

## Precise measurements of cosmic-ray antiproton spectrum following the solar field reversal

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**Abstract.** The energy spectrum of cosmic-ray antiprotons ( $\bar{p}$ 's) has been measured by BESS in an energy range of 0.18 to 4.20 GeV successively in 1993, 1995, 1997, 1998, 1999 and 2000. Based on these successive  $\bar{p}$  measurements at various solar activity, the effect of the solar modulation and the origin of cosmic-ray  $\bar{p}$ 's are discussed. The  $\bar{p}/p$  ratios showed no distinctive year-to-year variation during 1993 – 1999. On the other hand, a preliminary result on the  $\bar{p}/p$  ratio in 2000 shows a sudden increase following the Solar field reversal. These interesting features were predicted by a drift model of the solar modulation, which depends explicitly upon particle charge sign.

modulation (Bieber et al., 1999a). The suggested charge sign dependence of the solar modulation is supported by the results from experiments that measured the temporal variation of cosmic ray ratios,  $e^-/He^{2+}$  (Garcia-Munoz et al., 1991) and  $e^-/p^+$  (Raviart et al., 1997), although electrons would behave differently from helium and  $p$  due to their lighter mass. On the other hand, since  $\bar{p}$ 's and  $p$ 's are different only in the charge sign, the  $\bar{p}/p$  ratio provides an ideal probe for studying the charge dependence of the solar modulation.

We report here new measurements of cosmic-ray  $\bar{p}$ 's in the energy range between 0.18 and 4.20 GeV, based on 668 and 558 events detected by the BESS spectrometer in 1999 and 2000 flights, respectively, where a sudden increase of  $\bar{p}/p$  ratio was predicted following the solar field reversal (Bieber et al., 1999a).

### 1 Introduction

The origin of cosmic-ray antiprotons ( $\bar{p}$ 's) has attracted much attention since their observation was first reported by Golden et al. (1979). In a recent solar minimum period, the BESS spectrometer, which has large acceptance and high sensitivity, observed a characteristic peak around 2 GeV in  $\bar{p}$  spectrum. This expected peak is due to the existence of “secondary”  $\bar{p}$ 's produced by cosmic-ray interactions with interstellar gas. While there remains room for “primary”  $\bar{p}$  sources such as annihilation of neutralino dark matter or evaporation of primordial black holes in the low energy region, it has become evident that the dominant component of cosmic-ray  $\bar{p}$ 's has a secondary origin.

Apart from investigation of its origin, secondary  $\bar{p}$ 's offer a unique probe for studying solar modulation of cosmic rays because (i) the input spectrum for the solar modulation can be computed with reasonable confidence, (ii) protons ( $p$ 's) and  $\bar{p}$ 's are ideal for studying the charge sign dependent solar

### 2 BESS Spectrometer

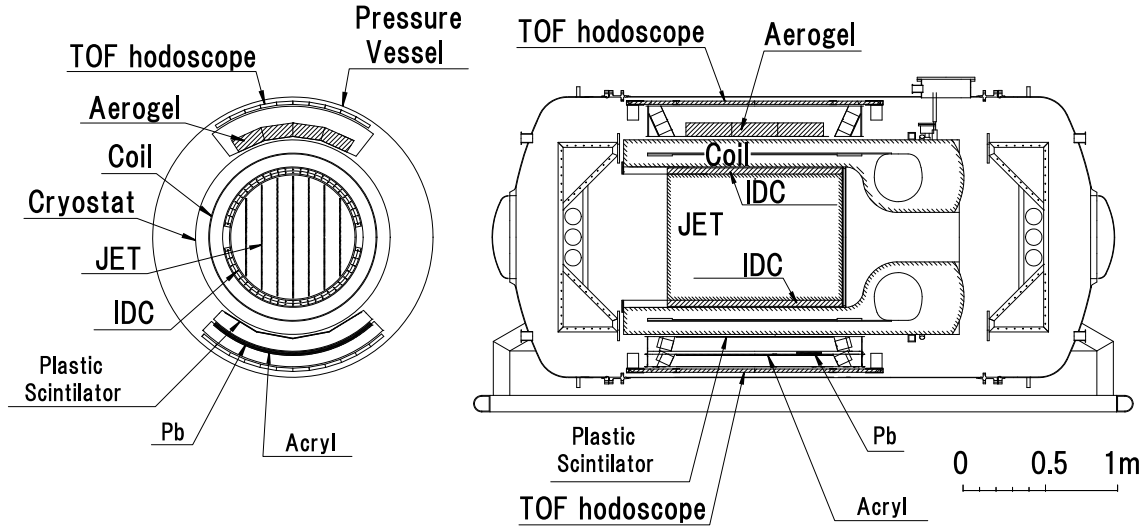
The BESS spectrometer, shown in Fig. 1, was designed (Orito et al., 1987; Yamamoto et al., 1988) and developed (Yamamoto et al., 1994; Ajima et al., 2000; Asaoka et al., 1998; Shikaze et al., 2000) as a high-resolution spectrometer with the capability to search for rare cosmic rays and provide various precision measurements of cosmic-ray primaries. A uniform magnetic field of 1 Tesla is produced by a thin superconducting coil (Makida et al., 1995), with substantial incident particles passing through without interaction. Here, cylindrical coordinates ( $r$ ,  $\phi$ , and  $z$ ) and Cartesian coordinates ( $x$ ,  $y$ , and  $z$ ) are used for representing the BESS instrument, where  $y$  and  $z$  are respectively the vertical axis and axis of the solenoid. The magnetic-field region is filled with tracking detectors composed of a jet type drift chamber (JET) and inner drift chambers (IDCs). This geometry results in an acceptance of 0.3 m<sup>2</sup>sr. Tracking is performed by fitting up to 28 hit-points in the drift chambers, resulting in magnetic-rigidity ( $R \equiv Pc/Ze$ ) resolution of 0.5% at 1 GV. Tracking in the  $z$  coordinate was done by

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**Fig. 1.** Cross-sectional view of the BESS spectrometer.

fitting points in IDCs measured by vernier pads with an accuracy of  $470 \mu\text{m}$  and points in the JET chamber measured by charge division with an accuracy of 2.5 cm. This continuous and redundant 3-dimensional tracking enabled us to recognize multi-track events and tracks having interactions or scatterings, thus minimizing such backgrounds. Energy deposit in the drift chamber gas is also obtained as a truncated mean of the integrated charges of hit pulses. The upper and lower scintillator-hodoscopes (TOF) (Shikaze et al., 2000) provide two  $dE/dx$  measurements and the time-of-flight of particles. Timing resolution of each counter was 55 ps, resulting in  $1/\beta$  resolution of 0.014, where  $\beta$  is defined as particle velocity divided by the speed of light. The instrument also incorporates a threshold-type Cherenkov counter (Asaoka et al., 1998) with a silica-aerogel radiator that can identify  $\bar{p}$ 's from an  $e^-/\mu^-$  background up to a kinetic energy of 4 GeV. From 1999 flight, a newly developed shower counter was installed above the lower TOF hodoscopes to perform  $e/\mu$  separation. It contains thin scintillators (not installed in the 2000 flight), 2 radiation length lead (which covered 1/5 of the whole acceptance), and an acrylic plate. Although it was not used in this analysis, it performed well in both the 1999 and 2000 flights.

### 3 Analysis

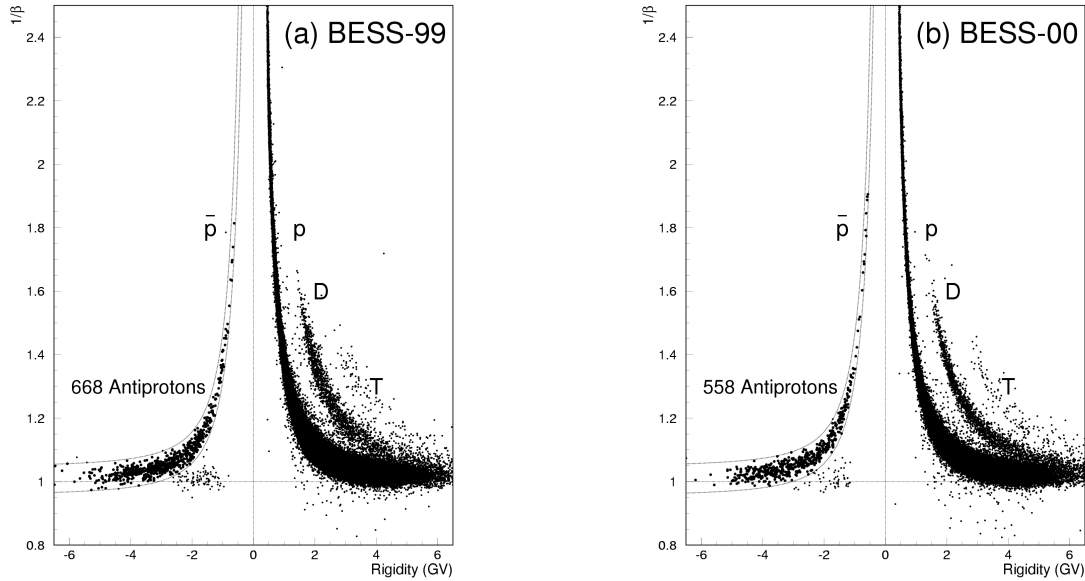
The experiments were carried out in northern Canada, where the geomagnetic cutoff rigidity ranges from 0.3 to 0.5 GV. The scientific data for 1999 and 2000 data, respectively, were taken for 100,403 and 90,766 sec of live time at altitudes above 34 km (residual air of 4.3 and 5.0  $\text{g}/\text{cm}^2$  on average). Regarding the 2000 flight, where considerable amounts of data were taken at lower altitude, we used only the data whose residual air thickness was below 7  $\text{g}/\text{cm}^2$ .

The first-level trigger was provided by a coincidence between the top and the bottom scintillators, with the thresh-

old set at 1/3 of the pulse height from minimum ionizing particles. The second-level trigger, which utilized the hit-patterns of the hodoscopes and IDCs, first rejected unambiguous null- and multi-track events and then made a rough rigidity-determination to select negatively-charged particles predominantly. In addition, one of every 60 (30) first-level triggered events were recorded to build a sample of unbiased triggers in 1999 (2000).

The off-line analysis (Maeno et al., 2001) selects events with a single track fully contained in the fiducial region of the tracking volume with acceptable track qualities. The three  $dE/dx$  measurements are loosely required as a function of  $R$  to be compatible with  $p$  or  $\bar{p}$ . These simple and highly-efficient selections are sufficient for a very clean detection of  $\bar{p}$ 's in the low velocity ( $\beta < 1/1.10$ ) region. At higher velocities, where the  $e^-/\mu^-$  background starts to contaminate the  $\bar{p}$  band, we require the Cherenkov veto, i.e., (i) the particle trajectory to cross the fiducial volume of the aerogel, and (ii) the Cherenkov output to be less than 0.08 of the mean output from  $e^-$ . This cut reduces the acceptance by 25 %, but rejects  $e^-/\mu^-$  backgrounds by a factor of 4000, while keeping 94 % efficiency for  $p$ 's and  $\bar{p}$ 's which cross the aerogel with rigidity below the threshold (4.7 GV).

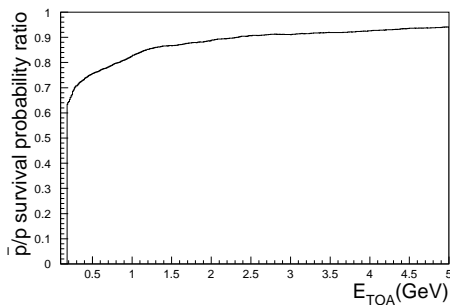
Figure 2 shows the  $\beta^{-1}$  versus  $R$  plot for the surviving events. We see a clean narrow band of 668 and 558  $\bar{p}$ 's at the exact mirror position of the  $p$ 's for the 1999 and 2000 data, respectively. The  $\bar{p}$  band is slightly contaminated with the  $e^-/\mu^-$  backgrounds due to the inefficiency of the aerogel Cherenkov counter, while the  $p$  band contamination was completely negligible. This background was estimated and subtracted as follows: (i) At first, we counted the number of  $e^-/\mu^-$  events overlapping with the  $\bar{p}$  band before the requirement on the Cherenkov output. (ii) Next, we obtained the probability that  $e^-/\mu^-$  gave a lower Cherenkov output than the threshold from the distribution of the output for high rigidity  $p$ 's ( $\geq 25$  GV), which should emit enough output. (iii) Finally, from the above two quantities we estimated the



**Fig. 2.** The identification plots of  $\bar{p}$  events for (a) 1999 and (b) 2000 flight. The dotted curves define the  $\bar{p}$  mass bands.

amount of  $e^-/\mu^-$  background as 0 (0), 0.7 (0.6) and 3.4 (1.9) %, respectively, at 0.3, 2 and 4 GeV for 1999 (2000) data. Backgrounds of albedo and mis-measured positive-rigidity particles were totally excluded by the excellent  $\beta^{-1}$  and  $R^{-1}$  resolutions. To check against the “re-entrant albedo” background, we confirmed that the trajectories of all  $\bar{p}$ 's could be traced numerically through the Earth's geomagnetic field back to the outside of the geomagnetic sphere.

Based on the observed  $\bar{p}$ 's and  $p$ 's, the  $\bar{p}/p$  ratio at the top of the atmosphere (TOA) was calculated as follows. (i) The TOA energy ( $E_{\text{TOA}}$ ) of each event was calculated by tracing back the particle through the detector material and the residual air. (ii) The survival probability (non-interacting efficiency) of the  $\bar{p}$ 's and  $p$ 's through the air and the instrument was evaluated by Monte Carlo simulation based on GEANT/GHEISHA with modified cross sections. Note that the simulation model was verified and tuned by an accelerator beam test (Asaoka et al., 2001a,b). The  $\bar{p}$  to  $p$  ratio of the survival probability is shown in Fig. 3. (iii) The trigger



**Fig. 3.**  $\bar{p}/p$  ratio of the survival probability in the residual atmosphere and the instrument itself.

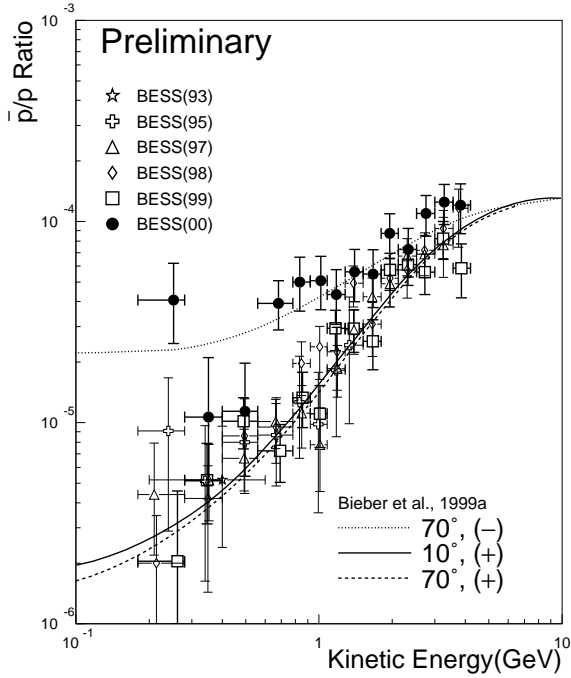
efficiencies for non-interacting particles were determined by using proton samples in the unbiased trigger samples. (iv) The expected atmospheric secondaries were subtracted based

on the recent calculations by Mitsui et al. (1996); Pfeifer et al. (1996); Stephens et al. (1997) for  $\bar{p}$ 's and by Papini et al. (1996) for  $p$ 's. Since we have not yet determined the absolute fluxes, we obtained a normalization factor for the atmospheric fluxes by comparing our measured  $p$  spectrum integrated above 20 GeV for  $\bar{p}$ 's (above 3 GeV for  $p$ 's) with the spectrum used for the secondary calculations. For  $\bar{p}$ 's, the secondary fraction is nearly constant, and the subtraction amounts to  $22 \pm 5$  % ( $27 \pm 7$  %) regardless of its energy in 1999 (2000). For  $p$ 's, on the other hand, they are  $33 \pm 7$  ( $50 \pm 10$ ),  $4 \pm 1$  ( $12 \pm 2$ ) and  $3 \pm 1$  % ( $4 \pm 1$  %) for 0.2, 1 and 2 GeV in 1999 (2000), respectively. Since systematic uncertainty due to interaction losses in the instrument and residual air was remarkably reduced by the accelerator beam test, the dominant systematics comes from atmospheric subtraction. Note that intensive studies on atmospheric secondaries are now in progress by using  $\bar{p}$  and  $p$  data at mountain altitude (Fujikawa et al., 2001) and low energy  $p$  data during ascent (Shikaze et al., 2001). As a preliminary result, we estimate  $\pm 15$  % relative error and obtained  $\bar{p}/p$  ratio.

## 4 Results

Figure 4 shows the BESS 1999 and 2000  $\bar{p}/p$  ratios, together with the previous measurements performed by BESS (Yoshimura et al., 1995; Moiseev et al., 1997; Matsunaga et al., 1998; Orito et al., 2000; Maeno et al., 2001). Taking the charge sign dependence of the solar modulation into account (Bieber et al., 1999a), the  $\bar{p}/p$  ratio is expected to be nearly identical during the Sun's positive polarity phase. But when the polarity switches to negative, the  $\bar{p}/p$  ratio should rapidly increase as indicated by the dotted curve in Fig. 4. The BESS 1993 – 1999 spectra were measured in the positive polarity phase, and the  $\bar{p}/p$  ratios showed no distinctive year-to-year variation as predicted. On the other hand,  $\bar{p}/p$  ratio in 2000

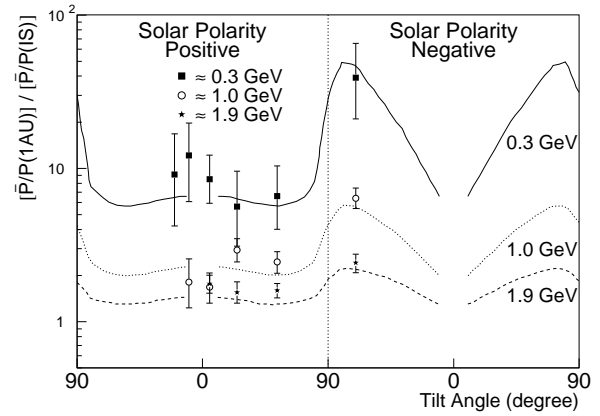
shows a sudden increase following the solar field reversal. As a result, predicted dynamics of the ratio were verified by our measurements.



**Fig. 4.** Comparison of the BESS 1993, 1995, 1997, 1998, 1999 and 2000  $\bar{p}/p$  ratios with the calculation (Bieber et al., 1999a) taking the charge sign dependence of the solar modulation into account. The solid and dashed curves represent the calculated  $\bar{p}/p$  ratios at a solar minimum and at a solar maximum in the positive Sun's polarity. On the other hand, the dotted curve represent the calculated  $\bar{p}/p$  ratios at a solar maximum in the negative Sun's polarity.

Annual variation of the  $\bar{p}/p$  ratio at the respective energies of 0.3, 1.0 and 1.9 GeV are shown in Fig. 5 as a function of tilt angle to compare theoretical predictions (Bieber et al., 1999b) which are represented by solid, dotted and dashed curves. The vertical axis is normalized to the interstellar  $\bar{p}/p$  ratio (Bieber et al., 1999a) and the abscissa values have been arranged so that the curves have the appearance of two successive solar cycles evolving in time. As a measure of tilt angle, we use the mean position of the maximum latitudinal extent of the current sheet (Hoeksema, <http://quake.stanford.edu/~wso/Tilts.html>). To compare the prediction of a steady state drift model, the tilt angle for each data point are averaged over six months before the date of observation, considering the expanding neutral current sheet in the heliosphere at the solar wind speed (Roux et al., 1990). Note that measured  $\bar{p}/p$  ratio shows a good agreement with the prediction.

As a conclusion, for the first time we have measured the dynamics of the  $\bar{p}/p$  ratio from minimum to maximum solar activity with unprecedented accuracy. We observed its stable features in the positive polarity phase and a sudden increase following the solar field reversal, which should be caused by charge sign dependence of the solar modulation. These



**Fig. 5.** Tilt angle dependence of  $\bar{p}/p$  ratio at 0.3 (closed squares), 1.0 (open circles) and 1.9 GeV (closed stars) kinetic energy measured by BESS (1993 – 2000, from left to right), together with predicted variation by Bieber et al. (1999b).

combined observations are stunning validation of the importance of drift effects in solar modulation including a solar maximum period. Moreover, deep understanding of the solar modulation is also inevitably important for investigating the origin of low energy  $\bar{p}$ 's.

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