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Measurement of Cosmic-Ray Antiproton Spectrum in the Energy Range 0.18 to 3.56 GeV at Solar Minimum

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Abstract

The absolute flux of cosmic-ray antiprotons has been measured at solar minimum, based on 458 antiprotons unambiguously detected by the BESS detector. In the resultant antiproton spectrum, we have detected a distinctive peak of “secondary” antiprotons (i.e., produced by the interaction of cosmic-rays with interstellar gas) for the first time, and measured its flux to 10 % accuracy. The position and the absolute flux of the peak agree with the prediction of the Standard Leaky Box model for the ”secondary” antiprotons. At low energies below 1 GeV, we observe a possible excess antiproton flux over the simple Standard Leaky Box calculations. We will also present the status of the BESS’98 data, in which we have detected about 400 antiprotons.

1 Introduction

Most cosmic-ray antiprotons($\bar{p}$’s) are generally thought to be produced in energetic collision of Galactic cosmic-ray with the interstellar medium. The energy spectrum of such “secondary” $\bar{p}$’s is expected to show a characteristic peak around 2 GeV, due to kinematics of $\bar{p}$ production. The peak intensity and the flux shape will provide important informations on the propagation process of the cosmic rays in Galaxy. As other possible source of $\bar{p}$’s, one can conceive novel processes, such as evaporating primordial black holes [1]. The signal from such “primary” source would be prominent in the low energy region [2] and could be detected as an excess over the signal for “secondary” $\bar{p}$’s, which is sharply declining below the peak.

The detection of the “secondary” peak and search for the low-energy “primary” $\bar{p}$ have been difficult, due to huge backgrounds and the extremely small flux[3]. BESS spectrometer, with a large acceptance and high sensitivity, has been designed and constructed for this purpose. Here we present a new high-statistic measurement of the $\bar{p}$ spectrum, based on 458 $\bar{p}$’s detected in the ’95 and ’97 flights, and the status of the ’98 flight data analysis.

2 Instruments

Figure 1 shows the BESS spectrometer, which will be described in detail elsewhere [4]. We only note the essential features here. A uniform field of 1 Tesla is produced by a thin superconducting coil, and the field region is filled with the central tracking volume. This cylindrical geometry gives a large acceptance of 0.3 m^{2}sr. Tracking is performed by fitting up to 28 hit-points in the drift chambers, resulting in a magnetic-rigidity (R) resolution of 0.5 % at 1 GV/c. The continuous and redundant 3-dimensional tracking enable us to recognize even complicated events having interactions or multiple tracks.

Particle identification is performed by a time of flight hodoscope (TOF), aerogel Cherenkov counter, and the central drift chamber (JET). The TOF consists of upper 10 and lower 12 scintillator paddles, which are placed at the outer-most radii. The TOF system provides two dE/dx and time of flight informations for each track. In the '95 experiment, the TOF resolution was 110 ps, which was improved to 70 ps in '97, resulting in β^{-1} resolution of $\sigma(\beta^{-1})$=0.008. The aerogel Cherenkov counter, located between the upper TOF and the coil, was first installed in '97 with silica-aerogel, which has a refractive index n = 1.032, corresponding to the threshold momentum of 3.8 GeV/c[5]. In addition, dE/dx in the drift chamber was obtained as a truncated mean of the hit charges. Using the informations, $\bar{p}$'s can be identified in the energy range of 0.18 $\sim$ 1.4 GeV and 0.18 $\sim$ 3 GeV, respectively for the '95 and '97 data.

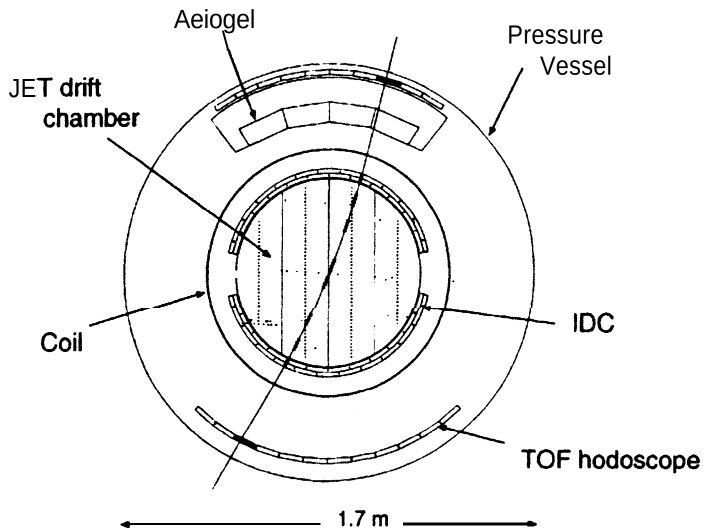

Figure 1: Cross-sectional view of the BESS spectrometer in its '97 configuration. Overlayed is one of the $\bar{p}$ events.

3 Data and Analysis

The experiments were carried out in northern Canada, where the geomagnetic cutoff rigidity ranging from 0.3 to 0.5 GV/c. Scientific data were taken during the level flight at altitudes 35 to 38 km (average residual atmosphere $\sim$ 5.3 g/cm'). The total livetime for '95 and '97 was 2.72 x 10^4 sec and 5.70 x 10^4 sec, respectively.

Data taking was initiated by two trigger levels. The first-level was provided by a coincidence between upper and lower TOF with threshold set at 1/3 of the pulse height for minimum ionizing particles. The second-level, which utilized the hit pattern of the TOF and the inner drift chamber (IDC), first rejected null- and multitrack- events and made a rough rigidity cut to select negatively charged particles. In addition, a portion of the first-level triggers was recorded to build an unbiased sample from which the efficiencies were determined.

The off-line analysis [6] select events with a single track fully contained in the fiducial region of the tracking volume with acceptable track quality. We then required that three measured dE/dx are compatible with $\bar{p}$'s and protons as a function of R. The combined efficiency of this off-line selection was found to be 83 % to 88 % for R of 0.5 to 4 GV/c. This highly efficient selection rejectd all particles with charge greater than 1 and most of the low energy e/μ background.

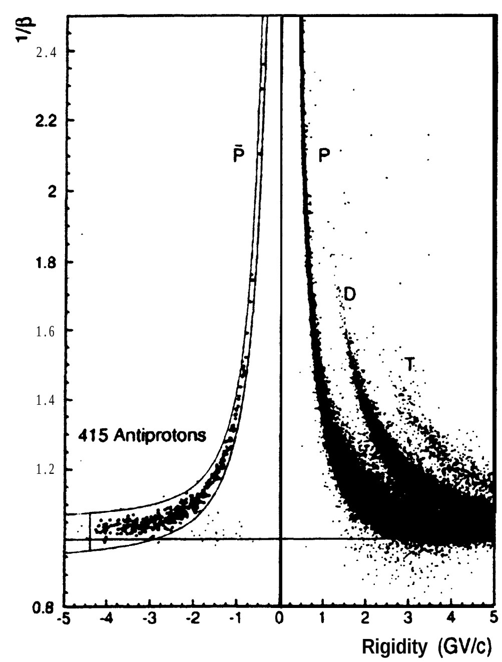

Figure 2: The identification of $\bar{p}$ events for '97 flight. The solid curves define the $\bar{p}$ mass bands used for the spectrum measurement.

As for the '97 data samples, we required, for $\beta^{-1} \leq 1.1$, the Cherenkov veto, i.e., that the Cherenkov output be less than 0.09 of the mean output from e^-. This cut rejected e^-/μ^- background by a factor of 6000 at the expense of 20 % loss of acceptance, while keeping 93 % efficiency for $\bar{p}$'s.

Figure 2 shows a scatter plot of β^{-1} vs rigidity for the remaining samples of the '97 data. A clean band of

$\bar{p}$'s is cleary evident at the exact opposite side to the protons. The Cherenkov cut reduces e^-/μ^- background and $\bar{p}$'s are mass-identified up to rigidity below threshold (3.8 GeV/c). We defined the $\bar{p}$ events using the band shown in Fig.2. The number of detected $\bar{p}$'s are 43 and 415, respectively, for '95 and '97 data.

All $\bar{p}$ events were scanned in detail and found to have no problem in tracking or particle identification. To check against the re-entrant albedo background, we confirmed that the trajectories of all low-energy $\bar{p}$'s can be traced back to the outside of the geomagnetic sphere.

4 Antiproton Spectrum

Based on the observed $\bar{p}$'s, we calculate the $\bar{p}$ flux at the top of the atmosphere (TOA) using the parameters obtained in the following way:

The TOA energy of each event was calculated by tracing back the particle through the detector material and the air. The geometrical factor was calculated both analytically and by Monte Carlo(M.C.) methods. The efficiencies of the second-level trigger and of the off-line selections were determined by using both the unbiased trigger sample and the M.C. simulated samples of protons and $\bar{p}$'s. The simulated samples were generated by GEANT/GEISHA code, which incorporates the detailed material distribution, realistic detector performance and correct $\bar{p}$-nuclei cross sections. We also subtracted the expected number of atmospheric $\bar{p}$'s, produced by the collision of cosmic-rays in the air, by 9 ± 2 %, 15 ± 3 %, and 19 ± 5 %, respectively, at 0.25, 0.7, and 2 GeV, where the errors correspond to the maximum difference among the three independent recent calculations [7-9].

Figure 3 shows the combined ('95 + '97) spectrum in which we detect the distinctive peak of "secondary" $\bar{p}$ for the first time, together with the previous measurements and various theoretical calculations. The solar activities at the time of the '95 and '97 flights were both close to the minimum.

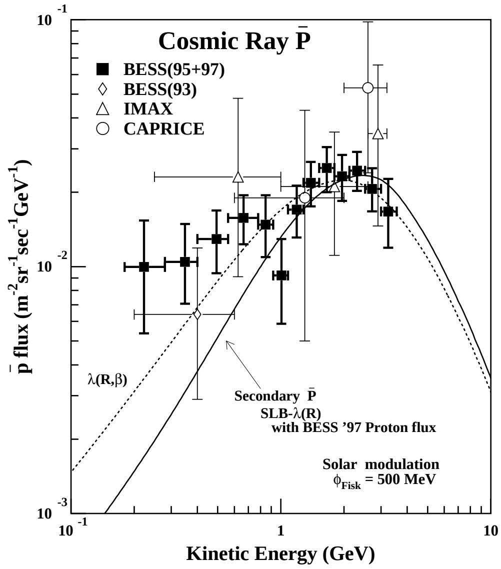

Figure 3: BESS '95+'97 $\bar{p}$ fluxes at TOA together with the previous data. The error-bars represent the quadratic sums of the statistical and systematic errors. The curves represent solar modulated spectra of the "secondary" $\bar{p}$'s

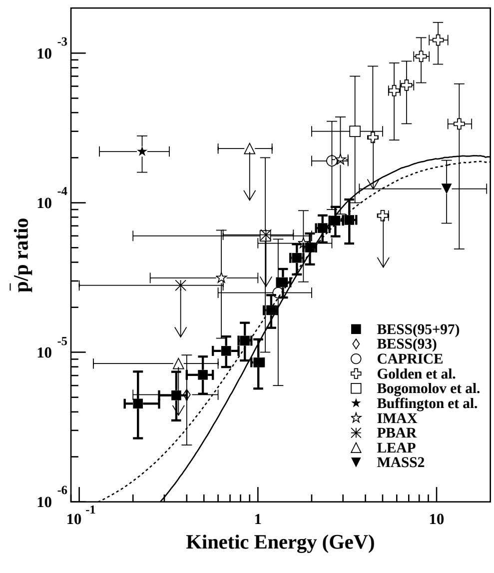

Figure 4: BESS '95+'97 $\bar{p}/p$ flux ratios with previous data [10] and the SLB calculations.

5 Discussion

The resultant spectrum is consistent with recent measurements, all of which have much larger statistical errors. Two variations of the Standard Leaky Box (SLB) calculation well reproduce the data in the peak region within ± 15 %. At low energy below 0.7 GeV, our data tend to show an excess over the two calculated spectra. This might be due to statistical fluctuation, might indicate a much larger escape length, or might suggest a contribution of low energy primary $\bar{p}$ from novel source such as the evaporating black holes.

Figure 4 shows the measured $\bar{p}/p$ flux ratios, which demonstrate the unprecedented accuracy of out data.

6 BESS'98 Antiproton

The BESS '98 experiment was carried out on July 29, at Lynn Lake, Canada. The instrumental setup was almost identical to that of the '97 flight, except that we used a Cherenkov radiator with refractive index n = 1.022, resulting in the threshold momentum of 4.8 GeV/c. During the flight, the BESS detector functioned properly and was safely recovered. We accumulated **16.2** $\times 10^6$ cosmic-ray events during the livetime of 6.05×10^4 sec.

We applied the same off-line selections as described above and clearly detected about 400 $\bar{p}$'s in the energy range 0.18 GeV to 4.5 GeV. Figure 5 shows the identification plot for the '98 data. We are now concentrating on a detailed systematic study to obtain the spectrum of the '98 $\bar{p}$'s, and to investigate further the "secondary" or possibly "primary" $\bar{p}$'s.

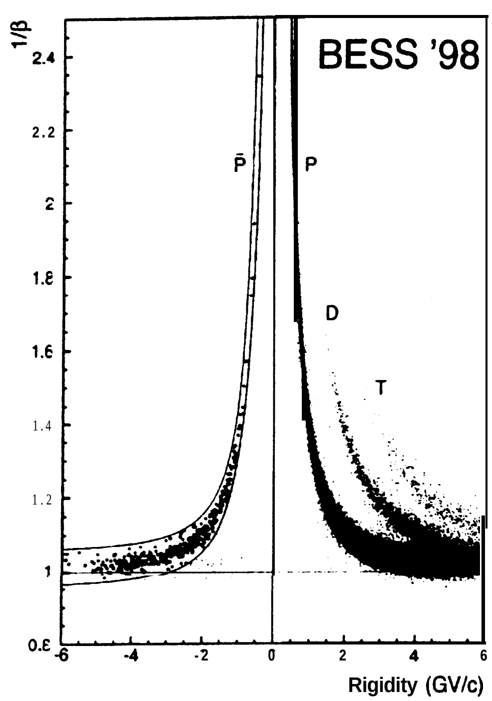

Figure 5: The identificationof $\bar{p}$'s for '98 flights.

Acknowledgement

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