and possibly an associated slow electron. The most probable assignment is a negative π meson, although a negative μ meson cannot be ruled out.

In addition to the three stopping π mesons there are two other tracks which we know were caused by light particles, presumably π mesons. Track 8 had $p\beta=190\pm30$ Mev/c and $g/g_0=1.10\pm0.04$, which is consistent with a π meson of 125±25 Mev energy, but is not consistent with a much heavier particle. After 16 mm it shows a 17° scattering with no detectable change in energy. Track 3 is very steep (dip angle=73.5°) and its ionization is about minimum. The particle traversed 81 plates and disappeared in flight after an observed range of 50 mm. The $p\beta$ has been determined by a new modification of the multiple scattering technique to be 250±45 Mev/c. The new method, which is applicable to steep tracks, is based on measurements of the coordinates of the exit point of the track in each emulsion with reference to a well-aligned millimeter grid[5] printed on each pellicle in the stack. A detailed description of this method will be given in a subsequent paper.

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TABLE II. Measurements and data on the eight prongs of the P^- star shown in Fig. 2.

Track number	Range mm	Number of plates traversed	Dip angle	Projected angle	$p\beta$ Mev/c	Ionization g/g_0	Identity	E_{kin} Mev	Total energy Mev
1	0.59	2	−56.5°	103°			$p(?)$	10	18
2	27.9	11	+6.5°	61.5°			π^-	43	183
3	>50	81	−73.5°	14.5°	250±45	1.10±0.04	$\pi(?)$	174±40	314±40
4	>14.2	16	+53°	318.5°			$p(?)$	70±5	78±5
5	6.2	3	+4°	305.5°			π^+	30±6	170±6
6	9.5	15	−63.5°	281°			$T(?)$	82	98
7	18.6	30	−83.5°	255°			π^-	34	174
8	>22.3	16	+33°	163°	190±30	~1	$\pi(?)$	125±25	265±25
							Total visible energy[a]:		1300±50 Mev
							For momentum balance:		≥100 Mev
							Total energy release:		≥1400±50 Mev

[a] To obtain the minimum possible value of the visible energy release, still consistent with our observations, one has to make the very unlikely assumptions about the identity of tracks 3, 6, 7, and 8: that tracks 3 and 8 are due to electrons, track 6 to a proton, and track 7 to a μ^- meson. The total visible energy release in this case becomes 1084±55 Mev. To this must be added at least 50 Mev to balance momentum, bringing the total energy release to ≥1134±55 Mev.

The observations do not allow us to rule out the possibility that tracks 3 and 8 are due to electrons. It is, however, very unlikely that a fast electron could travel 50 mm (1.7 radiation lengths) in the emulsion (as does track 3) without a great loss of energy due to bremsstrahlung. The energy (particle 3) deduced from the measured $p\beta(E=250$ Mev) must be considered a lower limit.

In Table II, the pertinent data on the eight prongs are summarized. The last column gives the total visible energy per particle (E_{kin}+8-Mev binding energy per nucleon, or E_{kin}+140-Mev rest energy per π meson) for the most probable assignments as discussed above. The total visible energy is 1300±50 Mev, and the momentum unbalance is 750 Mev/c. To balance momentum, an energy of at least 100 Mev is required in neutral particles (i.e., about 5 neutrons with parallel and equal momenta), which brings the lower limit for the observed energy release to 1400±50 Mev.

However, as some of the identity assignments to the star prongs are not certain, we have also computed the energy release for the extreme and very unlikely assignments, given at the foot of Table II, which are chosen to give the minimum energy release. In this case the total visible energy is 1084±55 Mev and the resultant momentum is 380 Mev/c, which to be balanced requires at least 50 Mev in neutral particles (three or four neutrons). In this unrealistic case the lower limit for the observed energy release is 1134±55 Mev, which still exceeds the rest energy of the incoming particle by about three standard deviations.

We conclude that the observations made on this reaction constitute a conclusive proof that we are dealing with the antiparticle of the proton.

A second important observation is the high multiplicity of charged π mesons (one π^+, two π^-, and two π mesons with unknown charge). The fact that so many π mesons escaped from the nucleus where the annihilation took place, together with the low number of heavy particles emitted (three), may indicate that the struck nucleus was one of the light nuclei of the emulsion (C, N, O). Two of the outgoing heavy prongs carried rather high energies (70 Mev for the proton, 82 Mev for the triton), and they may have resulted from the reabsorption of another two π mesons.

We are greatly indebted to the Bevatron crew for their assistence in carrying out the exposure. We also wish to thank Mr. J. E. Lannutti for help with measurements and the analysis of the event.

* This work was performed under the auspices of the U. S. Atomic Energy Commission.

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Antineutrons Produced from Antiprotons in Charge-Exchange Collisions*

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(Received October 3, 1956)

THE principle of invariance under charge conjugation gained strong support when it was found that the Bevatron produces antiprotons.[1–3] Another prediction of the same theory which could be tested experimentally was the existence of the antineutron. Additional interest arises from the fact that charge conjugation has somewhat less obvious consequences when applied to neutral particles than it has when applied to particles with electric charge.

The purpose of this experiment was to detect the annihilation of antineutrons produced by charge exchange from antiprotons. Because the yield of antineutrons was expected to be low, a relatively large flux of antiprotons was required. Protons of 6.2-Bev energy bombarded an internal beryllium target of the Bevatron (Fig. 1). With a system of two deflecting magnets and five magnetic lenses a beam of 1.4-Bev/c negative particles was obtained. Six scintillation counters connected in coincidence distinguished antiprotons from negative mesons by time of flight. In Figs. 1 and 2, F is the last counter of this system, which counted 300 to 600 antiprotons per hour. Antiprotons interacting in the thick converter, X (Fig. 2), sometimes produce antineutrons which pass through the scintillators S_1 and S_2 without detection and finally interact in the lead glass Čerenkov Counter C, producing there a pulse of light so large as to indicate the annihilation of a nucleon and an antinucleon.

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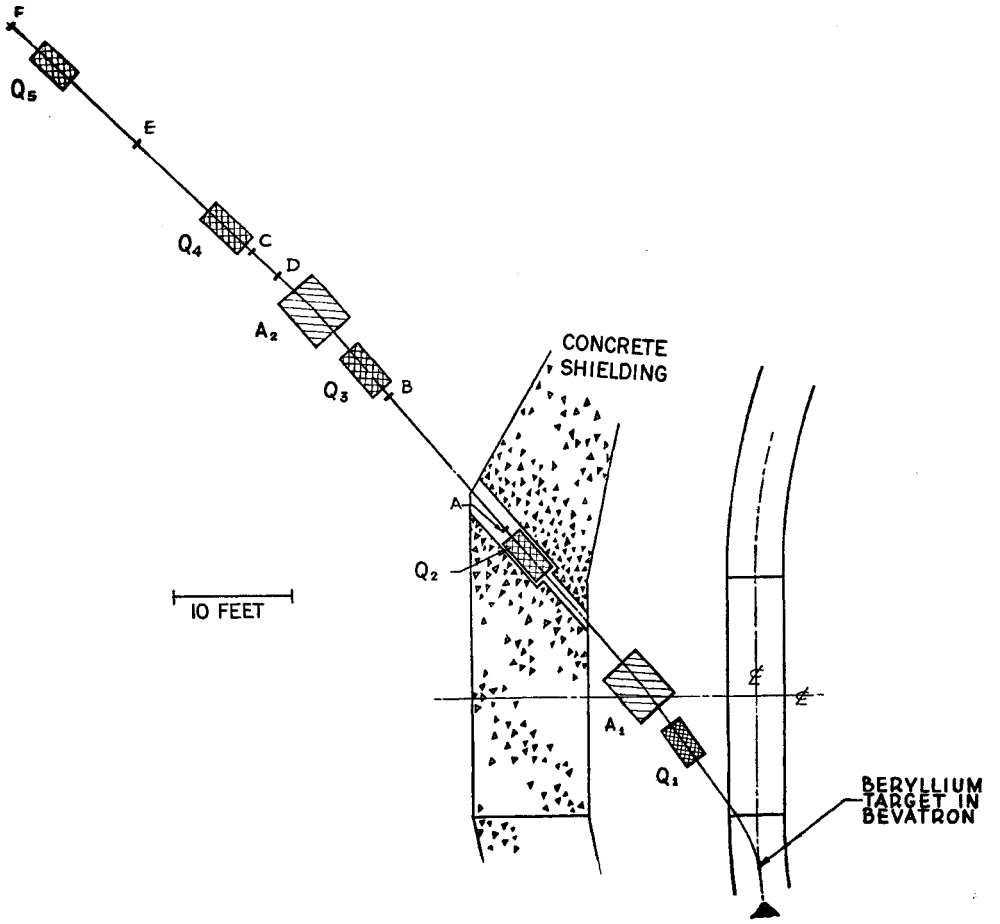


FIG. 1. Antiproton-selecting system. Q_1 through Q_5 are focusing quadrupoles. A_1 and A_2 are analyzing magnets. A through F are 4-by-4-by-$\frac{1}{4}$-inch scintillators.

The Čerenkov Counter C is a piece of lead glass, 13 by 13 by 14 in., density=4.8, index of refraction =1.8, viewed by 16 RCA 6655 photomultipliers. This instrument is similar to the one used in a previous experiment on antiprotons.[2] A 1-in. lead plate is placed between S_1 and S_2 to convert high-energy gamma rays which could otherwise be confused with the antineutrons. Ordinary neutrons and neutral mesons (heavier than pions) can be detected by the Čerenkov counter but their average light pulse is much smaller than that from the annihilation of an antineutron. However, a relatively small background of these neutral secondaries would distort the apparent spectrum of antineutrons.

To discriminate against these neutral secondaries, the charge-exchange converter, X, was made of a scintillating toluene-terphenyl solution, viewed by four photomultipliers connected in parallel. In this way neutral particles producing pulses in the Čerenkov counter ("neutral events") could be separated according to whether they originated in an annihilation, indicated by a large pulse in X, or in the less violent process expected to accompany the charge-exchange production of an antineutron. A quantitative criterion for this separation is derived from a comparison between the pulse-height spectra in X, shown in Fig. 3. The dashed curve, obtained in a separate experiment, is the spectrum produced by antiprotons passing through but not interacting in X. The sharp peak in the spectrum provides the calibration of X; the ionization loss for

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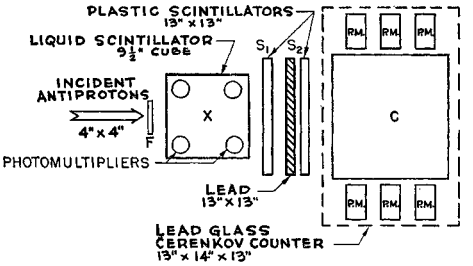


FIG. 2. Antineutron-detecting system. X is the charge-exchange scintillator; S_1 and S_2 are scintillation counters; C is a lead-glass Čerenkov counter (later a large scintillator).

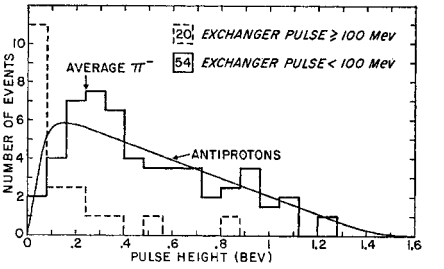


FIG. 4. Pulse-height spectrum in lead glass counter for neutral events. The solid histogram is for 54 antineutron events (energy loss in charge-exchange scintillator less than 100 Mev). Dashed histogram is for 20 other neutral events. Smooth solid curve is for antiprotons and is normalized to the solid histogram.

transmitted antiprotons is readily computed to be 50 Mev. The smooth solid curve of Fig. 3, obtained with the geometry of Fig. 2, represents all antiproton interactions in X from which no pulse was observed in S_1 and S_2, whether or not a pulse in C occurred. For those events in which a neutral particle produced a pulse in C, the histogram of Fig. 3 gives the pulse-height distribution.

The difference between the solid curve and the histogram is remarkable in that it shows that the rare interactions that produce neutral particles detected by the Čerenkov counter release much less energy in X than the other unselected interactions. In fact, the peak of the histogram is at a smaller pulse height than that which corresponds to the ionization loss of a noninteracting antiproton (50 Mev). This is what we should expect if the neutral particles were antineutrons, for in this case no nucleonic annihilation could take place in X. Conversely, production of other energetic neutrals should exhibit the characteristic large pulse of an annihilation event in X. The histogram suggests, therefore, that the apparatus detects a small background of events of this latter type. The pulse height of 100 Mev in Fig. 3 has been selected to separate this background from antineutron events. Figure 4 shows the separate pulse-height distributions in the Čerenkov counter for the events which produced in X a pulse less than 100 Mev (solid histogram), and for the events which produced a pulse larger than 100 Mev (dashed histogram). The great difference between the two histograms with respect to both average pulse height and shape confirms the interpretation by which the neutral events are divided into antineutrons and background.

The energy scale in Fig. 4 is obtained by relating the pulse height produced by π mesons going through the glass to the computed ionization energy loss of 240 Mev. This calibration was repeated every day.

The standard for annihilation pulses is provided by the smooth curve of Fig. 4, which is the pulse-height distribution for antiprotons entering the lead glass when S_1, S_2, and the lead plate are removed. Comparison of the solid histogram with this antiproton curve justifies our interpretation that the solid histogram is produced by antineutrons.

For comparison with the annihilation spectra of Fig. 4, Fig. 5 shows the spectra obtained with 750-Mev positive protons (solid curve) and with 600-Mev negative pions incident on the glass Counter C. These spectra indicate that large pulses are rarely produced by particles of such energies. From this it is apparent that even high-energy neutrons could not produce a spectrum like the solid histogram of Fig. 4.

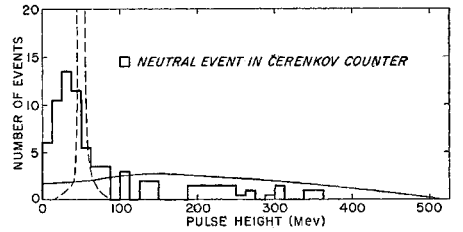


FIG. 3. Pulse-height spectrum in charge-exchange scintillator for 74 neutral events in lead glass. Histogram is for all neutral events. The smooth solid curve is for calibrating antiprotons for which no pulse occurred in S_1 or S_2. Smooth dashed curve is for noninteracting antiprotons. Smooth curves are each normalized to histogram.

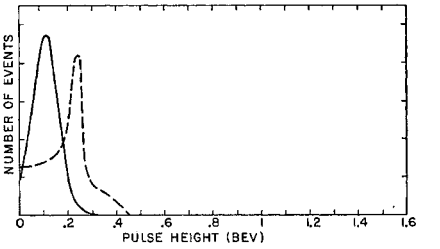


FIG. 5. Pulse-height spectrum in lead glass counter for π mesons (dashed curve) and for positive protons (solid curve). The curves are normalized.

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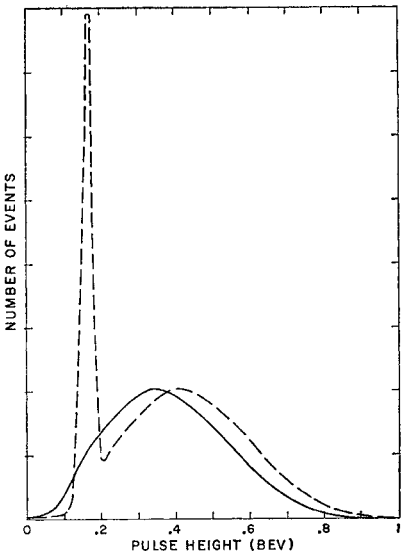


FIG. 6. Pulse-height spectrum of antiprotons in large scintillation counter. The dashed curve is for all incident antiprotons. The solid curve has had noninteracting antiprotons removed and includes a correction to permit comparison with antineutrons.

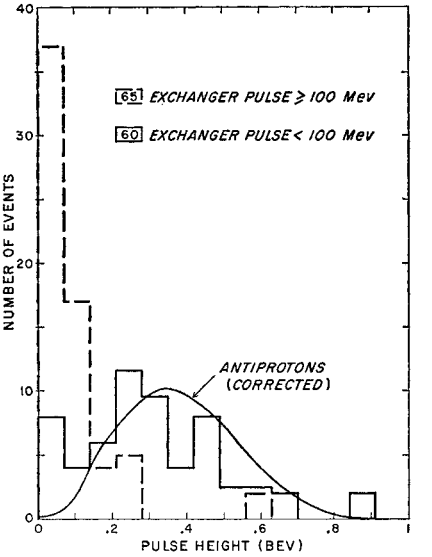


FIG. 7. Pulse-height spectrum in large scintillation counter for neutral events. Solid histogram is for 60 antineutrons (energy loss in charge-exchange scintillator less than 100 Mev). Dashed histogram is for 65 other neutral events. The smooth solid curve is the corrected antiproton curve from Fig. 6.

To determine the number of γ rays incident on S_1, the lead between S_1 and S_2 was removed. The number of neutral events per incident antiproton increased by a factor of 7. From the known probability that a single high-energy γ ray would be transmitted through 1 in. of lead without converting (3% for a γ-ray energy of 300 Mev), this observed increase shows that our neutral events contain at most 20% of γ-ray background before selection on the basis of pulse height in X.

The lead glass Counter C is very sensitive to γ rays and insensitive to ionization losses by slow particles. The desirability of comparing the spectra of antineutrons and antiprotons obtained with an entirely different type of detector led us to repeat the experiment with Counter C replaced by a liquid scintillator. This scintillator, 28 in. thick and 5 ft^3 in volume, was large enough to detect a substantial part of the energy of an annihilation event. For this experiment the thickness of the lead converter between S_1 and S_2 was increased to 1.5 in. As before, the antineutron detector was calibrated with antiprotons. The pulse-height distribution of antiprotons in the large scintillator is given by Fig. 6. The noninteracting antiprotons produce the sharp peak.

The solid smooth curve in Fig. 7 is the solid curve of Fig. 6, obtained by correcting the pulse height by 70 Mev toward lower energy because antiprotons ionize before interacting in the scintillator. Sixty neutral events were obtained (Fig. 7) after selection with the same criterion as before on the pulse height in X. Again the selected neutral spectrum and the antiproton spectrum are in agreement, although not so strikingly as with the lead glass. The sixty selected events apparently include some contamination. This interpretation is confirmed by the shape of the spectrum in X for all neutral events (Fig. 8). There are now many more neutral secondaries from inelastic collisions of antiprotons than there were in the experiment with the lead glass, and the separation between antineutrons and background is therefore not so good. The larger number of neutral secondaries is probably to be attributed to the greater sensitivity of the scintillator to neutrons.

The lead glass and the scintillator are of nearly equal efficiency in detecting the antineutrons. The observed

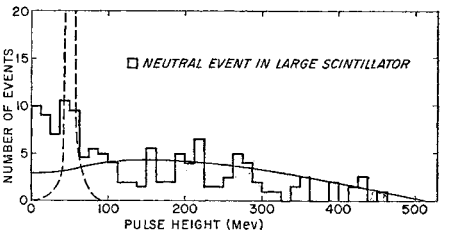


FIG. 8. Pulse-height spectrum in charge-exchange scintillator for 125 neutral events in large scintillator. The smooth curves are the same as in Fig. 3, each normalized to histogram.

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yield from about 20 g/cm² of toluene is 0.0030±0.0005 antineutrons per antiproton with the lead glass, and 0.0028±0.0005 with the liquid scintillator. With the assumption that the interaction cross section for antineutrons is the same as for antiprotons, the inefficiency of the detector due to attenuation in S_1, S_2, and the lead converter, and to transmission of the detector can be calculated, and is found to be about 50%. From the observed antineutron yield the mean free path for charge exchange of the type detected is about 2300 g/cm² of toluene (C_7H_8); or, in other words, the exchange cross section is about 2% of the annihilation cross section for this material. This corresponds to a cross section of approximately 8 millibarns in carbon for this process.

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