Flux time variation measurements of cosmic-ray helium isotopes with BESS-Polar I

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Abstract: The Balloon-borne Experiment with Superconducting magnet Spectrometer (BESS) instrument includes various particle detectors, such as plastic scintillator counters and a central jet-type drift chamber surrounded by a superconducting solenoid magnet. Measurements provided by these detectors allow precise identification of cosmic-ray helium isotopes. The long-duration flight of the BESS-Polar I instrument, about 8.5 days over Antarctica in 2004, allows for the first time to measure time variations of isotope fluxes. The time variation of the helium isotope flux for rigidities from 1.2 GV to 2.5 GV is presented, and the results are discussed and compared with previously reported proton data and neutron monitor data.

Keywords: cosmic-ray isotopes; cosmic-ray flux time variations; solar modulation; solar activity

1 Introduction

The central goals of the BESS program are to precisely measure low energy cosmic-ray antiprotons [1] and to search for antihelium in the cosmic rays [2]. In addition, the BESS instruments allow fluxes of hydrogen and helium isotopes to be determined [3]. The measurements of the fluxes of antiprotons and normal nuclei give complementary information on solar modulation and provide information on cosmic-ray origins and propagation in interstellar space.

BESS [4] is a Japanese-US program that has carried out 11 successful balloon flights, 9 of which took place in northern Canada from 1993 to 2002. To take advantage of low geomagnetic cutoff and improve the exposure time for data taking the BESS-Polar I and BESS-Polar II instruments were developed for Antarctic long-duration balloon flights and were flown for 8.5 days in December 2004 and 24.5 days in December 2007/January 2008 respectively.

These long-duration flights over Antarctica allow studies of cosmic-ray flux time variations on time scales of a few hours, and a preliminary work on proton transient variations was reported in [5]. With the BESS-Polar I instrument, time variations of ^{3}He and ^{4}He fluxes could be measured for the first time. They are presented in this paper from the full flight period of December 13th to December 21st 2004.

After presenting the instrument in section §2, the analysis to separate isotopic elements is described in section

§3, and the time variations of helium isotope fluxes are discussed in sections §4 and §5.

2 The BESS-Polar I instrument

The BESS-Polar I instrument is shown in Figure 1. Its detectors and solenoidal magnet were concentrically arranged. From the top to the bottom of the instrument, a downward-going particle passes through a top plastic scintillator hodoscope, a solenoidal superconducting magnet producing a uniform magnetic field of 0.8 T, two layers of inner drift chambers, a central jet-type drift chamber, a middle plastic scintillator hodoscope, an aerogel Cherenkov counter, and a bottom plastic scintillator hodoscope. More detailed information can be found in [6].

The difference in the measured times when a particle passes the top and bottom (or top and middle) layers of time-of-flight hodoscopes (TOF) gives the velocity of the particle. A time resolution of about 120 ps is achieved for singly-charged particles, yielding a resolution of about 3 % in the velocity β. The ionization energy losses dE/dx in the TOF gives the charge Z of the particle. Using hits in the TOFs and in the tracker to reconstruct the track of the particle deviated by the magnetic field, the rigidity R can be obtained. The mass M of the crossing particle is then determined with:

$$M = ZR\sqrt{1/\beta^2 - 1}. \tag{1}$$

The particle rigidity is measured inside the magnetic

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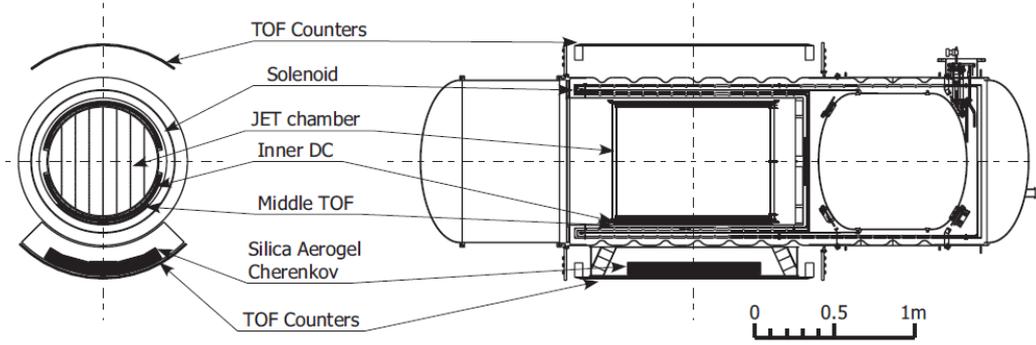33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013

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Fig. 1: Cross-sectional views of the BESS-Polar I payload.

spectrometer. The corresponding kinetic energy per nucleon E_k is:

$$E_k = \sqrt{(R/A)^2 Z^2 + M_p^2} - M_p, \qquad (2)$$

where M_p is the proton mass and A the mass number of the particle. Its kinetic energy and rigidity at top of instrument are determined by correcting the measured energy for losses in the different layers in the upper part of the instrument. Based on Monte Carlo simulations (see section §3), we estimate the rigidity resolution to be better than 1 % below 5 GV for both ^{3}He and ^{4}He.

3 Data Analysis to separate isotopes

For the present study, helium isotopes crossing the BESS-Polar I spectrometer were simulated using the GEANT3 Monte Carlo code [7]. 800 million downward-going ^{3}He and ^{4}He particles were simulated incident isotropically on a semi-sphere above the instrument. Particles were selected from a flat energy spectrum (dN/dE proportional to E^{-1} on a logarithmic scale) from 0.001 to 25 GeV. The GEANT3 simulations, which include a full set of hadronic interactions, are used primarily to determine the geometric acceptance of the detector and its detection efficiency, after rejecting events that interacted in the detector.

Due to a high failure rate when exposed simultaneously to low pressure and low temperature, only 60 % of BESS-Polar I TOF photomultipliers were operational during the flight. The analysis to separate isotopes requires precise measurements of velocity and charge. To achieve the best performance, only TOF scintillator paddles that had both photomultipliers working were used in the analysis. This led to a geometric acceptance of 0.05 m^{2}sr at a rigidity of 2 GV.

As discussed above, the charge of the crossing particle can be determined from measurements of dE/dx in the TOFs. To separate $Z = 1$ and $Z = 2$ events to identify hydrogen and helium, band cuts in dE/dx vs. rigidity are used with data from both the top and bottom TOFs. To illustrate these cuts, Figure 2 shows the selection cut applied to the dE/dx vs. rigidity measured with flight data from the top TOF. The distributions of ^{1}H, ^{2}H, ^{3}He and ^{4}He can be distinguished at low rigidities in this plot.

Many contaminating events are present in the data sample, and selection criteria are defined to remove these events. They are divided into two categories, the "single track" cuts, and the "quality" cuts.
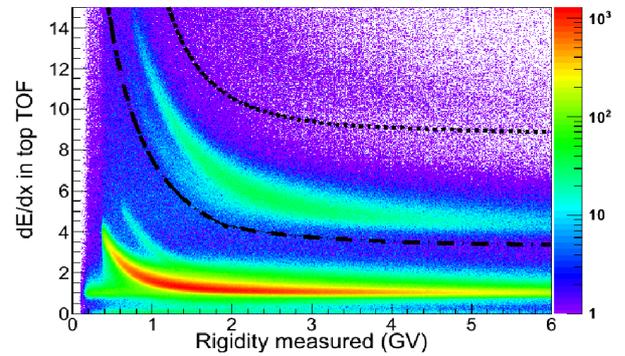

Fig. 2: The dE/dx in the top TOF counter versus the measured rigidity for the whole BESS-Polar I flight data set. The long-dashed line represents the cut selection used to separate $Z = 1$ (below) and $Z = 2$ (above) events with the top TOF. The dotted line corresponds to the maximum dE/dx allowed for $Z = 2$ events.

The "single track" cuts remove particles interacting hadronically inside or above the detector. dE/dx band cuts are among these selection criteria, and ensure that only $Z = 1$ or $Z = 2$ events are used in subsequent analysis. We require there to be only one hit each in the top and bottom TOFs, and only one reconstructed track. In addition to these selection cuts, it is required that the track pass through the center of the jet chamber to remove effects from the detector sides, and that the measured velocity is less than the speed of light to ensure real masses (c.f. Eq. 1). The single-track cut selection efficiency is estimated with Monte Carlo simulations to be about 60 %.

The "quality" cuts remove particles for which tracks are poorly reconstructed because of noise or detector limitations. To improve the quality of the data set, a minimum of 3 inner drift chamber pads and a maximum of 100 hits in the jet chamber are required. To get better measurements, only events with good fitting parameters χ^2 in both Z-Y and r-ϕ planes, and for which the measured rigidity has a good estimated error, are kept. Other criteria include consistency cuts that require a good match between the reconstructed track and hits in the tracking detectors and TOF paddles. Quality cuts give a selection efficiency of about 45 %.

After refining the flight data with the single-track and quality selection cuts, we determine particle masses from

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the measurements of rigidity, velocity and charge, as explained in section §2. In order to separate ^{3}He and ^{4}He, mass distributions are fitted by double Gaussian distributions. The numbers of remaining helium isotope events are then obtained from the integrals of the fitted Gaussian distributions. Figure 3 shows the mass distributions of ^{3}He and ^{4}He events in the rigidity range from ~ 1.2 GV to ~ 2.5 GV for the whole flight data set. 1.2 GV corresponds to the minimum rigidity needed for ^{4}He particles to cross both the atmosphere and the BESS-Polar I detector.
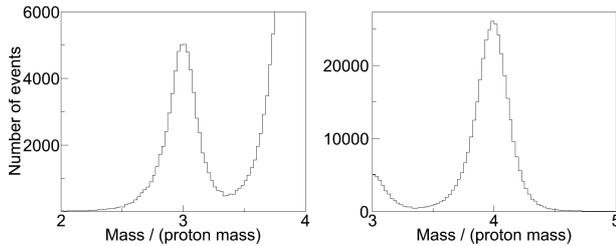

Fig. 3: Mass distributions of ^{3}He (left) and ^{4}He (right) events for a rigidity range from ~ 1.2 GV to ~ 2.5 GV for the whole flight data set.

4 Results

Data collected by BESS-Polar I over the 8.5-day period provide, for the first time, the possibility to measure flux time variations of light cosmic-ray isotopes at Earth. In this study, we calculate average fluxes for every 14.4 hours of data, chosen to provide sufficient statistical precision to show the time-dependent variations in the measured helium isotope fluxes. The resulting statistical uncertainties are about 2.5 % for ^{3}He and 1.5 % for ^{4}He. The calculation takes into account the time dependence of the instrument response, which is corrected by considering variations of efficiencies with time. The average atmospheric overburden of 4.3 g.cm^{-2} during the flight is used to correct for particle energy losses in the atmosphere. Short-term variations in the atmospheric overburden during the flight, from 3.8 to 5.3 g.cm^{-2}, are not taken into account in this analysis. Their impacts on the measured isotope fluxes are negligeable compared to statistical uncertainties.

In Figure 4 we show the normalized flux as a function of time for ^{3}He and ^{4}He during the BESS-Polar I flight using the mean time of each bin. The rigidity range from 1.2 GV to 2.5 GV and data from 13 to 21 December 2004 were used. Distributions were normalized for every time bin for each isotope by dividing the average flux in that bin by the mean flux over the whole data taking period. For comparison, the previously reported transient variations of proton fluxes for rigidities from 1.5 GV to 2.1 GV [5] are displayed with a time resolution of 4 hours and average statistical errors lower than 0.3 %. CLIMAX Neutron Monitor data [8] are also shown using the normalized counts per hour averaged every 12 hours. The counts are sensitive to neutrons from cosmic rays with a minimum rigidity of about 5 GV.

The time variations of helium isotope fluxes and previously reported proton transient variations, exhibit the same general behavior with a flux increase of about 10 % from 13 to 17 December, followed by a quasi-stable period from 18 to 21 December. A similar tendency is observed in neu-
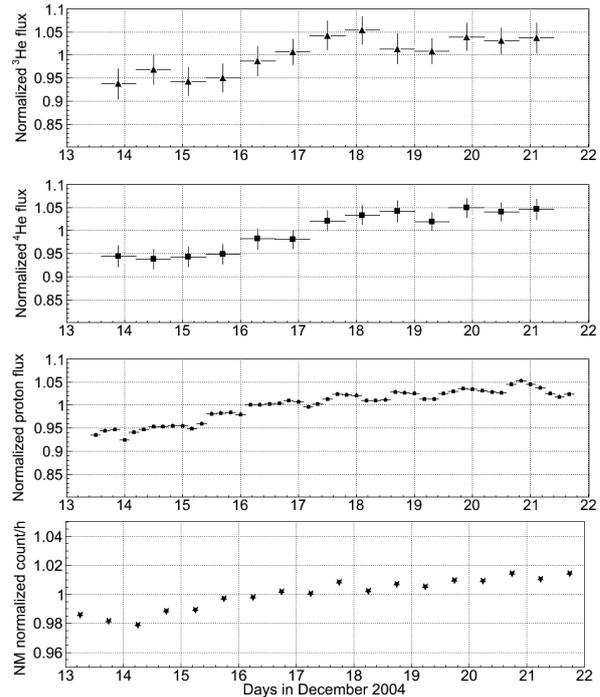

Fig. 4: From top to bottom are shown the flux time variations normalized by the mean flux values over the whole 13-21 December 2004 data taking period for ^{3}He and ^{4}He in the rigidity range from ~ 1.2 GV to ~ 2.5 GV with BESS-Polar I using a binning of time of 14.4 hours. The normalized proton flux in the rigidity range from ~ 1.5 GV to ~ 2.1 GV taken from [5] is also plotted, with a time resolution of 4 hours. The last plot shows the normalized counts per hour of CLIMAX Neutron Monitor data [8] averaged every 12 hours, with a rigidity threshold of about 5 GV for the parent particles.

tron monitor data, which shows a flux increase of about 3 %, followed by a more stable period.

5 Discussion and conclusion

Figure 4 shows that fluxes of cosmic-ray ^{3}He, ^{4}He and protons, studied in similar rigidity ranges, varied similarly during the data taking period. The same physical processes must have caused the features observed in these time variations, and are most likely related to the changes in solar activity that occurred during the flight.

Sudden flux increases of about 10 % are observed for cosmic-ray helium isotopes and for protons from 13 to 17 December, whereas neutron monitor data exhibit an increase of only about 3 %. Fluxes are shown for rigidities from 1.2 GV and 1.5 GV respectively for helium isotopes and protons, and effectively for cosmic rays above 5 GV from the neutron monitors. The differences in the relative increases in flux for different species and rigidity ranges are consistent with changes of solar activity that should affect low-rigidity particles more strongly.

Some interpretations can be proposed to explain the features observed in the flux time variations, as suggested in [5]. ACE measurements [9] could indicate a possible magnetic cloud [10] or corrotating interaction region hap-

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pening around 12 December [11]. Such phenomena is often characterized by a cosmic-ray flux decrease followed by a recovery period, which would be observed during the BESS-Polar I flight period as a sudden cosmic-ray flux increase from 13 to 17 December. High speed solar winds appeared around 17 December [9], and may have caused a flux transition period after the sudden increase. After 18 December, a quieter and more stable period can be seen. Given the large statistical uncertainties in the helium isotope flux time measurements, quasi-periodic flux time-dependent fluctuations, likely due to the motion of Earth through the isotropic Galactic cosmic rays, are only observable with proton and neutron monitor data.

Acknowledgements

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