Precise measurement of the cosmic-ray proton spectrum and the time variation with BESS-Polar I


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Abstract. The Balloon-borne Experiment with a Superconducting Spectrometer over Antarctica (BESS-Polar) had two successful flights in December 2004 and 2007. During the first flight in 2004 (BESS-Polar I), 0.9 billion cosmic-ray events have been recorded in an 8.5-days long-duration flight. Here we report on the primary cosmic-ray proton and helium spectra measured with BESS-Polar I. Using the spectrometer with a high rigidity resolution, we measured precise proton and helium spectra in kinetic energy ranges of 0.22-100 GeV/n and 0.22-54 GeV/n, respectively. With the detailed analysis of detector response and the correction of atmospheric secondary particles in short-term period, we also obtained the time variation of the primary proton and helium fluxes.

Keywords: cosmic-ray proton, superconducting spectrometer, long-duration balloon, solar modulation

I. INTRODUCTION

Among cosmic-ray particles, protons and helium nuclei are the dominant components. The absolute fluxes and energy spectra of primary cosmic-ray protons and helium nuclei are fundamental information in cosmic-ray physics. The interstellar spectra carry important information on the origin and propagation history of cosmic-rays in the Galaxy. The spectra are also essential as an input to calculate spectra of cosmic-ray antiprotons and positrons which are mainly secondary products of cosmic-ray interactions with the interstellar gas. At low energies, observable spectra in the heliosphere are much deformed in a manner that depends on the solar activity. Therefore the low-energy proton and helium spectra provide significant information on the solar activity and the propagation of cosmic-rays. Here we report on the measurement of the cosmic-ray proton and helium spectra in energy ranges of 0.22-100 GeV/n and 0.22-54 GeV/n, respectively, based on the data from the first Balloon-borne Experiment with a Superconducting Spectrometer over Antarctica (BESS-Polar I) which was carried out in 2004. The BESS-Polar experiment was proposed as an advanced BESS[1][2][3][4] program with long-duration balloon flights over Antarctica and had been prepared since 2001[5][6][7]. The result of BESS-Polar I antiproton spectrum with discussions for primary antiprotons, which is the main science objective of the BESS-Polar project, is described in Ref. [8]. The BESS-Polar spectrometer features high-precision rigidity measurement with wide rigidity range, large geometrical acceptance, and small material thickness. We were successful to perform the precise measurement of cosmic-ray proton and helium fluxes and its short-term variation with this long-duration flight, in a transient period to the solar minimum. Further discussion and physics interpretation for proton short-term variation are described elsewhere in these proceedings[9].

II. BESS-POLAR I SPECTROMETER

Figure 1 represents a cross-sectional view of BESS-Polar I spectrometer, which consists of a top, bottom, and middle time-of-flight (TOF) hodoscopes[10], a JET-type and two inner drift chambers (JET/IDC)[11][12], an Aerogel Cherenkov Counter (ACC)[13] and a superconducting solenoid[14][15]. The rigidity (R) of incoming particles is measured by the JET/IDC central tracker in a 0.8 Tesla uniform magnetic field which is produced by the thin superconducting solenoid. The TOF counters measure the velocity (β), and provide three independent ionization energy loss (dE/dx) measurements in the scintillators. Particle identification by mass is performed with these measurements (R, β, and dE/dx). ACC is also installed for the background (e±, µ±) rejection.
The event trigger is generated by the simple coincidence of the signal of top-bottom TOFs or top-middle TOFs. The total cross-sectional mass of the BESS-Polar spectrometer is only 4.5 g/cm$^2$ for top-middle TOFs coincidence events to measure low-energy cosmic-ray particles precisely.

III. BESS-POLAR I FLIGHT

The BESS-Polar I was launched from Williams Field ($77^\circ51.8'S$, $167^\circ5.4'E$) near McMurdo Station on December 13, 2004[16]. During the flight, some PMTs of the TOF hodoscopes had to be turned off because of their excessive drawing current. The resulting usable geometrical acceptance was consequently reduced to 73 percent of the design value. The flight was terminated on December 21 and the payload landed at the south end of the Ross Ice Shelf ($83^\circ6.0'S$, $155^\circ35.4'W$) after a continuous observation period of 8.5 days. The flight trajectory was so close to the South magnetic pole that the geomagnetic cutoff rigidity was below 0.2 GV, as shown in Fig. 2. During a live data-taking time of 507,075 seconds at an average floating altitude of 38.5 km (residual atmosphere of 4.3 g/cm$^2$), 894,482,590 cosmic-ray events were accumulated.

IV. DATA ANALYSIS

A. Data Reduction

For the analysis of protons and helium nuclei, only the top and bottom TOF hodoscopes were used. As the first selection, events with (1) a single track, a downward-going and a positive rigidity particle fully contained in the fiducial region of the tracking volume, (2) only one or two hits each in the top and bottom TOFs, (3) the hit position of r-φ direction at the TOFs consistent with the extrapolated track inside the JET and IDCs, (4) cosine of zenith angle of the incident particle larger than 0.8, and (5) either top or bottom TOFs read by PMTs at both ends, are selected. Then as the fiducial selection, events were required to pass through the fiducial volume defined by the central region of the JET chamber and TOFs. Events entering unstable IDC region or noisy JET region were also not used. After the fiducial selection, the quality cut was applied, which required the residual between hit position at TOF obtained from the time difference in two PMTs and the extrapolated track of the JET to be less than 80 mm. Each analog-to-digital board for TOF has an individual dead time due to the period of switching reference capacitors used for baseline subtraction[10]. Events digitized during the dead time have incorrect charge data. We also rejected these events, which are 52% of total data, to ensure the quality of the data.

B. Particle Identification

After the above event selections, the particle identification was performed. The charge of the particle is identified by the ionization loss measurement. Both dE/dx signals from top and bottom hodoscopes were required to be proton-like. Then, particles with proton mass were selected by a 1/β-band cut. The selection of protons with the dE/dx-band cut and 1/β-band cut are shown on top and bottom in Fig. 3, respectively. Particle identification for helium nuclei was performed in the same way. However, $^3$He nuclei were included in 1/β-band cut and were counted as helium-like events. In conformity with previous experiments, all the helium-like events were treated as $^4$He nuclei in the analysis such as the reconstruction from rigidity to kinetic energy, and the efficiency estimation with the Monte Carlo (MC) simulation.

C. Flux determination

1) TOI: The numbers of protons and helium nuclei passing through the BESS spectrometer during the observation were obtained after correcting the detection efficiency. Then absolute flux at the top of the instrument (TOI) was obtained by taking account of the energy loss inside the detector, live time, and geometrical acceptance. The energy of each particle at TOI was calculated by summing up the ionization energy losses inside the instrument by tracing back the event trajectory. The
geometrical acceptance and some of selection efficiencies were estimated using a MC simulation by applying the same selection criteria to the simulated events as to the observed data. The MC simulation was based on a GEANT3/GHEISHA code[17][18] and tuned to reproduce the results of an accelerator beam test of the previous BESS spectrometer[19] in which the detector configuration and materials are similar to the BESS-Polar spectrometer. The effective geometrical acceptance was 0.053 m²sr at 2 GeV/n for protons. The efficiencies for particle identifications, trigger, track reconstruction, accidental TOF hits, accidental tracks, quality cut, were estimated from real data.

2) TOA: The flight-averaged flux at TOI was measured under the residual atmosphere of about 4.3 g/cm². It consists of a primary component surviving without any nuclear interactions with air, and of a secondary component produced inside the overlying atmosphere. In order to obtain the flux at the top of the atmosphere (TOA), secondary proton production and interaction loss of primary particles inside the atmosphere were estimated by solving simultaneous transport equations[20] with the modified production spectrum to reproduce the observed proton spectra which were measured by previous BESS flights at several atmosphere depths[21]. The primary spectrum at TOA was determined in an iterative procedure so that the estimated spectrum at TOI agrees with the observed one. Figure 4 shows a calculated TOI/TOA correction factor for proton and helium spectra at the atmospheric depth 4.3 g/cm².

V. RESULTS AND DISCUSSIONS

We obtained the absolute primary fluxes of protons and helium nuclei at TOA in the kinetic energy ranges of 0.22-100 GeV/n and 0.22-54 GeV/n, respectively. The flight-averaged fluxes which were obtained from all 8.5-days data are shown in Fig. 5, 6 together with results from previous BESS flights[12][21][22]. The uncertainties including statistical and systematic errors are ±7.5% at 0.23 GeV/n and ±3% at 93 GeV/n for protons, ±4% at 0.23 GeV/n and ±5.5% at 50 GeV/n for helium nuclei. In low energies, the resultant proton and helium fluxes are between BESS-1999 and BESS-2002 as shown in Fig. 5. The effect of the solar modulation was clearly observed. In high energies, the resultant fluxes of BESS-Polar 1 were consistent with BESS-1998 and BESS-2002. Figure 7 shows a time variation of proton and helium fluxes normalized to the flight-averaged fluxes in kinetic energy ranges of 0.22-0.50, 0.50-1.0, 1.0-3.5, 3.5-10 GeV/n, together with the residual air during the flight and Bartol South Pole neutron monitor[23]. Here the time-divided data analysis has been done with the same way of the flight-averaged flux. The residual air above the instrument and its TOI/TOA correction factor for protons varied between 3.8-5.3 g/cm² and 1.45-1.63 at 0.23 GeV/n respectively with these time bins. Further discussion for the short-term variation of protons and its relation to the solar activity is described elsewhere[9].

VI. CONCLUSION

The BESS-Polar experiment had a first successful long-duration flight in December 2004. We reported the absolute fluxes and energy spectra of the primary cosmic-ray protons and helium nuclei in kinetic energy ranges of 0.22-100 GeV/n and 0.22-54 GeV/n respectively, during the transient period to the solar minimum. Using the advantage of long-duration flight and large geometrical acceptance, the fluxes with short-term period have been also calculated. These precisely measured data are fundamental information on the origin and propagation history of cosmic-rays and also important to study the effect of solar activity.

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Flux x E

Proton and Helium flux (m$^2$ sr$^{-1}$ sec$^{-1}$ GeV$^{-1}$)

Relative Flux

Residual Air

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