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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 the cosmic rays has been measured in the energy range from 3.7 to 19 GeV. This measurement was carried out using a balloon-borne superconducting magnetic spectrometer along with a gas Cherenkov 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 show 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.

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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 et al. (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 the 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 unambiguously demonstrated that the observed \bar{p} energy spectrum below 3 GeV is consistent with the hypothesis that \bar{p} 's are produced as secondaries in the frame work of the leaky box model for cosmic ray propagation. However, the secondary production hypothesis can not explain the 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, which is the first to verify the result of Golden et al. (1979) and covers a wider momentum range of 4.55 to 20 GeV. These results were obtained using the MASS91 (Matter Antimatter Superconducting Spectrometer) instrument, an improved version of the original payload flown in 1979.

2. Instrument

The MASS91 instrument, shown in Fig.1, is composed of a magnet spectrometer, a plastic scintillator time-of-flight (TOF) system, a gas Cherenkov counter and an imaging calorimeter. The spectrometer consists of a single-coil superconducting magnet with a

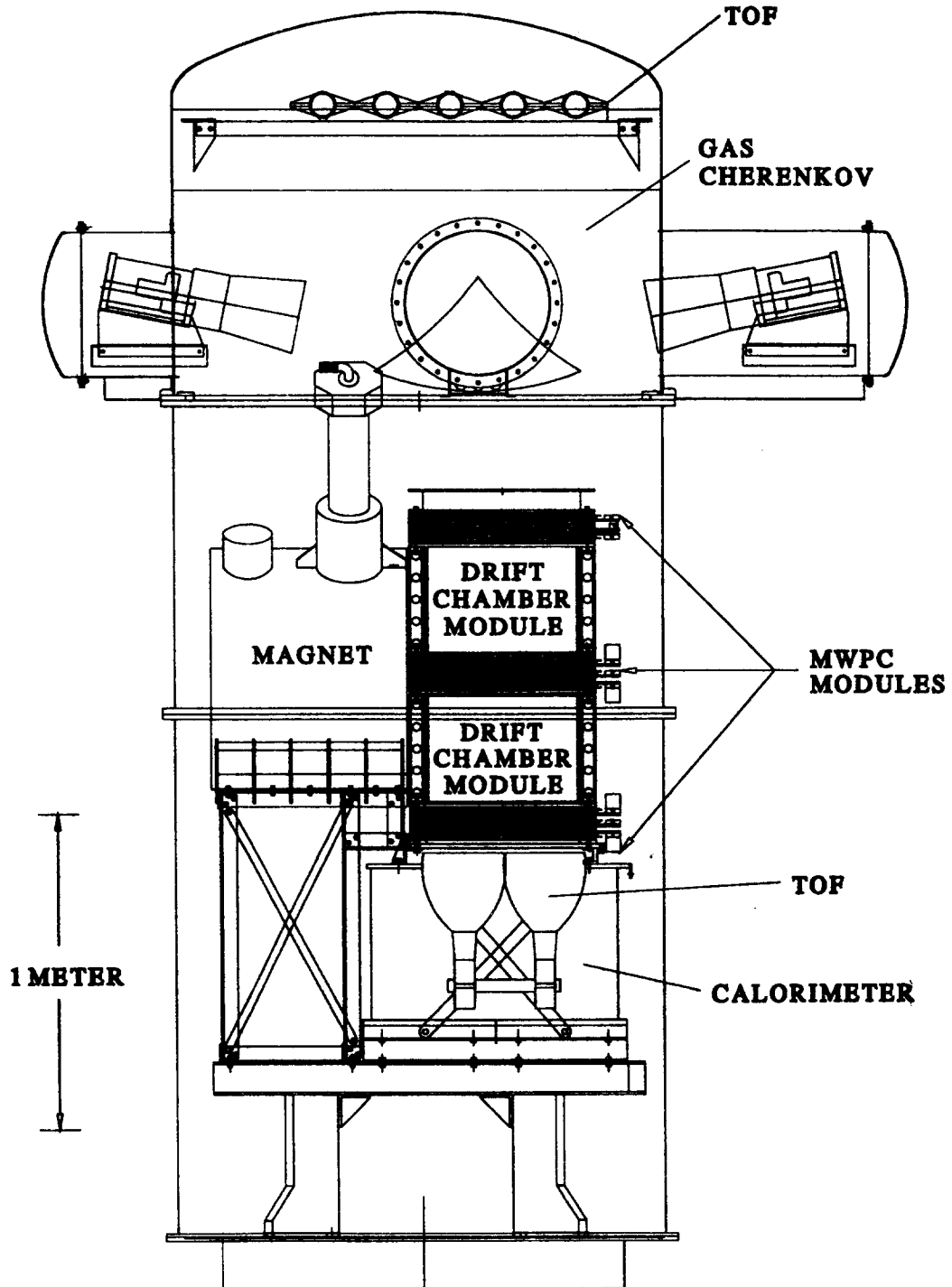


Fig. 1.— Schematic diagram of the MASS91 Apparatus.

system of drift chambers (DC) (Hof et al., 1994) and multiwire proportional chambers (MWPC) (Golden et al., 1991), and was used to determine the particle's trajectory in the magnetic field. The trajectory was measured at 19 positions (12 DC, 7 MWPC) in the bending direction, x , and 11 positions (8 DC, 3 MWPC) in the non-bending, y , direction. The most probable value for the maximum-detectable-rigidity (MDR), was 210 GV/c 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 were 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 bottom paddles were a single scintillator layer, viewed by phototubes at both ends. With this configuration, we were able to achieve a timing resolution of 370 ps for singly charged particles, and as a result upward going albedo particles were separated from downward moving particles by more than 35 sigma.

The gas Cherenkov 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 Cherenkov threshold of $\gamma_{th} \approx 25$, where γ is the Lorentz factor. The Cherenkov light was focused by a 4 segment mirror onto 4 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 September 23, 1991 from Fort Sumner, New Mexico, where the geomagnetic cut off rigidity is approximately 4.5 GV/c. The balloon floated at

an altitude of about 36 km for 9.8 hours and the mean residual atmosphere during the float was 5.8 g/cm².

3. Analysis and Results

We first selected particles with charge $|Z| = 1$ by making use of 3 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 assure 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 8 in the non-bending direction, y , for fitting the trajectory. b) The reduced chi-squares 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 one another. 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 Cherenkov 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 Cherenkov threshold for protons at the upper end and well above the Cherenkov threshold for muons at the lower end. Thus negatively charged particles in this rigidity range, which were not accompanied by Cherenkov light, were identified as \bar{p} candidates. An extensive study of the gas Cherenkov

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 $2.5 \times 2.5 \text{ cm}^2$ 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 photo-electrons (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 Cherenkov 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 Cherenkov. 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 $137 \text{ cm}^2 \text{ sr}$. Fig. 2 shows the distribution of events as a function of deflection ($1/\text{rigidity}$) 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, while in the same rigidity range we observed 69311 protons. This range of rigidity corresponds to a kinetic energy range from 3.70 to 19.08 GeV. 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} 's events that interacted below the bottom TOF plane

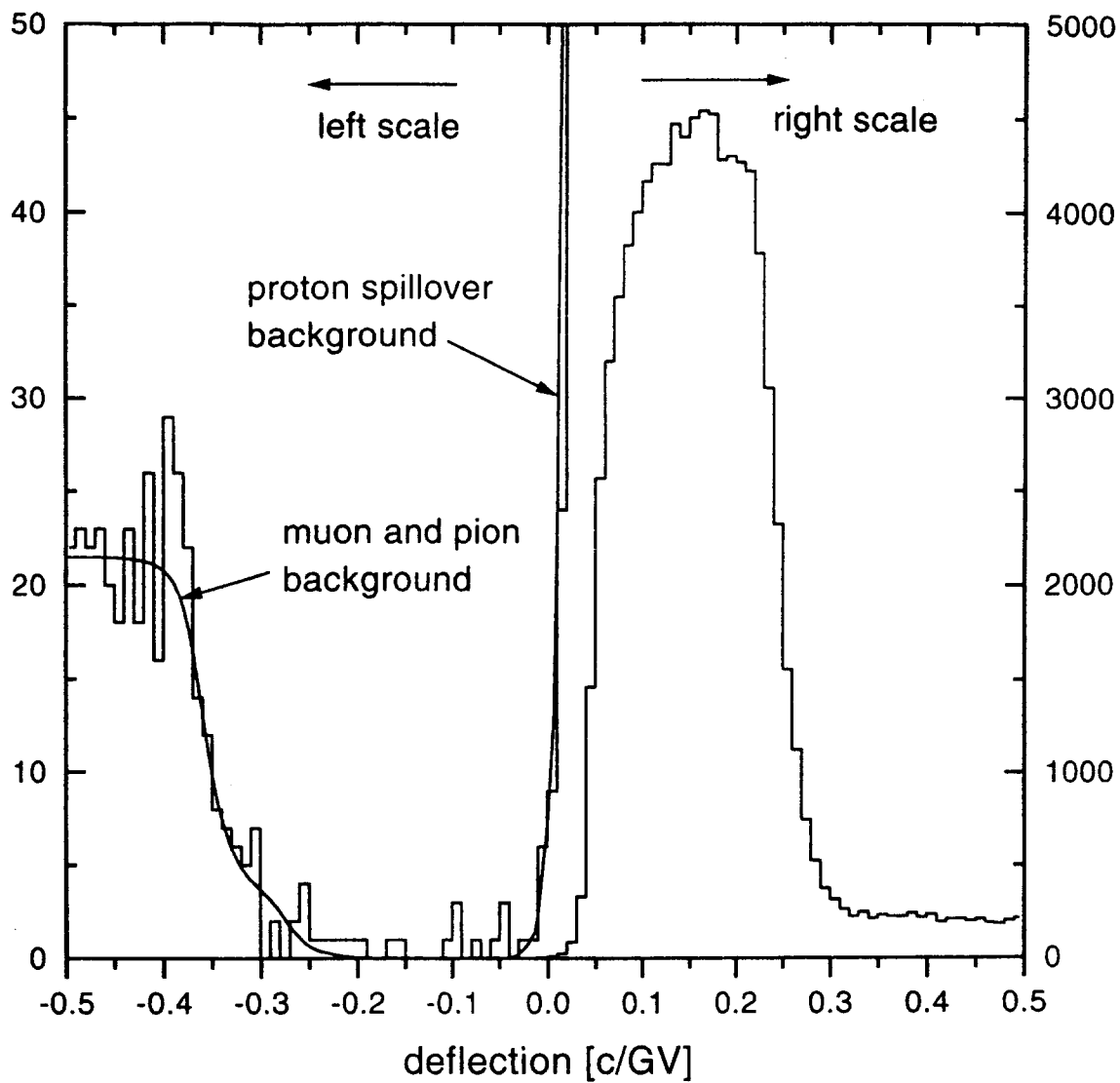


Fig. 2.— Data from the flight with $|Z| = 1$, no shower, no Cherenkov light and the tracking cuts described in the text.

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, 6 interacted in the calorimeter. Using the 5 non-interacting \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 4 \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} due to self-vetoing.

The backgrounds due to albedo as well as that due to spillover from the positive deflection side are both negligible. Due to the inefficiency (0.2%) of the Cherenkov 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 Cherenkov 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 side of Fig.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 by normalizing 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 inelastic interactions since the cross section 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 $1.24 (+0.68, -0.51) \times 10^{-4}$ in the energy range from 3.70 to 19.08 GeV at the top of the atmosphere.

4. Conclusion

The present value of \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 of 5.6 to 12.5 GV/c. When we restricted our rigidity to closely match the original measurement, we find no change in our result within the quoted error. Although the principle structure of both instruments is similar, all the detector systems were considerably improved, providing better reliability and higher rejection power for the present configuration. Thus, we are confident that the \bar{p}/p ratio reported here is reliable. It should be pointed out that the result of Golden et al. (1979) was associated with large errors and differ from the present result by about 3 standard deviations, when compared over the same energy range.

In Fig. 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 within the uncertainties of the existing measurements,

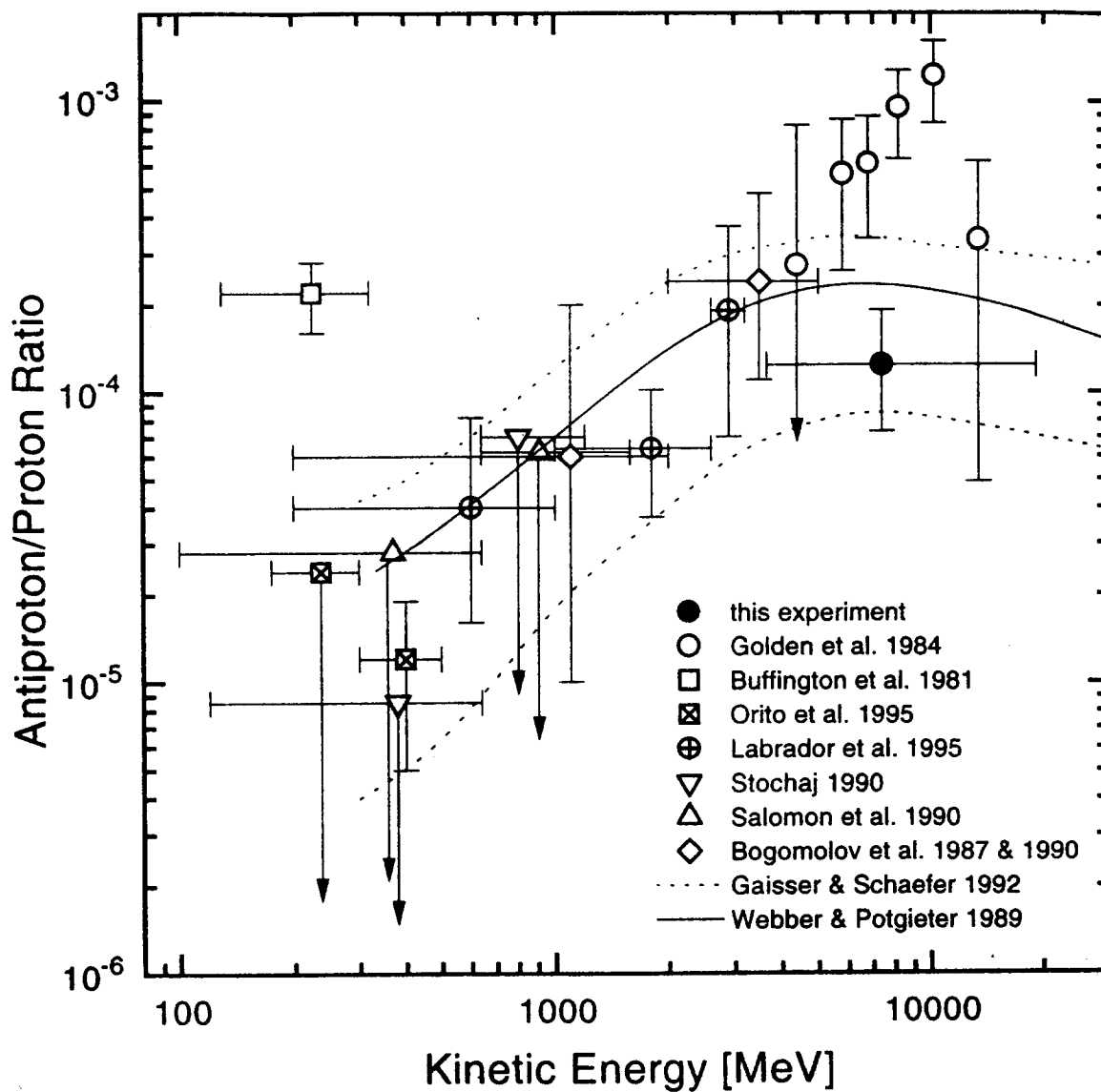


Fig. 3.— Measured antiproton/proton ratio from the MASS91 experiment in comparison with other data and calculations by Gaisser & Schaefer, (1992) and Webber & Potgieter (1989)

the observed antiprotons are consistent with the secondary production hypothesis. It is essential to improve the statistics on the \bar{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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