Measurement of cosmic-ray antiproton spectrum at solar minimum with a long-duration balloon flight in Antarctica

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Abstract: The energy spectrum of cosmic-ray antiprotons ($\bar{p}$'s) has been measured in the range 0.17 to 3.5 GeV, based on 7886 $\bar{p}$'s collected by the BESS-Polar II instrument during a long duration flight over Antarctica in a Solar minimum period of December 2007 through January 2008. The $\bar{p}$ spectrum measured by BESS-Polar II shows good consistency with the secondary $\bar{p}$ calculations. Given this background of secondary $\bar{p}$'s, cosmologically primary $\bar{p}$'s have been searched for using the observed $\bar{p}$ spectrum. BESS-Polar II result shows no evidence of primary $\bar{p}$'s that originated from the evaporation of PBH.

Keywords: Antiproton, BESS-Polar II

1 Introduction

The precise measurement of the spectrum of cosmic-ray antiprotons ($\bar{p}$'s) is crucially important to the investigation of elementary particle phenomena in the early universe and cosmic-ray phenomena. The main origin of cosmic-ray $\bar{p}$'s is considered to be energetic nuclear cosmic rays, mostly protons, interacting with the interstellar gas, mostly hydrogen shown in Fig. 1. The energy spectrum of such "secondary" $\bar{p}$'s is expected to show a characteristic peak around 2 GeV, with sharp decreases of the flux below and above peak, due to the kinematics of $\bar{p}$ production. The secondary $\bar{p}$'s offer a unique probe of cosmic-ray propagation and of solar modulation. Other possible sources of cosmic-ray $\bar{p}$'s, such as evaporating primordial black holes (PBH), can been sought. The "primary" sources, if they exist, are expected to be prominent at low energies and to exhibit large solar modulations.

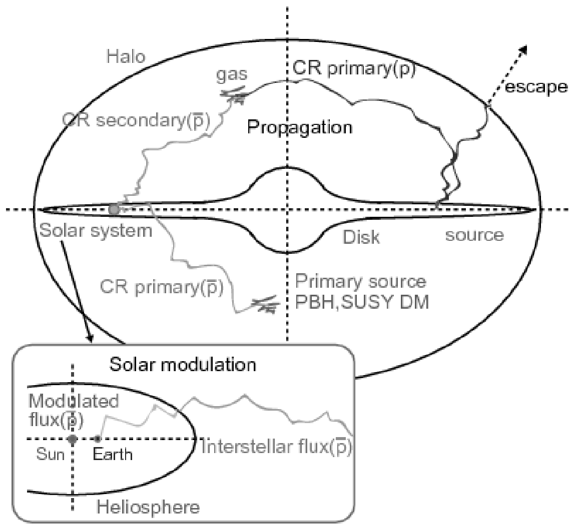

Figure 1: Time-history of cosmic-ray secondary and primary $\bar{p}$'s from their birth to arrival at the earth.

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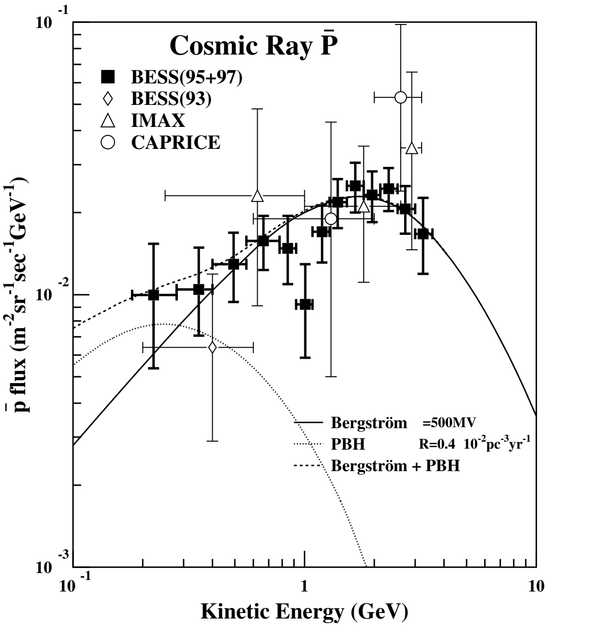

Figure 2: $\bar{p}$ flux at the top of the atmosphere obtained with BESS95&97. The solid curve denotes the secondary $\bar{p}$ flux at the solar minimum. The dotted curve representes the expected $\bar{p}$ spectrum from evaporating PBHs.

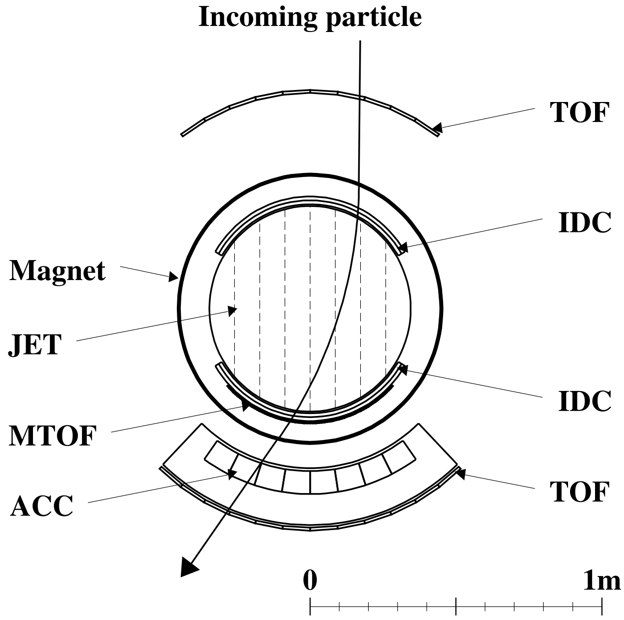

Figure 3: Cross sectional view of BESS-Polar II spectrometer. Overlayed is sample of the $\bar{p}$ events.

1.1 Antiproton measurement with BESS

In the previous solar minimum period, the BESS experiment (BESS95&97) revealed that $\bar{p}$ spectrum has a distinct peak around 2 GeV. It has become evident that $\bar{p}$'s are predominantly of secondary origin [1]. However a low energy component of the $\bar{p}$ spectrum measured by BESS95&97 was slightly flatter than that of calculations with secondary $\bar{p}$ models. Though this result might suggest the existence of novel processes for production of cosmic-ray $\bar{p}$'s in the universe, the large statistical error of BESS95&97 data did not allow us to draw a firm conclusion. The BESS-Polar project was proposed to evaluate the possibility of excess $\bar{p}$ flux suggested in the BESS95&97 observations by measuring with unprecedented precision the $\bar{p}$ flux based on a longer duration measurement in Antarctica, solar minimum, and enhanced minimization of systematic errors.

2 Spectrometer

The BESS spectrometer was designed and developed as a high-resolution spectrometer. A uniform field of 0.8 T is produced by a thin superconducting solenoid, which field region is filled with tracking detectors. This geometry results in an acceptance of 0.23 m^{2}sr. Tracking is performed by fitting up to 48 hit points in drift chambers (JET) and 4 hit points in inner drift chambers (IDC), resulting in a magnetic-rigidity ($R \equiv Pc/Ze$) resolution of 0.4% at 1 GV, and a maximum detectable rigidity (MDR) of 270 GV. The upper and lower scintillator hodoscopes provide time-of-flight (TOF) and dE/dx measurements. The timing resolution of each hodoscope is 120 ps, resulting in a β^{-1} resolution of 3.3%. The instrument also incorporates a threshold-type Cherenkov counter with a silica aerogel radiator with index $n = 1.03$ (ACC) that can reject e^- and μ^- backgrounds by a factor of 6000, distinguishing $\bar{p}$'s from such backgrounds up to 3.5 GeV. In addition, a thin scintillator middle-TOF (MTOF) is installed on the lower surface of the solenoid bore to detect low energy particles which cannot penetrate the magnet wall. The timing resolution of each of these hodoscopes is 320 ps.

3 BESS-Polar II flight

The BESS-Polar II flight was carried out in December 2007 through January 2008. The payload was launched on December 23 from Williams Field near the U.S. McMurdo Station in Antarctica and circulated around the South Pole for 29.5 days. Data for flux measurements were taken for live-time periods of 1286460 seconds at altitudes of 34 km to 38 km (residual air of 5.8 g/cm^2 on average). Cutoff rigidity was below 0.2 GV/c. $4,7 \times 10^9$ cosmic-ray events were accumulated without any online event selection as 13.6 terabytes of data recorded on the hard disk drives. During the 24.5 days of observation, all detectors operated well and exhibited their expected performance except for the central tracker. The JET tracker had an instability and discontinuous status due to JET high-voltage fluctuation. However more than 90% of the data has been successfully calibrated while keeping sufficient tracker quality,

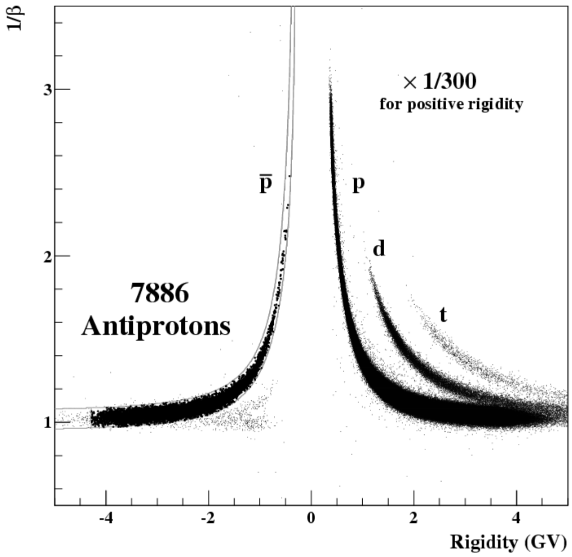

Figure 4: The β^{-1} versus rigidity plot. and $\bar{p}$'s selection band. The solid curves define the $\bar{p}$ mass bands.

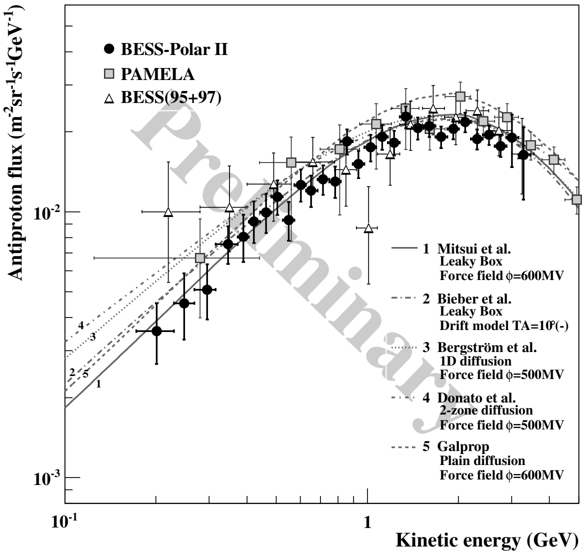

Figure 5: Antiproton fluxes at the top of the atmosphere obtained with the BESS-Polar II at Solar minimum together with BESS flights around previous Solar minimum (BESS95&97) and PAMELA experiment.

an achievement realized by development of time-dependent tracker calibration. Analysis was performed in the same way as described in Ref. [2]. The same selection criteria for $\bar{p}$'s and p's were applied because nonintercating $\bar{p}$'s behave similar to p's except for deflection in the symmetrical configuration of BESS.

4 Antiproton identification

Figure 4 shows β^{-1} versus R plots for surviving events. We see a clean narrow band of 7886 $\bar{p}$'s at the exact mirror position of the protons. The Cherenkov veto based on improved rejection power functioned to identify $\bar{p}$ events by removing the overwhelming background of e^- and μ^-. The fraction of contamination were 0.0%, 1.0% and 2.4%, respectively, in the 0.2-1.0 GeV, 1.0-2.0 GeV, and 2.0-3.5 GeV energy bands. Other backgrounds such as albedo, mismeasured positive-rigidity particles, and reentrant albedo were found to be negligible.

5 Results

Shown in Fig. 5 is the resultant $\bar{p}$ flux together with previous measurements in BESS95&97[1], PAMELA[3] experiment and various secondary $\bar{p}$ calculations [4, 5, 6, 7, 8]. Improved statistical precision of $\bar{p}$'s results in 14 and 30 times more events than were measured in BESS95&97 and PAMELA experiment below 1 GeV respectively.

5.1 Comparison with secodanry $\bar{p}$ calculations

By comparing our measured spectrum with various secondary $\bar{p}$ spectra calculated using models which describe well the cosmic-ray propagation process and Solar modulation effects, the $\bar{p}$ spectrum measured by BESS-Polar II shows good consistency with the secondary $\bar{p}$ calculations modulated by reasonable parameter (Φ=500 MV,600 MV, TA=10°(-)) estimated with BESS-Polar II proton flux. Secondary $\bar{p}$'s are produced by interaction of primary p's which collide with interstellar gas as they diffuse from their sources through the turbulent magnetic fields of the Galaxy. Since observations are performed at 1 AU, the observed fluxes is modulated as particles diffuse into the inner Solar system. Thus observed intensities of secondary $\bar{p}$'s depend both on the propagation model and the modulation model. This dual dependency causes difficulty in cosmic-ray calculations and the interpretation of cosmic-ray data. In order to extract the features of propagation models from the resultant calculations depending on both propagation and modulation, the differences of calculated spectrum shapes in low-energy region are evaluated.

In comparing the different spectral shapes among these secondary $\bar{p}$ calculations, the BESS-Polar II results show better consistency with the models which do not require a component of low-energy $\bar{p}$'s from sources such as tertiary $\bar{p}$'s and soft spectrum due to Diffusive Reacceleration model (curve 3 and curve 4 in Fig. 5).

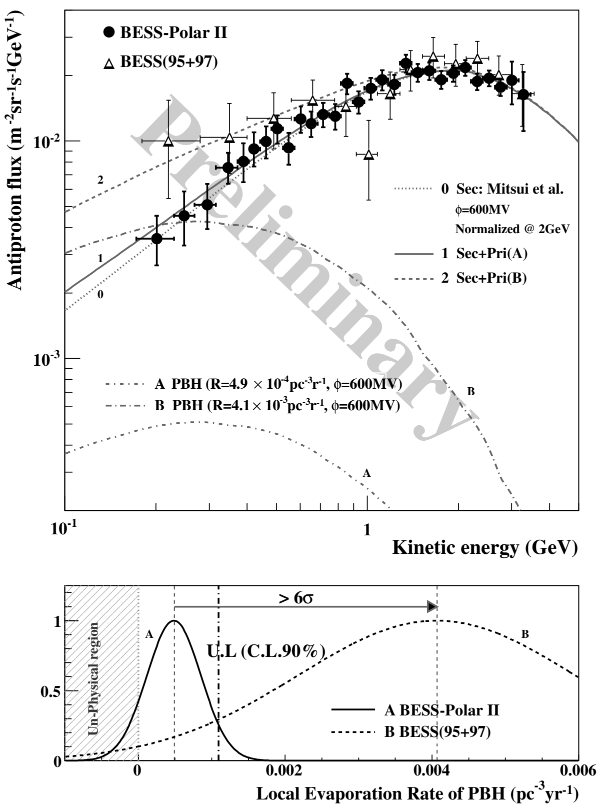

Figure 6: Primary antiproton fluxes from evaporating PBHs expected by fitting with BESS-Polar II and BESS95&97 observation respectively (Top). Distribution of the explosion rate of PBH ($\mathcal{R}$) calculated with Mitsui secondary $\bar{p}$ flux (Top), for BESS-Polar II and BESS95&97 (Bottom).

5.2 Search for primary $\bar{p}$'s

Among the various, possible sources of primary $\bar{p}$'s, the most relevant candidate which BESS is capable of studying is the evaporation of PBHs [9, 10]. PBHs may have formed in the early Universe via initial density fluctuations, phase transitions, or the collapse of cosmic strings, PBHs are the only black holes which have small mass enough to emit particles with significant evaporation rate by quantum effects. The possible existence of primary $\bar{p}$'s has been quantitatively evaluated by focusing on the PBH evaporation rate parameter ($\mathcal{R}$). The $\mathcal{R}$ is calculated by fitting the difference between $\bar{p}$ spectra measured in BESS-Polar II (BESS95&97) and theoretical secondary $\bar{p}$ calculations that have been normalized near the spectrum peak at 2.0 GeV respectively. The normalization of secondary $\bar{p}$ is performed to avoid biased evaluation from ambiguity of propagation models. The dependency of model selection is also considered by checking the possible $\bar{p}$'s under several models of secondary $\bar{p}$'s as background. As shown in Fig. 6, the possibility of the primary $\bar{p}$'s slightly suggested from the $\mathcal{R}$ distribution with a mean value of $4 \times 10^{-3}\mathrm{pc}^{-3}\mathrm{yr}^{-1}$ in BESS95&97 has been excluded with 6 σ separation in the BESS-Polar II measurement. The BESS-Polar II result shows no evidence of primary $\bar{p}$'s that originated from the evaporation of PBH within statistics . Thus we have determined an upper limit of $\mathcal{R} = 1 \times 10^{-3}\mathrm{pc}^{-3}\mathrm{yr}^{-1}$ with a 90% confidence level, which is 10 orders of magnitude more stringent than the previous BESS limit.

6 Conclusion

The second scientific flight of the BESS-Polar project called BESS-Polar II was successfully performed in December 2007 through January 2008 over Antarctica. The resultant $\bar{p}$ flux with the unprecedented statistics, which is 14 times more events than were measured in BESS95&97, shows good consistency with the secondary $\bar{p}$ calculations. Given this background of secondary $\bar{p}$'s, cosmologically primary $\bar{p}$'s has been searched for with use of the observed $\bar{p}$ spectrum. The possibility of primary $\bar{p}$'s existence has been evaluated by using the PBH evaporation rate parameter ($\mathcal{R}$). BESS-Polar II result shows no evidence of primary $\bar{p}$'s originated by PBH within statistical limits.

7 Acknowledgment

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