PROCEEDINGS OF SCIENCE

BESS-Polar Measurements of the Cosmic-ray Proton and Helium Spectra

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The energy spectra of cosmic-ray protons and helium near solar minimum were measured with BESS-Polar (Balloon-borne Experiment with a Superconducting Spectrometer-Polar) during long-duration flights over Antarctica in December 2004 and December 2007, and are discussed here. The absolute fluxes and spectral shapes of primary protons and helium probe the origin and the propagation history of cosmic rays in the Galaxy. The spectra are also essential as inputs to calculate the spectrum of cosmic-ray antiprotons, which are secondary products of cosmic-ray interactions with the interstellar gas. We report absolute spectra at the top of the atmosphere for cosmic-ray protons in the kinetic energy range 0.2-160 GeV and helium nuclei 0.2-80 GeV/nucleon [1].

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1. Introduction

The absolute fluxes and spectral shapes of primary cosmic rays are important for understanding the origin and the propagation history of the cosmic rays in the Galaxy. The proton and helium spectra are also essential as inputs to calculations of the spectra of cosmic-ray antiprotons and positrons, which are secondary products of cosmic-ray interactions with the interstellar gas. During propagation through the ISM, cosmic rays undergo interactions with gas atoms and loose energy, significantly modifying their spectra and composition. Then when Galactic cosmic rays enter the heliosphere, they are scattered by irregularities in the heliospheric magnetic field and undergo convection and adiabatic deceleration in the expanding solar wind. This process, modifying the energy spectra of cosmic rays, is known as “solar modulation”. The abundant protons and helium nuclei are among the most important keys to understanding these processes.

2. BESS Program

The BESS instrument [2, 3] 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 flew 8 times over Lynn Lake, Canada and once from Fort Sumner, USA during the period of 1993 through 2002 with continuous improvement in the instrument [4]. The BESS-Polar project was proposed as an advanced BESS program using long duration balloon (LDB) flights over Antarctica (around the south pole) to provide high-statistics, low-energy cosmic-ray measurements [5, 6, 7].

The scientific flight of the BESS-Polar I instrument was launched from Williams Field, near McMurdo Station, on December 13th, 2004 (UTC). The flight duration was over 8.5 days at 37 km to 39.5 km (residual air of 4.33 g/cm^2 on average) and more than 9×10^8 cosmic-ray events were recorded. 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 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 5.81 g/cm^2 on average), and the cutoff rigidity

Figure 1: Flight trajectories over Antarctica of BESS-Polar I in 2004 (green) and BESS-Polar II in 2007/2008 (first orbit blue, second orbit red).

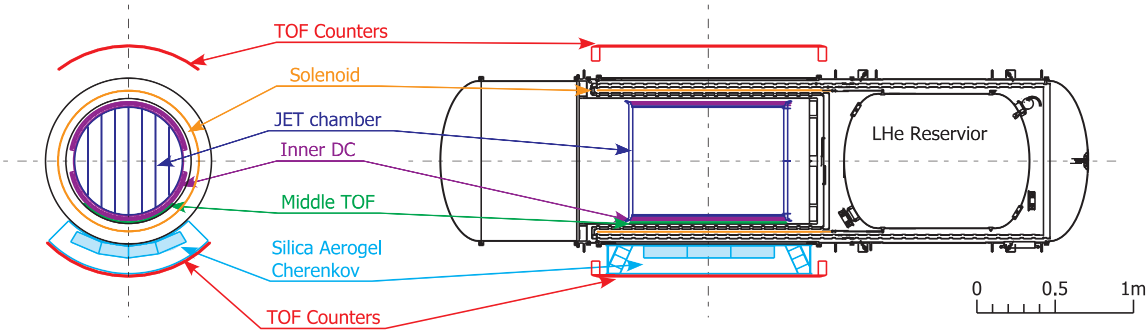


Figure 2: Cross sectional view of BESS-Polar II spectrometer

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 program has produced precise measurements of antiprotons [8, 9] and a sensitive antihelium search [10]. 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. The 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.

3. BESS-Polar Instrument

In the BESS-Polar instruments, 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 $\sim 125\mu$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 with a geometric acceptance of $\sim$0.3 m^{2}sr. The timing resolution of the TOF system is 120 ps, giving a β^{-1} resolution of 2.5%. For antiproton measurements, the geometric acceptance of BESS-Polar is 0.23 m^{2}sr and for proton and helium measurements the acceptance is 0.20 m^{2}sr. In BESS-Polar I, 18 of 44 PMTs in TOF had to be turned off due to excessive current and this reduced to 75% of the acceptance. 2 of 44 PMTs had HV control problems during BESS-Polar II flight; however, 100% of the nominal acceptance was retained. The instrument also incorporates a threshold-type Cherenkov counter using a silica aerogel radiator and a thin scintillator middle-TOF. They are installed to identify antiprotons; therefore, they aren't used in this analysis for protons and helium.

4. Solar Modulation

The considerable variation in solar activity and details of the effects of the solar wind and its entrained magnetic fields on the incoming GCR fluxes have to be taken into account in deriving interstellar spectra. At energies above 30 GeV for protons and 15 GeV/nucleon for helium, solar modulation has negligible influence on the measured spectra. Figure 3 shows evidence of solar modulation of cosmic rays and solar activity illustrated by the changes with time of the Bartol neutron monitor counting rate (Blue points) [11] and the number of sunspots (Red points) [12] together the data of BESS flights. The solar cycle has an approximately 11-year period. In addition, the sun has a 22 year magnetic cycle with recurrent positive ($A > 0$) and negative ($A < 0$) phases, where $A < 0$ polarity cycles are defined as the periods when the heliospheric magnetic field (HMF) is directed towards the Sun in the northern hemisphere. Since the low-energy region of the cosmic radiation is most intensively affected by solar modulation, the absolute fluxes and spectral shapes of primary protons and helium obtained with BESS are essential probes. These are combined with the simultaneous BESS antiproton measurements to probe the effect of charge-sign dependent drift on the entering cosmic rays.

5. 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. To ensure the best tracking, an effective IDC fiducial region of about $\sim 85\%$ of the active area was defined by cuts on the drift time to exclude regions very near the sense wires and far from the wires. These definitions of the fiducial volume reduced the effective geometrical acceptance, but ensured the longest track fits and thus the highest resolution in the rigidity measurement. The effective acceptances at 10 GeV/nucleon in BESS-Polar I are 0.042 m^2sr for protons and 0.038 m^2sr for helium. In BESS-Polar II they are 0.056 m^2sr for protons and 0.051 m^2sr for helium. 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.

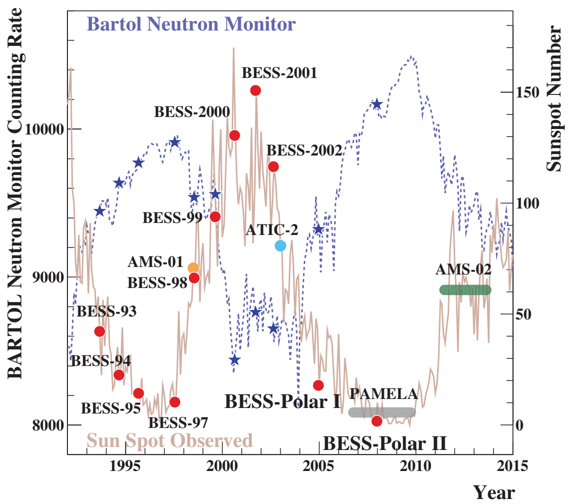
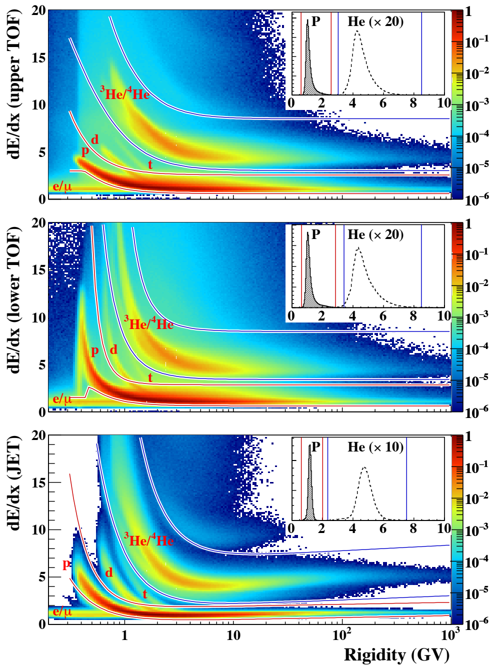


Figure 3: Variation of neutron monitor and sunspot number together the data of the BESS, AMS-01, ATIC-2, PAMELA, AMS-02 and BESS-Polar flights. The BESS-Polar II flight was carried out near the absolute solar minimum.



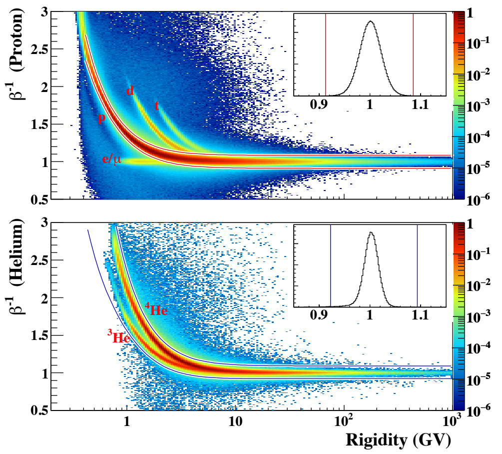


Figure 4: Proton and helium bands in dE/dx (top: upper TOF, middle: lower TOF, bottom: JET) vs. rigidity obtained from the balloon observation. The superimposed graph shows the selection criteria for protons and helium nuclei above 30 GV.

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

To estimate the efficiency of the single-track selection, Monte Carlo simulations with GEANT4 (Version 10.00.p01) were performed.

5.1 Event selection

To assure the accuracy of the rigidity measurement, the following track quality cuts were applied: (1) reduced χ^2 per degree of freedom <5 for track fits in both $r\phi$ and yz planes (where y is the vertical direction), (2) track fitting pathlength $\geq$500 mm, (3) ratio of fitted hits in the JET to expected hits $>$0.6, (4) ratio of dropped hits in the JET and IDCs to expected hits $<$0.25, (5) 2 hits in each of the 2 IDCs all giving both x and z positions, and (6) consistency between independent z positions measured by the tracking system and the TOF (determined using the time difference between each end of the hit paddle). Above $\sim$2 GV the efficiencies for both protons and helium are essentially constant. Particle identification was performed by requiring proper dE/dx measurements, in both upper and lower layers of the TOF hodoscopes, and β^{-1} as functions of rigidity. Figs. 4 and 5 show the selection criteria for protons and helium. 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 for protons and 6σ for helium, the efficiency is very close to unity.

5.2 Normalization and corrections

$$\Phi_{\rm TOA}(E_{\rm TOA}) = \frac{\Phi_{\rm TOI}(E_{\rm TOI})}{\eta(E_{\rm TOI\to TOA}) + R_{\rm air}(E_{\rm TOI\to TOA})} \tag{5.1}$$

$$\Phi_{\rm TOI}(E_{\rm TOI}) = N_{\rm p}/(\varepsilon_{\rm det}\cdot\varepsilon_{\rm MC})/(S\Omega\cdot T_{\rm live}) \tag{5.2}$$

where $N_{\rm p}$ is number of observed particles of that species, $\varepsilon_{\rm det}$ is detection efficiency that is related to the event selection, $\varepsilon_{\rm MC}$ is noninteracted single track efficiency estimated by using MC, $S\Omega$ is geometrical acceptance and $T_{\rm live}$ is the live time period. $(1-\eta)$ quantifies losses in the atmosphere and $R_{\rm air}$ is atmospheric secondary production.

In order to determine the primary cosmic-ray proton and helium spectra at the top of the atmosphere, the following normalization and corrections are required : (1) exposure factor, (2) ionization energy loss, (3) interaction loss, and (4) atmospheric secondary particle contribution.

The exposure factor is a product of geometrical acceptance and live time. The geometrical acceptance defined for this analysis was calculated by simulation technique described in Section 5. The simple cylindrical shape and the uniform magnetic field make it simple and reliable to determine the geometrical acceptance precisely. The live data-taking time was measured to be 5×10^5 s in BESS-Polar I and 1.3×10^6 s in BESS-Polar II. The energy of each incoming particle was calculated by integrating the energy losses inside the detector tracing back along the particle trajectory. In order to obtain the absolute flux of primary protons and helium nuclei at the top of the atmosphere, interaction loss and secondary particle production in the residual atmosphere were estimated. Both for air correction can be estimated by solving simultaneous transport equations following Papini et al [13]. The primary spectrum at TOA ($\Phi_{\rm TOA}$) is determined in an iterative procedure so that the estimated spectrum at TOI ($\Phi_{\rm TOI}$) agrees with the observed one.

6. Measured Spectra

In the present work, we have obtained the absolute fluxes of primary protons in the range 0.2-160 GeV and helium nuclei in the range 0.2-80 GeV/nucleon at the top of the atmosphere from BESS-Polar I and BESS-Polar II balloon-flight data, respectively. The corresponding ranges are 0.6-160 GV for protons and 1.3-160 GV for helium. The overall uncertainties, including both statistical and systematic errors, are less than $\pm10\%$ for BESS-Polar I protons, $\pm6\%$ for BESS-Polar II protons, $\pm7\%$ for BESS-Polar I helium, and $\pm5\%$ for BESS-Polar II helium. The results of primary proton and helium spectra are shown in Fig. 6 in comparison with BESS98 [14], AMS-01 [15, 16], BESS-TeV [17], ATIC-2 [18], PAMELA [19], and AMS-02 [20, 21].

Differences in the spectra measured by BESS-Polar I and BESS-Polar II resulting from solar activity (discussed in Section 4) below $\sim$10 GeV for protons and below $\sim$5 GeV/nucleon for helium are highlighted. This variation of measured spectra is consistent with the effect expected from charge-sign dependent drift [22, 23]. At energies above 30 GeV for protons and 15 GeV/nucleon for helium, the effects of solar modulation are effectively negligible and the proton spectra measured BESS-Polar I and BESS-Polar II are essentially identical, differing by less than 1% at 160 GeV despite having been obtained during quite different periods of solar activity (see further discussion

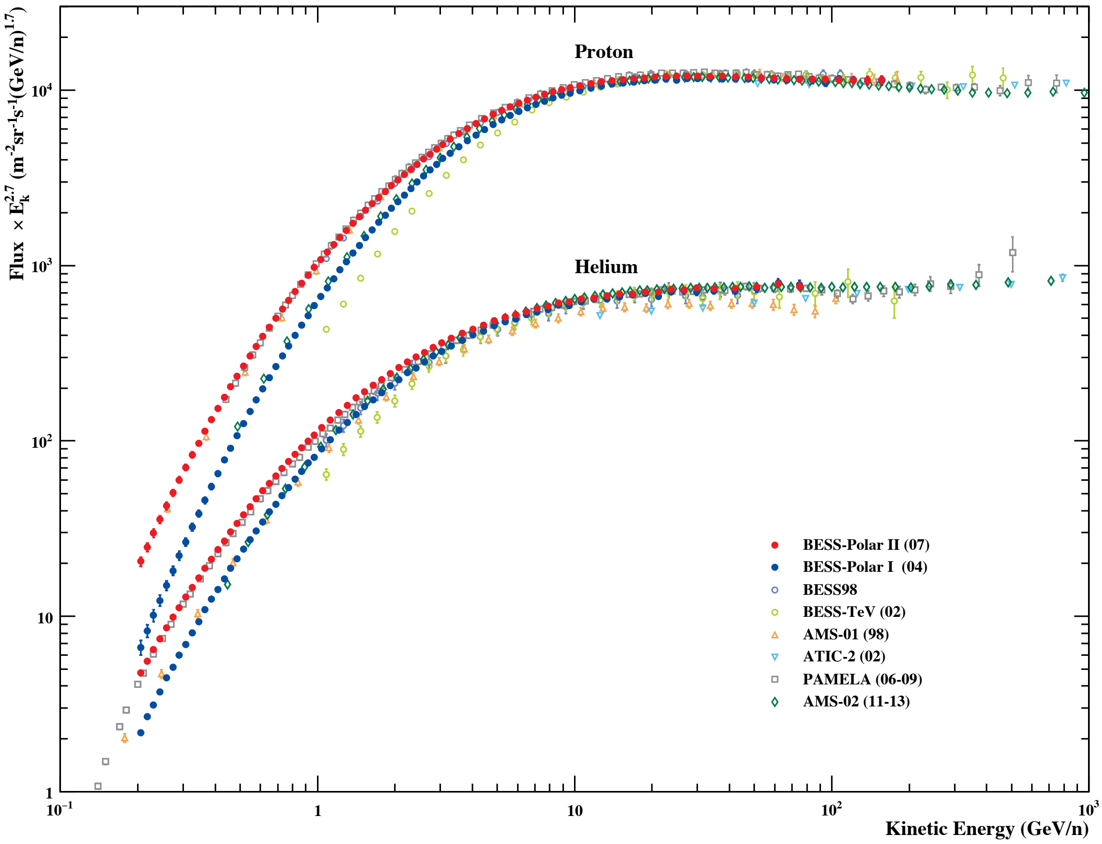


Figure 6: Absolute differential energy spectrum of primary protons and helium multiplied by $E_K^{2.7}$ measured by BESS-Polar I and BESS-Polar II. The spectra obtained by other experiments [14, 15, 16, 17, 18, 19, 20, 21] are also shown.

below). The same is true of the helium spectra above ∼15 GeV/nucleon where the BESS-Polar I and BESS-Polar II results differ by less than 1% at 80 GeV/nucleon.

7. Conclusion

We have measured energy spectra of primary protons in the range 0.2-160 GeV and helium nuclei in the range 0.2-80 GeV/nucleon at the top of the atmosphere from BESS-Polar I and BESS-Polar II. Full details of the analysis are described in a paper submitted to arXiv[1].

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