Observation of Antiprotons*

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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 anti-particle, 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 $S2$.

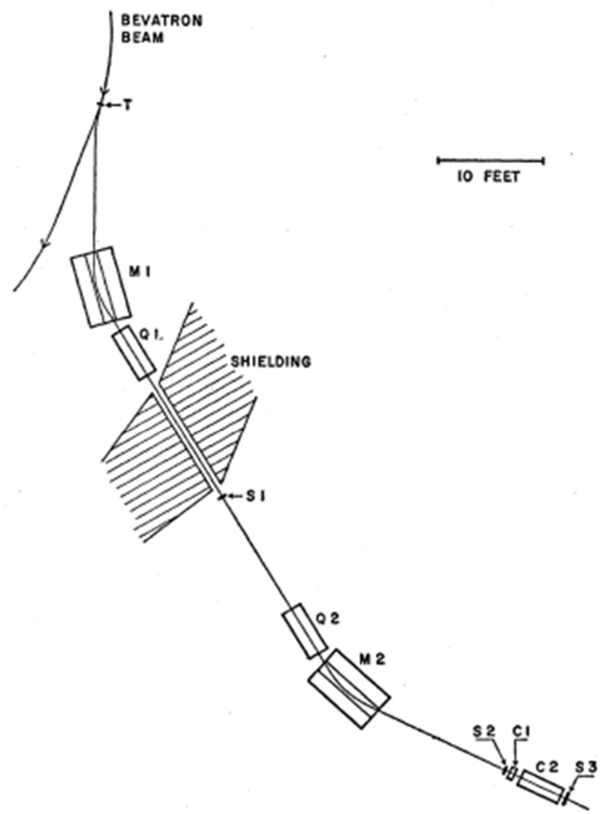

FIG. 1. Diagram of experimental arrangement. For details see Table I.

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 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.

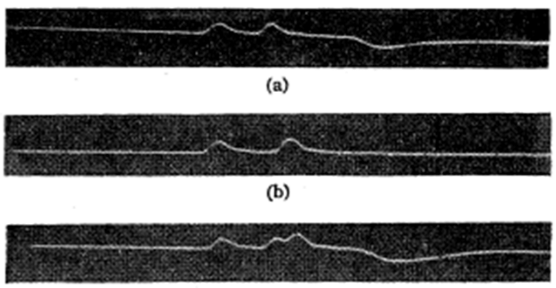

FIG. 2. Oscilloscope traces showing from left to right pulses from $S1$, $S2$, and $C1$. (a) meson, (b) antiproton, (c) accidental event.

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

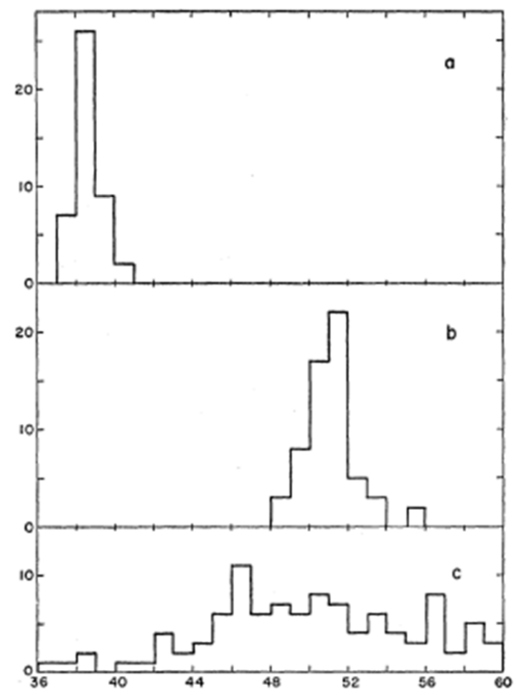

FIG. 3. (a) Histogram of meson flight times used for calibration. (b) Histogram of antiproton flight times. (c) Apparent flight times of a representative group of accidental coincidences. Times of flight are in units of 10^{-9} sec. The ordinates show the number of events in each 10^{-10}-sec intervals.

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 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 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.

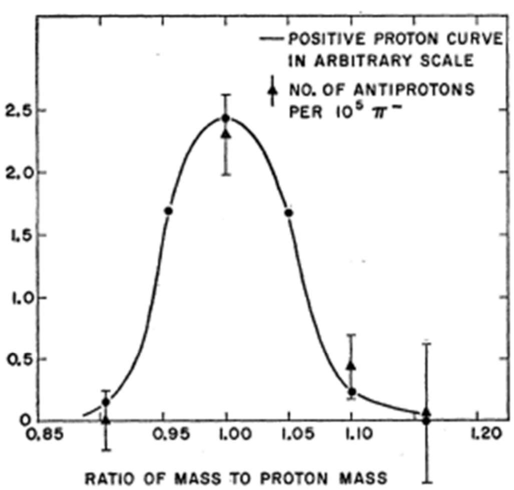

FIG. 4. The solid curve represents the mass resolution of the apparatus as obtained with protons. Also shown are the experimental points obtained with antiprotons.

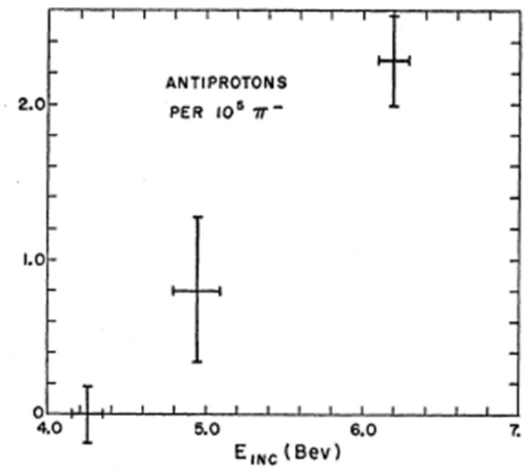

FIG. 5. Excitation curve for the production of antiprotons relative to meson production as a function of Bevatron beam energy.

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.

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.

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[1] G. Feldman, Phys. Rev. **95**, 1967 (1954).
[2] Evans Hayward, Phys. Rev. **72**, 937 (1947).
[3] Amaldi, Castagnoli, Cortini, Franzinetti, and Manfredini, Nuovo cimento **1**, 492 (1955).
[4] Bridge, Courant, DeStaebler, and Rossi, Phys. Rev. **95**, 1101 (1954).
[5] J. Marshall, Ann. Rev. Nuc. Sci. **4**, 141 (1954).

Observations of Negative K-Mesons and Charged Hyperons*

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TWO pellicle stacks were exposed, in a negative K-meson channel of the Bevatron, to particles from a target bombarded by 6.2-Bev protons. The pellicles were area scanned for stars produced by stopped K^--mesons. Thirty stars were found in the first stack and have been described in detail previously.[1] In the second stack, 177 stars produced by stopped K^--mesons were found. A summary of the salient features of these 207 K^--meson stars is reported here.

The prong distribution of the K^--meson stars with one or more prongs is shown in Fig. 1. The stopped K^--mesons which produced zero-prong stars or stars with only a fast π meson, would not be detected with a high efficiency by the method of scanning that was employed. A few such cases were found but are not included in this report.

In many cases, charged π mesons, charged hyperons, and hyperfragments are observed from the K^--meson stars. The frequency of these events is summarized in Table I.[2]

In 15 cases the hyperon ejected from the K^- star was clearly positively charged because it decayed from rest or decayed in flight into a proton. In 12 cases the hyperon was clearly negatively charged because it produced a star from rest. In addition there were 3 events where a particle of nucleonic mass, from a K-meson star, came to rest in the emulsion with an associated low-energy electron at the ending. Although it is possible that some of these electrons may be