PROCEEDINGS OF SCIENCE

Measurement of the Cosmic-ray Antiproton spectrum in the range 0.12 to 0.4 GeV with BESS-Polar II

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The energy spectra of cosmic-ray antiprotons and protons near solar minimum were precisely measured with BESS-Polar II (Balloon-borne Experiment with a Superconducting Spectrometer) during a long-duration flight over Antarctica in December 2007 and January 2008. The upper-TOF (UTOF) and lower-TOF (LTOF) scintillator hodoscopes measure the charge and velocity of incident particles. A thin plastic scintillator middle-TOF (MTOF) hodoscope is installed on the lower surface of the magnet bore to measure low-energy particles that cannot reach the LTOF. The MTOF further lowers the threshold energy to about 120 MeV for antiproton or proton measurements. We report absolute spectra of the cosmic-ray antiproton in the range 0.12 to 0.4 GeV and the antiproton/proton ratio calculated with UTOF-MTOF trigger events. These new results are independent of the UTOF-LTOF triggered antiproton spectrum published in 2012 and proton spectrum published in 2016.

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1. Introduction

The precise measurement of the spectrum of cosmic-ray antiprotons is crucially important to the investigation of elementary particle phenomena in the early Universe. Most of the observed cosmic-ray antiproton are well understood as secondary products of collisions between primary cosmic-rays and the interstellar medium. The energy spectrum of such "secondary" antiprotons peaks near 2 GeV, and decreases sharply below and above the peak, due to the kinematics of antiproton production and to the local interstellar (LIS) proton spectrum. Measured secondary antiproton spectra provide an important probe of cosmic-ray propagation and solar modulation because of their unique spectral shape [1, 2]. Cosmologically "primary" sources have also been suggested, including the annihilation of dark-matter particles and the evaporation of primordial black holes (PBH) by Hawking radiation [3]. Before the BESS experiment, the detection of the peak in the secondary antiproton spectrum and the search for a possible low-energy primary antiproton component had not been realized, because of huge backgrounds and the extremely small flux, especially at low energies.

2. BESS Program

The BESS instrument [4, 5] was developed as a high-resolution magnetic-rigidity spectrometer for cosmic-ray antiparticles and precise measurements of the absolute fluxes of various cosmic-ray components. The original BESS experiment performed 9 flights over northern Canada during the period of 1993 through 2002 with continuous improvement in the instrument. The BESS-Polar project was proposed as an advanced BESS program using long duration balloon (LDB)

Figure 1: Flight trajectory of the 2007 BESS-Polar II over Antarctica from Williams Field (first orbit blue, second orbit red) with 2004 BESS-Polar I flight (green).
[Launch]S77-51,E166-40, 06:27(McM) 12/23 2007
[Recovery]S83-51,W073-04, 09:02(UTC) 1/21 2008

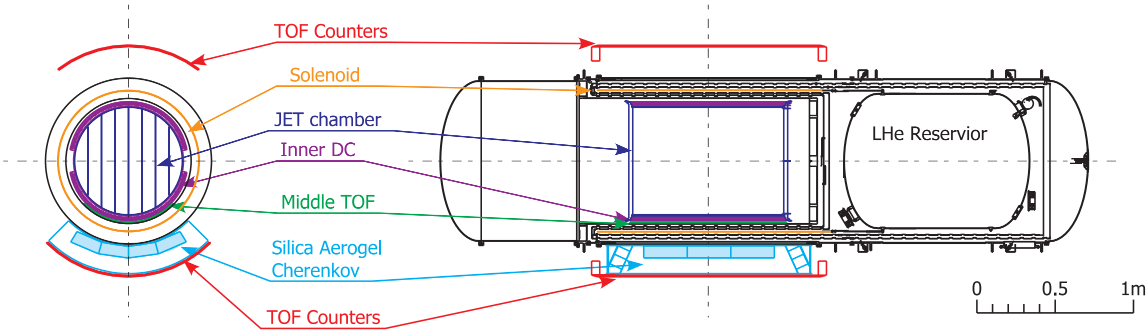

Figure 2: Cross sectional view of BESS-Polar II spectrometer

flights over Antarctica (around the south pole) to provide high-statistics, low-energy cosmic-ray measurements [6, 7, 8]. The first scientific flight of the BESS-Polar instrument was launched near McMurdo Station, on December 13th, 2004 (UTC). The flight duration was over 8.5 days and more than 9×10^8 cosmic-ray events were recorded [9]. Incorporating considerable improvements in instrument and payload systems compared to BESS-Polar I, the BESS-Polar II instrument was launched on December 23, 2007, from Williams Field near the US McMurdo Station in Antarctica and circulated around the South Pole for 24.5 days of observation with the magnet energized. The float altitude was 34 km to 38 km (residual air of 5.8 g/cm^2 on average), and the cutoff rigidity was below 0.5 GV. BESS-Polar II accumulated 4.7×10^9 events with no inflight event selection as 13.6 terabytes of data (Fig.1).

The BESS-Polar II program [10] has produced three papers giving precise measurements of antiprotons [11], a sensitive antihelium search [12] and the absolute spectra for cosmic-ray protons and helium nuclei [13]. The antiproton spectrum measured by BESS-Polar II shows good consistency with secondary antiproton calculations and no evidence of primary antiprotons originating from the evaporation of primordial black holes. And antihelium work has set a new limit in the ratio of possible antihelium to measured helium of 6.9×10^{-8} at 95% confidence, the lowest limit to date. Proton and helium spectra observed from PAMELA [14, 15], AMS-02 [16, 17] and BESS-Polar agree within one σ_E at high-energy. With further analysis of BESS-Polar II, solar modulation study with low-energy proton spectra and antiproton/proton ratio, precise measurements of isotope spectra [18] and, a search of antideuterons [19] will be reported.

3. BESS-Polar Instrument

In the BESS-Polar instruments shown in Fig.2, a uniform field of 0.8 T is produced by a thin superconducting solenoid, and the field region is filled with drift-chamber tracking detectors. Tracking is performed by fitting up to 52 hit points with a characteristic resolution of $\sim 140\mu$m in the bending plane, resulting in a magnetic-rigidity ($\equiv Pc/Ze$) resolution of 0.4% at 1 GV and a maximum detectable rigidity (MDR) of 240 GV. Upper and lower scintillator hodoscopes provide time-of-flight (TOF) and dE/dx measurements and the event trigger. For antiproton measurements, the acceptance of BESS-Polar is 0.23 m^{2}sr and for proton and helium measurements the acceptance is 0.18 m^{2}sr. The timing resolution of the TOF system is 120 ps, giving a β^{-1} resolution of 2.5%. The instrument also incorporates a threshold-type Cherenkov counter using a silica aerogel

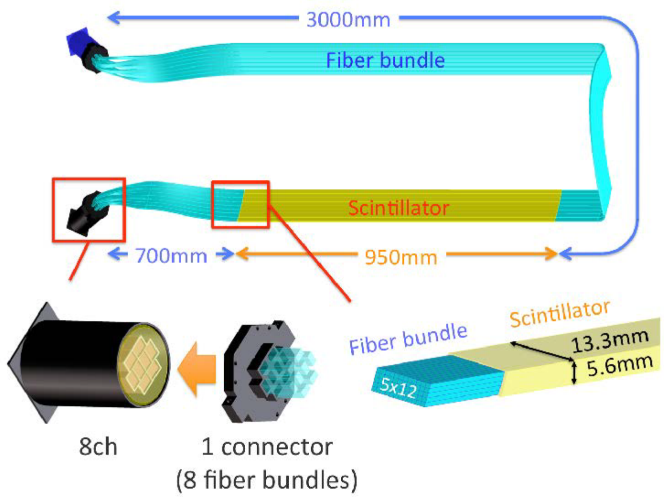

Figure 3: Layout of BESS-Polar II MTOF with both-end readout using fiberbundled light guide

radiator with index $n = 1.03$ (ACC) that can reject e^- and μ^- backgrounds by a factor of 12000 and distinguish $\bar{p}$'s from such backgrounds up to 3.5 GeV.

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. Its performance was very limited due to a singleended scintillator readout in BESS-Polar I, though. For BESS-Polar II, readout of both ends of the scintillators was realized for the new MTOF system by employing clear fiber-bundled light guides and splittable PMT attachment (cookie) as shown in Fig.3. The new system enabled axial position measurements by using timing and amplitude differences of both ends of the scintillators, in addition to improving timing resolution and efficiency.

4. Data analysis

In the first stage of data analysis, we selected events with a single track fully contained inside the fiducial volume defined by the central four columns out of eight columns in the JET chamber. This definition of the fiducial volume reduced the effective geometrical acceptance down to $\sim \frac{1}{3}$ of the full acceptance, but it ensured the longest track fitting and thus the highest resolution in the rigidity measurement. A single-track event was defined as an event which has only one isolated track and one or two hit counters in each layer of the TOF hodoscopes. The single-track selection eliminated rare interacting events. The single-track selection eliminated rare interacting events. To estimate the efficiency of the single-track selection, Monte Carlo simulations with GEANT4 were performed.

In standard analysis by using UTOF-LTOF triggered events, particle identification was performed by requiring proper dE/dx measurements with both UTOF and LTOF and β^{-1} as functions of rigidity. The efficiencies of dE/dx selection were estimated with another sample selected by independent measurement of energy loss inside the JET. Since the β^{-1}distribution is well described by Gaussian and a halfwidth of the β^{-1} selection band was set at 4σ the efficiency is very close to

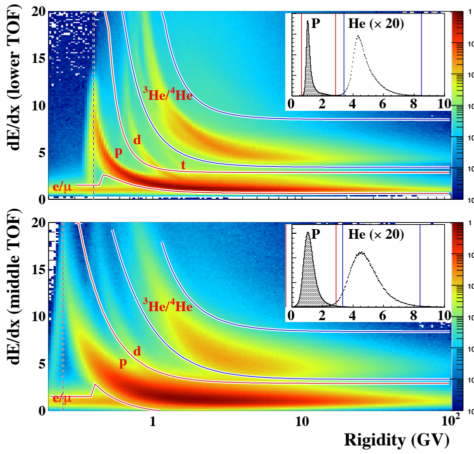

Figure 4: Proton bands in dE/dx (top: LTOF, bottom: MTOF) vs. rigidity obtained from the balloon observation. The superimposed graph shows the selection criteria for protons above 30 GV.

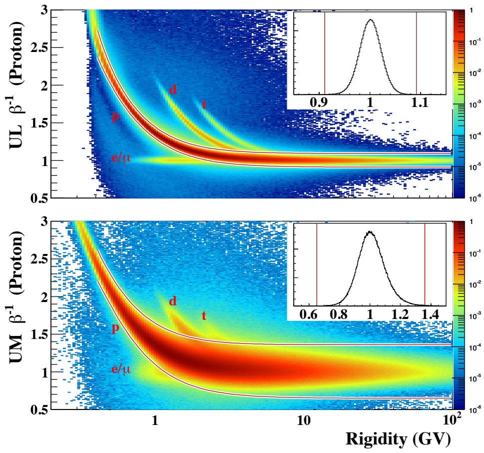

Figure 5: Scatter plot of β^{-1} vs. rigidity obtained from the balloon observation after proton dE/dx selection in UL (top) and UM (bottom). The superimposed graph shows the selection criteria for protons above 30 GV.

unity. The independent measurements of UTOF-MTOF spectra is performed by selecting UTOF-MTOF triggered events, applying the cut criteria related to MTOF selection instead of LTOF and calculating the effective acceptance with MTOF geometry. UTOF-MTOF triggered events contain 75% UTOF-MTOF-LTOF triggered events and 25% anti-coincidence events of LTOF. As shown in Fig.4, MTOF further lowers the threshold rigidity (black broken line) corresponding to about 120 MeV for antiproton or proton measurements. Since the primary objective of BESS-Polar II is a precise measurement of the low-energy antiproton spectrum below 1 GeV, extending the measurement to the lowest energies is significant. Meanwhile MTOF causes large contamination of background due to inferior timing resolution of 320 ps as compared to LTOF of 120ps (Fig.5). It limits the energy range of antiproton measurement below 0.4 GeV.

5. Data analysis of Protons

Flight data estimated efficiencies of antiprotons is calculated by using proton sample in the following conditions. (1) BESS spectrometer was designed to keep symmetry about charge sign, (2) antiproton had to behave a similar with proton except for the interaction process. All difference between antiproton and proton from interaction process was included in non-interaction efficiency. Figure6 shows UM absolute differential energy spectra of primary protons measured by BESS-Polar II together with earlier published BESS-Polar II UL measurement [13]. MTOF lowers the threshold to about 120 MeV. Except for 3% discrepancy from 1.0 to 3.0 GeV due to individual contamination of background corresponding to different timing resolution, UM proton spectrum is almost identical with UL proton spectrum.

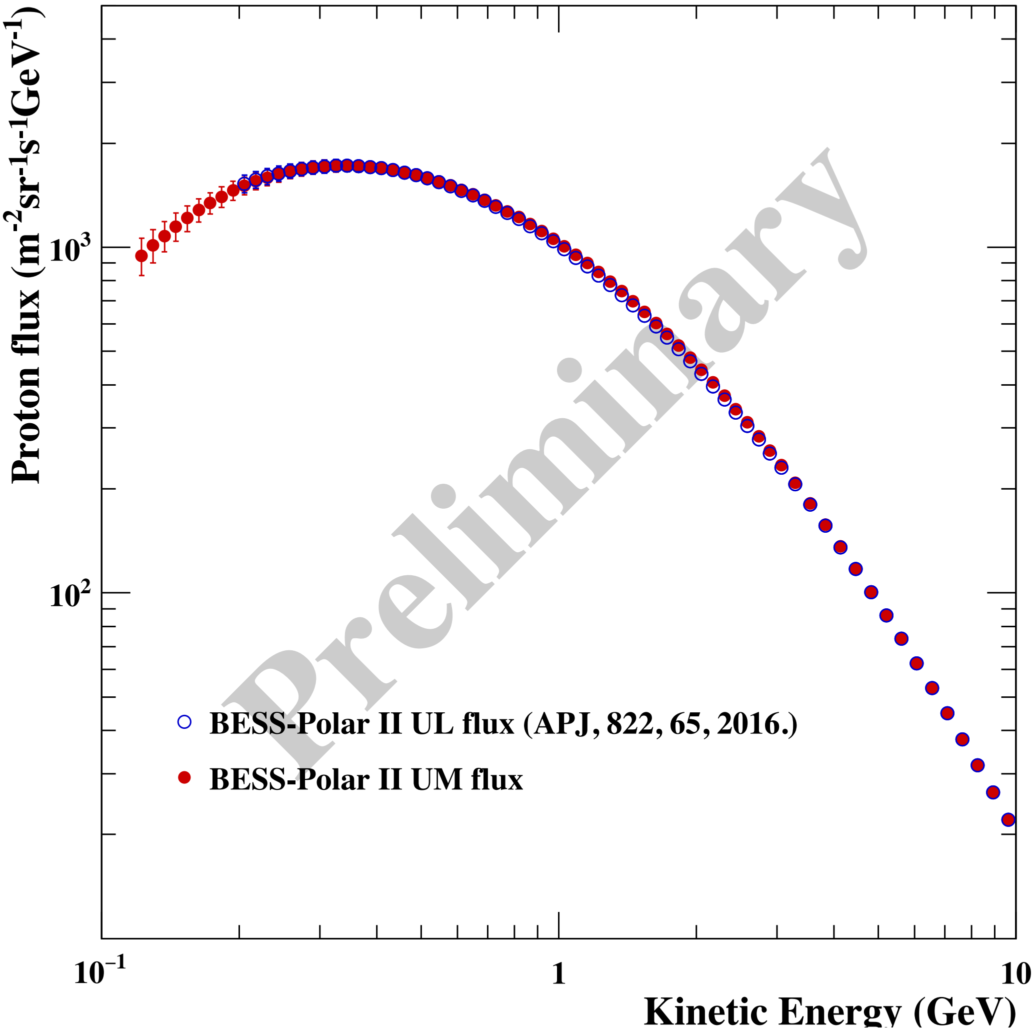

Figure 6: UM absolute differential energy spectra of primary protons measured by BESS-Polar II together with earlier published BESS-Polar II UL measurement [13]. MTOF lowers the threshold to about 120 MeV.

6. Data analysis of Antiprotons

The precise measurement of the lowest energy antiproton spectrum has been motivated by a low-energy antiproton spectrum measured by the BESS95+97 flights that was slightly flatter than the predictions of the secondary antiproton production by collisions between high-energy cosmic rays and interstellar matter. This might suggest the existence of novel cosmic-ray antiproton production in the Universe, such as evaporation of PBH [11]. The UL antiproton spectrum measured by BESS-Polar II shows good consistency with secondary antiproton calculations and no evidence of primary antiprotons originating from the evaporation of PBH. Figure7 show β^{-1} versus rigidity plots by incorporating data from MTOF. We see a band of about 180 antiprotons the exact mirror position of the protons. Based on 180 antiprotons, we will report absolute spectra of the cosmic-ray

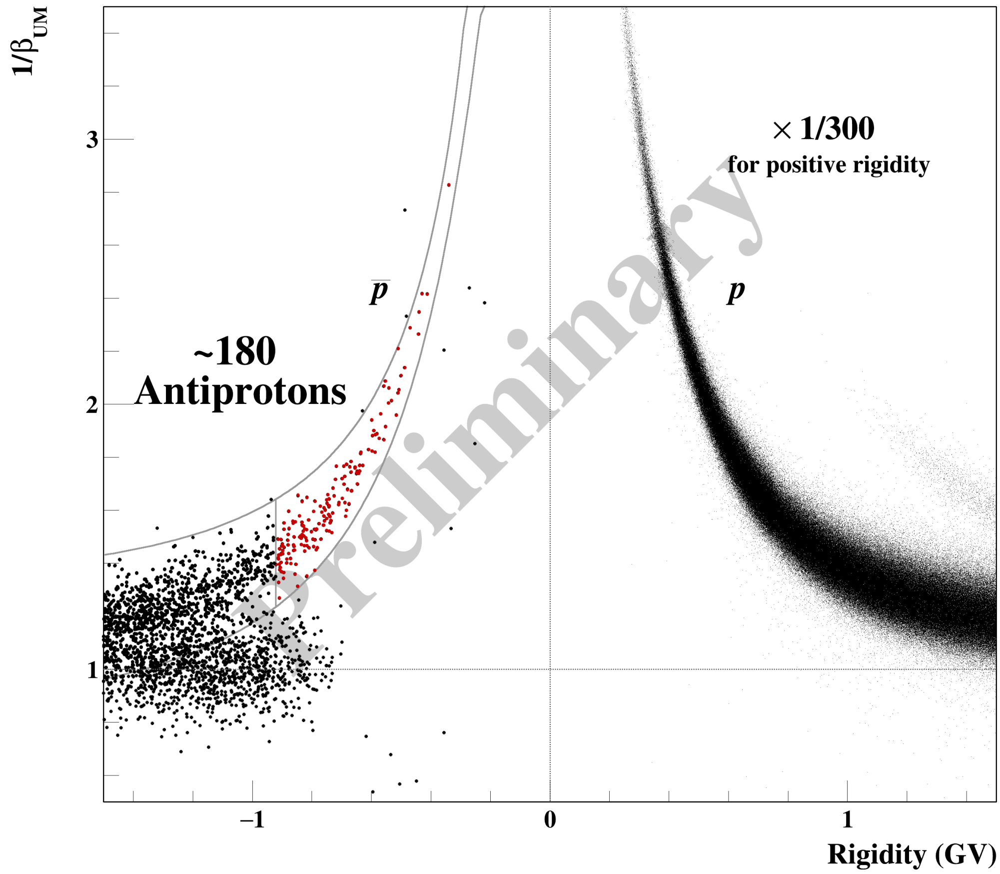

Figure 7: The β_{UM}^{-1} versus rigidity plot and antiproton's selection band. The solid curves define the antiproton mass bands.

antiproton in the range 0.12 to 0.4 GeV and the antiproton/proton ratio in the conference.

7. Conclusion

We have measured energy spectra of the cosmic-ray antiproton in the range 0.12 to 0.4 GeV and the antiproton/proton ratio by incorpolating data from MTOF. The antiproton/proton ratio strongly depends on the solar magnetic field polarity, and is an ideal tool for the study of charge-sign-dependent solar modulation. we will investigate the charge-sign dependence in more detail and work with solar modulation experts to develop more comprehensive drift models to reproduce the measured ratios[20, 21].

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