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, $p + p \to p + p + p + \overline{p}$, 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.

Additional verification was provided by using Čerenkov counters. Čerenkov 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 Čerenkov 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 4.12.)

In another effort to confirm the antiparticle nature of the new negative particles, Brabant *et al.* placed a lead glass Čerenkov 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,

Figure 4.12: 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)

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 ± 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 an another experiment at the Bevatron established the existence of the antineutron **(Ref. 4.6)** by observing the 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.

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 Čerenkov 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 Čerenkov 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 of the incident antiproton.

The final annihilations occurring in the Čerenkov 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 4.13. The antilambda ($\overline{\Lambda}$) 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 4.14. 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.

Figure 4.13: 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)

Figure 4.14: 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)

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 Čerenkov 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 Čerenkov 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)]?

REFERENCES

4.1 O. Chamberlain, E. Segrè, C. Wiegand, T. Ypsilantis, "Observation of Antiprotons." *Phys. Rev.*, **100**, 947 (1955).

4.2 O. Chamberlain *et al.*, "Antiproton star observed in emulsion." *Phys. Rev.*, **101**, 909 (1956). Also *Nuovo Cimento* **X 3**, 447 (1956).

4.3 J. M. Brabant *et al.*, "Terminal Observations on 'Antiprotons'." *Phys. Rev.*, **101**, 498 (1956).

4.4 O. Chamberlain *et al.*, "Example of an Antiproton-Nucleon Annihilation." *Phys. Rev.*, **102**, 921 (1956).

4.5 W. H. Barkas *et al.*, "Antiproton-nucleon annihilation process." *Phys. Rev.*, **105**, 1037 (1957).

4.6 B. Cork, G. R. Lambertson, O. Piccioni, and W. A. Wenzel, "Antineutrons Produced from Antiprotons in Charge Exchange Collisions." *Phys. Rev.*, **104**, 1193 (1957).

4.7 L. Agnew *et al.*, "$\overline{p}p$ Elastic and Charge-Exchange Scattering at about 120 MeV." *Phys. Rev.*, **110**, 994 (1958).

4.8 D. Prowse and M. Baldo-Ceolin, “ Anti-lambda Hyperon.” *Phys. Rev. Lett.*, **1**, 179 (1958).

4.9 J. Button *et al.*, “The Reaction $\overline{p}p \to \overline{Y}Y$.” *Phys. Rev.*, **121**, 1788 (1961).

4.10 J. Button *et al.*, “Evidence for the reaction $\overline{p}p \to \overline{\Sigma}^0\Lambda$.” *Phys. Rev. Lett.*, **4**, 530 (1960).

4.11 C. Baltay *et al.*, “Antibaryon production in Antiproton–Proton Reactions at 3.7 BeV/c.” *Phys. Rev.*, **140**, B1027 (1965).

4.12 H. N. Brown *et al.*, “Observation of Production of a $\Xi^-\overline{\Xi}^+$ Pair.” *Phys. Rev. Lett.*, **8**, 255 (1962).; CERN-Ecole Polytechnique - Saclay Collaboration, “Example of anticascade ($\overline{\Xi}^+$) particle production in $\overline{p}p$ interactions at 3 GeV/c.” *Phys. Rev. Lett.*, **8**, 257 (1962).

4.13 A. Firestone *et al.*, “Observation of the $\overline{\Omega}^+$.” *Phys. Rev. Lett.*, **26**, 410 (1971).