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MEASUREMENT OF COSMIC-RAY ANTIPROTONS FROM 3.7 TO 19 GeV

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ABSTRACT

The antiproton-to-proton ratio, $\bar{p}/p$, in cosmic rays has been measured in the energy range 3.7–19 GeV. This measurement was carried out using a balloon-borne superconducting magnetic spectrometer along with a gas Cerenkov counter, an imaging calorimeter, and a time-of-flight scintillator system. The measured $\bar{p}/p$ ratio was determined to be $1.24^{+0.68}_{-0.51} \times 10^{-4}$. The present result, along with other recent observations, shows that the observed abundances of antiprotons are consistent with models in which antiprotons are produced as secondaries during the propagation of cosmic rays in the Galaxy.

Subject headings: cosmic rays — elementary particles

1. INTRODUCTION

The understanding of the origin of antiprotons, $\bar{p}$'s, in cosmic rays has changed since their discovery in 1979 by Golden et al. (1979) and the subsequent low-energy measurements by Buffington, Schindler, & Pennypacker (1981). These early experiments reported abundances which were higher than one would expect if the $\bar{p}$'s originated in the interactions of cosmic-ray nuclei with the interstellar gas. While numerous interpretations were offered to account for the observed excess of $\bar{p}$'s (Stephens & Golden 1987 and references therein), additional experiments using better detector technology were proposed to verify these results. Some of these experiments (Salamon et al. 1990; Streitmatter et al. 1989) provided upper limits which were significantly lower than the measured $\bar{p}$ abundance below a few hundred MeV (Buffington et al. 1981). The results from the recent balloon-borne experiments (Orito et al. 1995; Labrador et al. 1995) have demonstrated that the observed $\bar{p}$ energy spectrum below 3 GeV is consistent with the hypothesis that $\bar{p}$'s are produced as secondaries. However, the secondary production hypothesis cannot explain the early results of Golden et al. (1979), which span the energy region between 5 and 12 GeV. We report in this Letter a new result covering the energy region between 3.7 and 19 GeV. This is the first result to report new $\bar{p}$ observations over an energy range that includes that of the original observations by Golden et al. (1979). These results were obtained using the MASS91 Matter Antimatter Superconducting Spectrometer (MASS91 instrument), an improved version of the original payload flown in 1979.

2. INSTRUMENT

The MASS91 instrument, shown in Figure 1, is composed of a magnet spectrometer, a plastic scintillator time-of-flight (TOF) system, a gas Cerenkov counter, and an imaging calorimeter. The spectrometer consists of a single-coil superconducting magnet with a system of drift chambers (DCs) (Hof et al. 1994) and multiwire proportional chambers (MWPCs) (Golden et al. 1991). These were used to determine the particle's trajectory in the magnetic field. The trajectory was measured at 19 positions (12 DCs, 7 MWPCs) in the bending direction, x, and 11 positions (8 DCs, 3 MWPCs) in the nonbending direction, y. The most probable value for the maximum detectable rigidity (MDR) was 210 GV c^{-1} for singly charged particles.

The TOF system was made of seven plastic scintillator paddles grouped in two planes separated by 236 cm. Each of the upper paddles was composed of two scintillators stacked on top of one another, and these scintillators were individually viewed at one end by a Hamamatsu R2490-01 phototube. The

[1] Deceased.

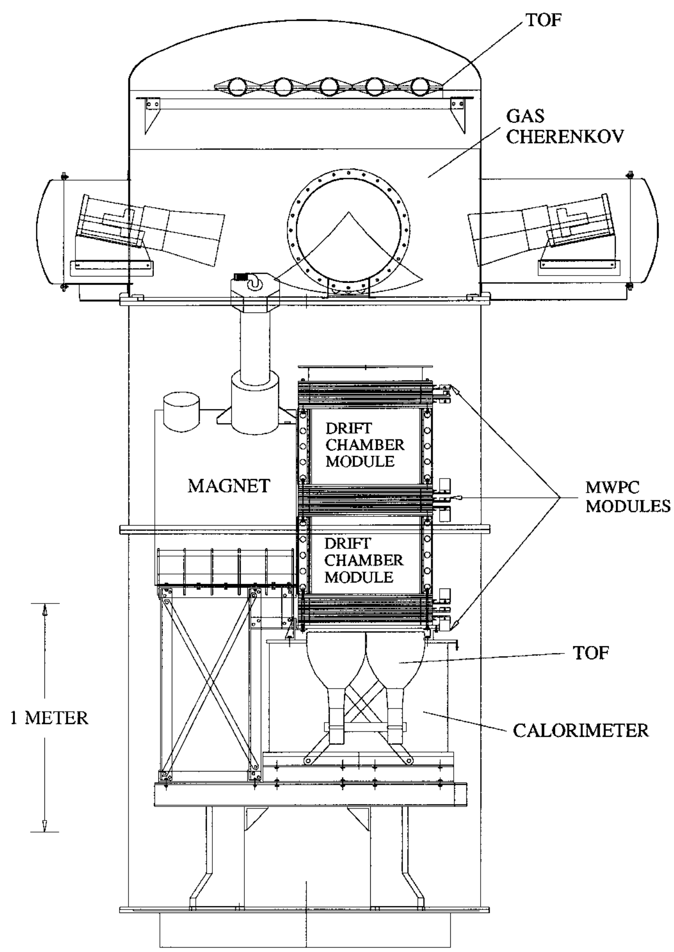

FIG. 1.—Schematic diagram of the MASS91 apparatus.

bottom paddles contained a single scintillator layer, viewed by phototubes at both ends. With this configuration we were able to achieve a timing resolution of 370 picoseconds for singly charged particles, and, as a result, upward-going albedo particles were separated from downward-moving particles by more than 35 σ.

The gas Cerenkov counter was used as a threshold device to separate the light particles (muons, electrons, and positrons) from the heavier protons and antiprotons. During the flight the gas volume was filled with Freon 12, which has a Cerenkov threshold of $\gamma_{\rm th} \approx 25$, where γ is the Lorentz factor. The Cerenkov light was focused by a four-segment mirror onto four phototubes. Each segment was a pie-shaped section of a spherical mirror having a radius of 101.6 cm.

The calorimeter consisted of 40 layers of brass streamer tubes. Each of these layers had 64 streamer tubes, and alternate layers were arranged perpendicular to each other in the x- and y-directions. The walls of these tubes served as the passive converting material providing 7.33 radiation lengths for the electromagnetic cascade development and an interaction mean free path of 0.75 for protons.

This instrument was flown on 1991 September 23 from Fort Sumner, New Mexico, where the geomagnetic cutoff rigidity is approximately 4.5 GV c^{-1}. The balloon floated at an altitude of about 36 km for 9.8 hr, and the mean residual atmosphere during the float was 5.8 g cm^{-2}.

3. ANALYSIS AND RESULTS

We first selected particles with charge $|Z| = 1$ by making use of three independent dE/dx measurements from the TOF scintillators. Using the TOF information, we next rejected all albedo particles from the subset containing the charge $|Z| = 1$ particles. In order to ensure a reliable rigidity measurement, the following criteria were applied: (a) There should be at least 15 good position measurements in the bending direction, x, and eight in the nonbending direction, y, for fitting the trajectory. (b) The reduced χ^2 values of the fitted track were required to be ≤ 4 for both the x- and y-directions. (c) The rigidity determined by the full tracking system and that obtained using the upper half and the lower half of the tracking system independently were required to be consistent with each other. This requirement is essential to eliminate events which undergo hard scattering. (d) Only ≤ 2 DC layers in either orientation were allowed to have an additional hit at distances ≥ 4 cm from the fitted track. (e) The position of the track in the TOF scintillators as derived from timing information and the intercepts of the calculated trajectory from the spectrometer had to agree within 10 cm. The last two criteria were implemented to reject events containing multiple tracks.

The gas Cerenkov counter is very important to eliminate muons, which are the major source of background in the atmosphere against $\bar{p}$'s. Therefore, the rigidity range of the $\bar{p}$ measurement was limited to less than the Cerenkov threshold for protons at the upper end and well above the Cerenkov threshold for muons at the lower end. Thus, negatively charged particles in this rigidity range, which were not accompanied by Cerenkov light, were identified as $\bar{p}$ candidates. An extensive study of the gas Cerenkov counter performance was carried out using the data taken on the ground prior to the flight. These data were then compared with Monte Carlo simulations. The mirror surface was mapped on a 2.5×2.5 cm^2 grid using the intercepts of the calculated trajectories of muons, as measured by the spectrometer. Those regions of the mirror having a response corresponding to more than 10 photoelectrons (pe's), for $\beta = 1$ particles were used in the analysis. It may be noted that during the flight the average response for these regions of the mirror was 18.4 pe's. The efficiency of the Cerenkov detector in suppressing muons in the range between about 3.7 and 19 GeV was better than 99.8%.

Electrons were identified and removed by the presence of an electromagnetic cascade in the imaging calorimeter and by a saturated signal in the Cerenkov detector. The above selection criteria were applied to all events, and particles with either charge sign were treated identically throughout the analysis. The geometric factor of the instrument, after including all of the selection criteria, was 137 cm^2 sr. Figure 2 shows the distribution of events as a function of deflection (1/rigidity) after applying all the above selection criteria. The right-hand side of the histogram is the proton distribution. The left-hand side shows the negative deflection histogram along with a solid curve that represents the various backgrounds. Negative deflection events within the deflection range from 0.05 to 0.22 are the $\bar{p}$ events. We have detected 11 $\bar{p}$'s in the rigidity range from 4.55 to 20 GV c^{-1}, while in the same rigidity range we observed 69,311 protons. This range of rigidity corresponds to a kinetic energy range from 3.70 to 19.08 GeV. The lower limit of the rigidity range corresponds to the observed geomagnetic cutoff at Fort Sumner, and the upper limit corre-

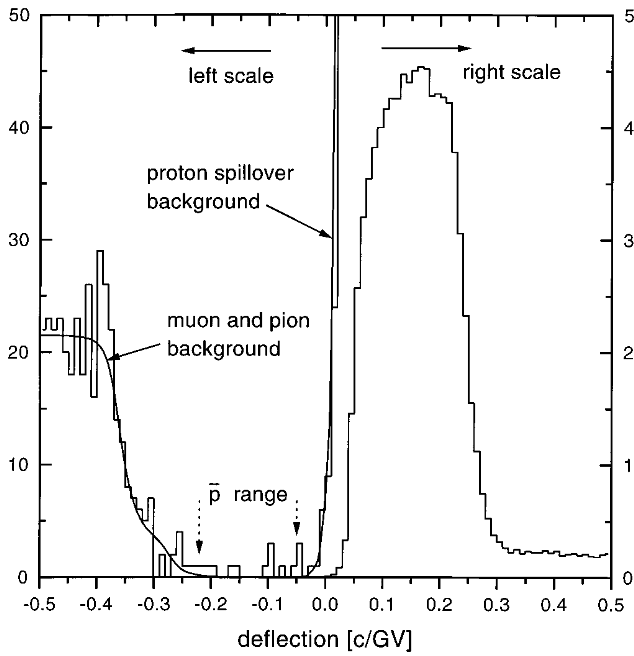

FIG. 2.—Data from the flight with $|Z| = 1$, no shower, no Cerenkov light, and the tracking cuts described in the text.

sponds to a value 2 σ below the $\bar{p}$ Cerenkov threshold rigidity. The upper value was chosen to restrict the analysis to $\bar{p}$ and proton events which, to within the resolution of the spectrometer, cannot produce any Cerenkov light. The spillover correction can be evaluated by studying the ratio of the deflection to the uncertainty in the deflection, η/σ_η. All of the $\bar{p}$ events gave a η/σ_η value greater than 5.2; thus the spillover correction for this measurement is negligible. The number of observed $\bar{p}$'s must be corrected for the losses in the detector and then for atmospherically produced $\bar{p}$'s. These procedures are described below.

First we considered the loss of $\bar{p}$ events that interacted below the bottom TOF plane and were self-vetoed by the upward-moving annihilation products. Since the total inelastic cross section including annihilation is approximately a linear function of deflection over the energy region of interest, we had chosen the energy corresponding to the mean deflection to evaluate the correction factors. Out of the 11 observed $\bar{p}$ events, six interacted in the calorimeter. Using the five noninteracting $\bar{p}$'s that we observed, we predicted that we should see 10.15 ± 4.54 $\bar{p}$ interactions in the calorimeter. This is in agreement with the 6 ± 2.45 interacting events that we observed. In order to check whether these numbers are consistent with each other within the estimated errors, we analyzed the raw data with no restriction on the bottom TOF scintillator and relaxing the criteria on the tracking system to allow multiple tracks. We predicted that the new relaxed criteria would have yielded at least one additional $\bar{p}$, and we found none. As a second cross check, we considered the four $\bar{p}$'s that interacted in the upper half of the calorimeter. On the basis of these events, we expected to see 2.3 ± 1.2 interactions in the lower half of the calorimeter, and we observed 2. From these additional checks we conclude that there was no significant loss of $\bar{p}$'s as a result of self-vetoing.

The background due to albedo as well as that due to spillover from the positive deflection side are both negligible. Because of the inefficiency (0.2%) of the Cerenkov counter, we expected a small fraction of the selected $\bar{p}$'s to be muons. In order to estimate this number, we calculated the number distribution of muons which survive the selection criteria. This distribution was determined by folding the Cerenkov counter inefficiency and the spectrometer resolution on the muon spectrum as observed before applying the selection criteria. The calculated distribution is shown as a smooth curve on the left-hand side of Figure 2, and on this basis we expected a muon contamination of only 0.2 events. The correction factor for the interaction losses in the instrument was found to be 1.098 for antiprotons and 1.063 for protons. Thus, the corrected number of $\bar{p}$ events at the float altitude was 11.86. In order to estimate the number of $\bar{p}$'s produced in the 5.8 g cm^{-2} of overlying atmosphere, we made use of the calculations of Stephens (1993) and normalized the calculated proton flux at the float altitude to the measured number of protons above 10 GeV. We estimated that 3.06 of the observed $\bar{p}$'s were produced in the overlying atmosphere. The remaining $\bar{p}$'s were then corrected for annihilations in the overlying atmosphere. No correction was made for nonannihilating inelastic interactions, since the cross section, at these energies, is the same for antiprotons and protons. The correction factor for annihilations was found to be 1.035 for the $\bar{p}/p$ ratio at the float altitude. Starting with 11 identified antiprotons and applying the above correction factors, we obtain a $\bar{p}/p$ ratio of $1.24^{+0.68} \times 10^{-4}$ in the energy range from 3.70 to 19.08 GeV at the top of the atmosphere. The quoted errors reflect the statistical uncertainty of the number of measured $\bar{p}$'s multiplied by the correction factors.

4. CONCLUSION

The present value of the $\bar{p}/p$ ratio is smaller than the only other existing result in this energy region, obtained by Golden et al. (1979) in the rigidity range 5.6–12.5 GV c^{-1}. When we

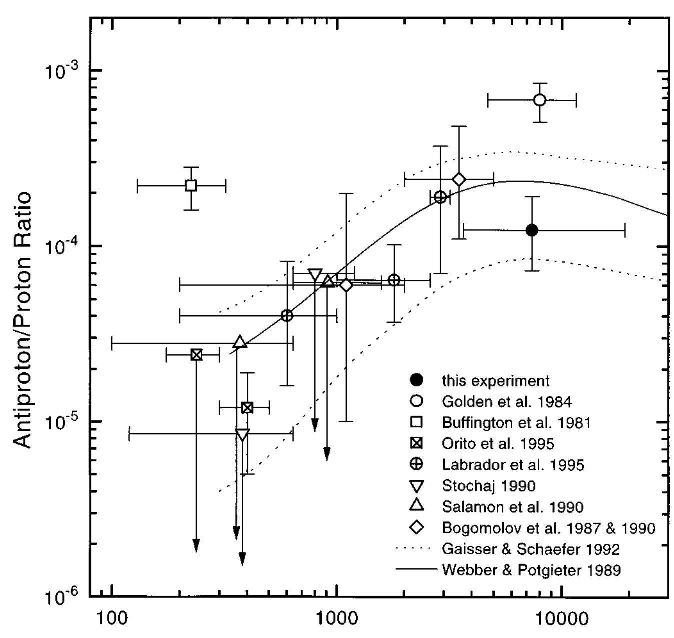

FIG. 3.—Measured antiproton/proton ratio from the MASS91 experiment in comparison with other data and calculations by Gaisser & Schaefer (1992) and Webber & Potgieter (1989).

restricted our rigidity interval to match closely the original measurement, we found no change in our result within the quoted error. Although the principal structure of the two instruments is similar, we are confident that the $\overline{p}/p$ reported here is reliable because of the large number of instrumental improvements. The new tracking system provides for more than twice the number of position measurements along the trajectory of a particle. This allows for consistency checks to be made on the rigidity determination. These checks are useful in eliminating hard-scatter proton events which mimic negative curvature events. The present spectrometer has an MDR nearly a factor of 2 better than that of the original instrument. This provides for an improved rejection power for spillover protons. The optical system of the Cerenkov detector has been improved to both increase the light collection efficiency and reduce the amount of material (grammage) above the spectrometer. Nearly a factor of 2 more photoelectrons are collected with this system compared to the original gas counter. These improvements provide for better reliability and a higher rejection power for the present configuration. Thus, we are confident that the $\overline{p}/p$ ratio reported here is reliable.

In Figure 3 we have plotted the result of this measurement along with the other currently available data. We have also shown by the two dashed curves the estimated ratio by Gaisser & Schaefer (1992) and by the solid curve the predictions by Webber & Potgieter (1989). These estimated ratios were based on the hypothesis that the cosmic ray-antiprotons are produced as secondaries by the cosmic-ray interactions during their propagation in the Galaxy. Thus we conclude that to within the uncertainties of the existing measurements, the observed antiprotons are consistent with the secondary production hypothesis. It is essential to improve the statistics on the $\overline{p}$ measurements, so that valuable information on the propagation of cosmic rays and on solar modulation of cosmic rays can be obtained.

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