predicted.[11]

The authors are indebted to D. Stroud and F. P. Esposito for many helpful discussions. This research was supported by the National Science Foundation, Grant No. DMR 78-09428.

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Evidence for the Existence of Cosmic-Ray Antiprotons

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(Received 31 August 1979)

Published without review at the request of Maurice M. Shapiro under policy announced 26 April 1976.

A search for cosmic-ray antiprotons was recently performed with use of a balloon-borne superconducting-magnet spectrometer. A total of 46 antiproton candidates were observed in the rigidity interval from 5.6 to 12.5 GV/c. Of these events 18.3 are expected to be atmospheric and instrumentation background. The $\bar{p}/p$ ratio is found to be $(5.2 \pm 1.5)\times10^{-4}$. This ratio is consistent with secondary production of antiprotons in the interstellar medium.

The results of a recent effort to observe antiprotons in the cosmic rays are presented in this paper. The data reported here were obtained from a balloon flight from Palestine, Texas, on June 21–22, 1979 under an average of 5.4 g/cm^2 of residual atmosphere. The data acquisition period was 2.84×10^4 sec long. Experiment live time (limited only by the telemetry rate) was 0.88 of the total time. The geomagnetic cutoff during the flight varied from 4.55 GV/c to 5.55 GV/c.

The magnet spectrometer consists of (a) a gas Cherenkov detector (called G) with a threshold Lorentz factor of 23.6, (b) scintillators $S1$ and $S2$ for charge determination, (c) eight multiwire proportional counters (MWPC) with spatial resolution of ~140 μm, and (d) seven scintillators ($P1$–$P7$) each separated by 1.2 radiation lengths of lead. Signals for G and all scintillators were pulse-height analyzed. In addition, the time of flight from $S1$–$P7$ was digitized. The magnet was operated at a current of 120 A producing a magnetic field from 10–40 kG in the MWPC region. Events satisfying the trigger criterion $S1\cdot P1\cdot P7$ were accepted for analysis. The geometric factor for this trigger is 315 cm^2 sr. The data were transmitted by telemetry and recorded on the ground. Determination of particle rigidities (momentum/charge) is done by using the MWPC data to reconstruct the particle trajectory through the magnetic field. An iterative least-squares fitting program then determines the best-fit trajectory and rigidity. Further details of the payload construction and performance may be found in Golden *et al.*[1]

At float altitude, the negatively charged, $Z=1$ component is comprised of π^- and μ^- mesons created in the atmosphere, electrons (both atmospherically produced and galactic), and antiprotons of atmospheric, and possibly galactic origin. The basic recognition scheme is to study the negatively charged particles which do not cascade (thus eliminating electrons) or emit Cherenkov light (thus eliminating μ^- and π^- mesons with rigidities above ~2.5 GV/c). In the region 4–15 GV/c, antiprotons should be the only surviving particles. In addition, if the antiprotons are predominantly of galactic origin, then the data observed in the 4–15–GV/c region should show the geomagnetic cutoff in the region 4.5–5.5 GV/c.

The above considerations highlight the necessity of good MWPC resolution and extremely high G-counter efficiency. The MWPC resolution is shown in Fig. 1(a). The horizontal axis is the inverse of momentum/charge which we call magnetic deflection. The data in Fig. 1 were gathered with use of atmospheric mesons in Palestine prior to the flight. The magnet was off during acquisition of the resolution data thus causing the mesons to simulate particles of infinite rigidity. The median resolution is 0.0081 (GV/c)$^{-1}$ corresponding to a maximum detectable rigidity

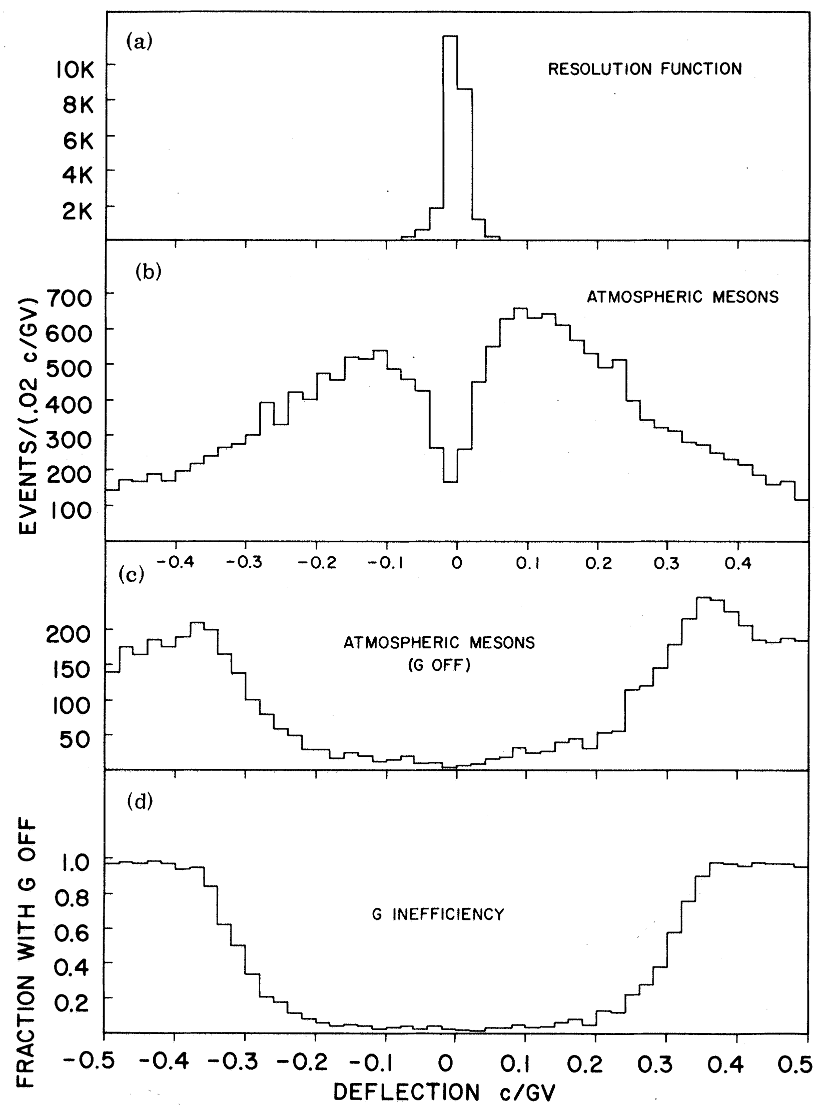

FIG. 1. Calibration data.

of 123 GV/c.

The efficiency of the G counter was also determined using atmospheric mesons prior to the flight. Figures 1(b) and 1(c) show the muon deflection spectrum and the spectrum of the G-counter-off muons measured at Palestine with the magnet charged to flight current. The resulting G-counter-inefficiency curve (i.e., fraction of events with G counter off) is shown in Fig. 1 (d).

In order to search for antiprotons of galactic origin, the following criteria were used: (1) At least 5 MWPC, including at least 1 each of the top, middle, and bottom pairs of the MWPC, registered the location of a single particle and that the reconstructed trajectory fitted the equations of motion with a $\chi^2 < 50$; (2) $S1$ and $S2$ indicate that a $Z=1$ particle traversed the payload; (3) the particles traverse the most sensitive portion of the G counter; (4) G is off; (5) the particles traverse the shower counter without cascading.

Figure 2 shows the deflection distribution of events satisfying the five selection criteria. Events on the right of zero deflection are positively charged and those on the left are negative. On the extreme left of the plot one would expect π^- and μ^- mesons which have a Lorentz factor below the threshold of 23.6. The smooth curve is a folding of the G-counter-inefficiency curve and the expected π^- and μ^- fluxes as determined using the cross sections of Badhwar *et al.*[2] The curve is normalized to the flux in the -0.3- to -0.5-(GV/c)$^{-1}$ region and agrees within 10% with the expected rate based on the flux of protons observed on the right-hand portion of the figure. The total number of π^- and μ^- events expected between -0.18 and -0.08 (GV/c)$^{-1}$ is 5.0

Events to the right of 0.0 (GV/c)$^{-1}$ deflection are predominantly G-counter-off protons. Note that the geomagnetic field cuts off the proton flux at > 0.2 (GV/c)$^{-1}$. The smooth curve on the right represents a folding of a power-law proton energy spectrum $E^{-2.75}$, the G-counter-inefficiency curve for protons (derived from the muon observations in Fig. 1) and the experiment resolution function. Note that the spillover of the proton data onto the negative-deflection side is expected to contribute only 0.2 events from -0.18 to -0.08 (GV/c)$^{-1}$.

Another source of negative-deflection events is nuclear interactions in the mirror of the G counter which produce π^- mesons that traverse the

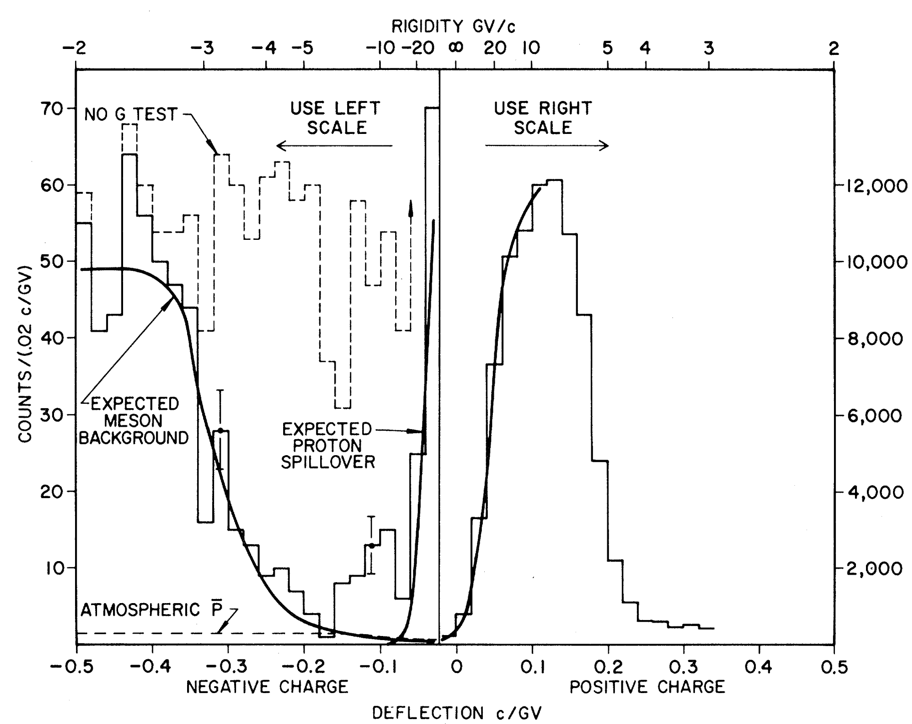

FIG. 2. Flight data. Events selected have $Z=1$, no shower and at least five good chambers with $\chi^2 < 50$. The dashed histogram is observed data without a G test. The solid histogram is observed data with G counter off.

lower portions of the experiment and satisfy our selection criteria. Fortunately, the MWPC are extremely efficient at recognizing multiple-particle events. This means that any mirror interaction must be caused by a nearly horizontal proton that produces one and only one large-angle, high-energy π^- that traverses the experiment geometry. Note that this background would be relatively flat and extend to rigidities well below geomagnetic cutoff. Badhwar *et al.*[3] have conservatively estimated this flux to be less than 6.2×10^{-5} of the proton flux thus contributing fewer than 3.4 events in the -0.18- to -0.08-$(\mathrm{GV}/c)^{-1}$ region. A cross check of the time-of-flight value reveals only 4 events in the overlap region between up- and down-moving particles. A conservative estimate results in 2.5 events being attributable to albedo protons. The combined π^-, μ^-, albedo, spillover, and mirror interaction processes lead to an expected 11.1 events from -0.18 to -0.08 $(\mathrm{GV}/c)^{-1}$ whereas 46 events are observed in this region. This is a 10.5-standard-deviation excess. The excess appears in the G-counter-off data but not in the G-counter-on data. Thus the particles must be more massive than ~400 MeV/c^2. Note that the excess shows a definite decrease near the geomagnetic cutoff. The most straightforward explanation is that the excess events are a combination of atmospheric and galactic antiprotons.

The flux of atmospherically produced $\bar{p}$ can be calculated using the $\bar{p}$ production cross sections of Badhwar *et al.*[2] The expected background is shown as the dashed curve in Fig. 2. It is normalized with use of the cross sections, the numbers of incident high-energy protons, and the 5.4 g/cm^2 of matter above the experiment. The total number of atmospheric $\bar{p}$ expected from -0.18 to -0.08 $(\mathrm{GV}/c)^{-1}$ is 6.5. K^- mesons are also produced in the atmosphere and the payload and could pass our $\bar{p}$ selection criteria. However, at 5–10 GV/c virtually all atmospheric K^- have decayed before reaching the payload. Payload-produced K^- are estimated to be less than 10% of the atmospheric $\bar{p}$ and have been neglected. Thus the estimated number of galactic antiprotons is 28.4. The $\bar{p}/p$ ratio is then estimated to be $(5.2\pm1.5)\times10^{-4}$ for the interval -0.18 to -0.08 $(\mathrm{GV}/c)^{-1}$ (i.e., 5.6 to 12.5 GV/c). As a final test for possible systematic errors, the $\bar{p}/p$ ratio was examined with more restrictive tests on the number of good MWPC readouts, χ^2 of the trajectory fit, and pulse height in the G counter. No significant changes in the $\bar{p}/p$ ratio were found.

Badhwar *et al.*[2] and Gaisser and Maurer[4] have calculated the $\bar{p}/p$ ratio expected from production of $\bar{p}$ by interactions of cosmic rays with the interstellar medium. Badhwar *et al.* predict a ratio $\bar{p}/p=4\times10^{-4}$ in the region 5.6 to 12.5 GeV/c and Gaisser and Maurer predict that $\bar{p}/p$ will vary from 10^{-4} at 5.6 GeV/c to $\sim2\times10^{-4}$ at 12.5 GeV/c. The Gaisser and Maurer predictions are based on scaling theory whereas Badhwar *et al.* use an empirically determined representation of measured cross sections (accurate to about 30%). Both calculations are based on the leaky-box model and assume 5 g/cm^2 of interstellar material are traversed by the primary cosmic rays.

The results presented here are consistent with the predictions of Badhwar *et al.*[2] and with the observational upper limits established by Badhwar *et al.*[3] The astrophysical implications of antiproton observations have been discussed by Stiegman,[5] Badhwar *et al.*,[2] and Gaisser and Levy.[6] Given the $\bar{p}/p$ ratio reported here, it is reasonable to infer that the antiproton lifetime is at least comparable to the cosmic-ray storage time (on the order of 10^7 yr) and that most of the matter traversed by high-energy cosmic rays is encountered after their acceleration.

Special thanks are due to National Aeronautics and Space Administration—Johnson Space Center and Wallops Flight Center, Lockheed Electronics Corporation (Houston) and the National Scientific Balloon Facility at Palestine, Texas. This work was supported by the National Aeronautics and Space Administration Contract No. NAS 9-15560.

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