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

K. SAKAI,1,a K. ABE,2,b H. FUKU,3 S. HAINO,4,c T. HAMS,5 M. HASEGAWA,4 A. HORIKOSHI,4 K. C. KIM,6 A. KUSUMOTO,2 M. H. LEE,6 Y. MAKIDA,4 S. MATSUDA,4 Y. MATSUKAWA,2 J. W. MITCHELL,5 J. NISHIMURA,1 M. NOZAKI,4 R. ORITO,2,d J. F. ORMES,7 M. SASAKI,5 E. S. SEO,6 R. SHINODA,1 R. E. STREITMATTER,5 J. SUZUKI,4 K. TANAKA,4 N. THAKUR,7 T. YAMAGAMI,3 A. YAMAMOTO,1,4 T. YOSHIDA,3 and K. YOSHIMURA4

1The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan
2Kobe University, Kobe, Hyogo 657-8501, Japan
3Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA), Sagamihara, Kanagawa 252-5210, Japan
4High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
5National Aeronautics and Space Administration, Goddard Space Flight Center (NASA/GSFC), Greenbelt,MD 20771, USA
6IPST, University of Maryland, College Park, MD 20742, USA
7University of Denver, Denver, CO 80208, USA
sakaik@post.kek.jp

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 be sought. The “primary” sources, if they exist, are expected to be prominent at low energies and to exhibit large solar modulations.

a. Present address: NASA/GSFC
b. Present address: ICRR, Tokyo
c. Present address: INFN, Perugia
d. Present address: Tokushima University

Figure 1: Time-history of cosmic-ray secondary and primary \(\bar{p}\)'s from their birth to arrival at the earth.
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 ($R \equiv P_c/Ze$) 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 $\beta^{-1}$ 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 $\mu^-$ 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,
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 $^p_p$'s and $^p_p$'s were applied because noninteracting $^p_p$'s behave similar to $^p_p$'s except for deflection in the symmetrical configuration of BESS.

4 Antiproton identification

Figure 4 shows $\beta^{-1}$ versus $R$ plots for surviving events. We see a clean narrow band of 7886 $^p_p$'s at the exact mirror position of the protons. The Cherenkov veto based on improved rejection power functioned to identify $^p_p$ events by removing the overwhelming background of $e^-$ and $\mu^-$. 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 re-entrant albedo were found to be negligible.

5 Results

Shown in Fig. 5 is the resultant $^p_p$ flux together with previous measurements in BESS95&97[1], PAMELA[3] experiment and various secondary $^p_p$ calculations [4, 5, 6, 7, 8]. Improved statistical precision of $^p_p$ 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 secodnary $^p_p$ calculations

By comparing our measured spectrum with various secondary $^p_p$ spectra calculated using models which describe well the cosmic-ray propagation process and Solar modulation effects, the $^p_p$ spectrum measured by BESS-Polar II shows good consistency with the secondary $^p_p$ calculations modulated by reasonable parameter ($\Phi=500$ MV,600 MV, $TA=10^9(-)$) estimated with BESS-Polar II proton flux. Secondary $^p_p$'s are produced by interaction of primary $p_p$'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 $^p_p$'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 $^p_p$ calculations, the BESS-Polar II results show better consistency with the models which do not require a component of low-energy $^p_p$'s from sources such as tertiary $^p_p$'s and soft spectrum due to Diffusive Reacceleration model (curve 3 and curve 4 in Fig. 5).
Given this background of secondary $p$'s, cosmologically primary $p$'s has been searched for with use of the observed $p$ spectrum. The possibility of primary $p$'s existence has been evaluated by using the PBH evaporation rate parameter ($\mathcal{R}$). BESS-Polar II result shows no evidence of primary $p$'s originated by PBH within statistical limits.

### 7 Acknowledgment

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### References


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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 Mitsu secondary $\bar{p}$ flux (Top), for BESS-Polar II and BESS95&97 (Bottom).