

SPECTRA OF H AND HE MEASURED IN A SERIES OF ANNUAL FLIGHTS

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ABSTRACT

We have obtained the absolute spectra of H and He by analyzing data collected by a series of annual flights of the Balloon borne Experiment with a Superconducting solenoid Spectrometer payload. This instrument is configured with a cylindrical magnet, a Time-of-Flight system, a set of cylindrical multiwire drift chambers inside and outside the magnet, and a central tracking device Jet chamber. The analysis involves Monte Carlo simulations of the effective geometry factor, studies of various efficiencies, and corrections for the ionization energy loss, attenuation and atmospheric secondaries. Variations of the H and He fluxes at different levels of solar modulation are presented.

INTRODUCTION

The Balloon borne Experiment with a Superconducting solenoid Spectrometer (BESS) has had four successful annual flights in 1993, 1994, 1995, and 1997. The payload was launched from Lynn Lake, Manitoba, Canada and recovered near Peace River. The float altitude was about 36.5 km with the residual atmospheric overburden of about 5 g/cm². Interpretation of antiproton and antihelium data, which is the primary goal of BESS, depends critically on knowing precisely the proton and helium spectra and fluxes in the interstellar medium. This in turn depends on unraveling the effects of solar modulation. In this paper, proton and helium spectra measured from the first three flights (BESS 93, 94, and 95) are reported. A summary of the characteristics for all four flights is shown in Table 1. See Yoshimura *et al.* (1995) and Moiseev *et al.* (1997) for the instrument details.

DATA ANALYSIS

To collect more negative particles for the antimatter investigation, a special trigger system was used, i.e., from the hit pattern in the drift chambers, particles with clearly positive curvature were rejected during the flight. However, certain fractions of the data were kept to be unbiased, e.g., for BESS-93, every 1/140 of the low threshold events, i.e., $Z = 1$ particles, and every 1/40 of high threshold events, i.e., $Z = 2$ particles, were saved as the "count-down" data set. The count-down rate for different flights is also summarized in Table 1. This unbiased data set is the source of our H and He spectral analysis. Protons were selected from the low threshold trigger, and helium nuclei were selected from the high threshold trigger.

The technique of dE/dx in the Time-of-Flight (TOF) scintillator versus rigidity was used for primary charge measurements. To remove background from secondaries produced in the instrument, the dE/dx in the top and bottom TOF were required to be consistent. The H and He candidates are selected by the single track cuts and generous dE/dx cuts. Figure 1 shows the dE/dx selection criteria with selected events before the mass cuts were applied. Totals

Table 1. BESS Flight Summary

	BESS-93	BESS-94	BESS-95	BESS-97
Float time (hrs)	17.5	17.0	17.5	20.5
Observation time (hrs)	14.0	15.0	12.3	18.3
Live time (hrs)	8.6	7.3	7.5	16.0
Dead time fraction (%)	39	50	39	13
Recorded data size (GB)	4.5	6.5	8	31
Number of recorded events	4.0 M	4.2 M	4.5 M	16.2 M
Count-down Rate	1/140 for p 1/40 for He	1/60 (120) for p 1/15 (30) for He	1/90 for p 1/20 for He	1/60 for p 1/25 for He
Number of countdown events	1.03 M	1.2 M	0.98 M	1.98 M
Momentum Resolution	0.005 /GV	0.005 /GV	0.005 /GV	0.005 /GV
TOF Resolution	300 ps	300 ps	110 ps	75 ps
Cherenkov counter			Acryl	Aerogel (n = 1.03)
Efficiency	61% for p 48% for He	49% for p 50% for He	52% for p 41% for He	--
Geometry Factor (m ² -sr)	0.42	0.42	0.32	0.28

of about 122 K, 157 K, and 138 K protons and 30 K, 51 K and 40 K helium nuclei were selected, respectively, for BESS 93, 94 and 95. Event selection involved (a) single track cuts, which i) reject events with no hits or multiple hits in either the top or bottom TOF, ii) require a single track in the central tracking device Jet chamber, iii) require the track length to be long enough to have at least 16 expected hits in the Jet chamber, and iv) require the extension of the track in the Jet chamber to traverse the fired counter in both the top and bottom TOF; (b) track quality cuts, which require i) a track to have at least 12 hits in the Jet chamber central region, ii) the number of Jet chamber hits used in the track fitting to be sufficient, i.e., ≥ 16 in $r\phi$ plane and ≥ 5 along the z-axis, iii) reduced χ^2 for each fit to be < 4 , iv) number of hits in Jet chamber not related to the track to be small, and v) the number of hits associated with the track but not used in the fit to be small; and (c) consistency cuts, which require hits in the cylindrical multiwire drift chambers inside (IDC) and outside (ODC) the magnet and the TOF system to be consistent with the track in the Jet chamber. Overall efficiencies for protons were 61%, 49%, and 52%, respectively, for BESS 93, 94 and 95, and those for He were 48%, 50%, and 41% as summarized in Table 1.

MONTE CARLO SIMULATIONS

Monte Carlo simulations are essential in understanding the instrument performance, e.g., geometry factors and various efficiencies. The BESS instrument configuration is set up by using the GEANT/GHEISHA simulation tool. GEANT simulates the passage of particles through matter, allowing arbitrary geometry, materials and magnetic field configuration. It provides for particle decays and interactions, with subsequent tracking of all secondary particles.

Particles, including P, D, ³He and ⁴He, are isotropically projected into the BESS instrument to simulate the BESS instrument performance. With all the physical processes turned off except ionization energy loss in GEANT, particles that pass through the top and bottom TOF counters and have a long enough track with at least 16 expected hits in the Jet chamber, are selected to define the geometry factor for the BESS. As summarized in Table 1, the resulting geometry factors are 0.42, 0.42, 0.32, and 0.28 m²-sr respectively for the BESS 93, 94, 95, and 97. Due to ionization energy loss, the geometry factors are slightly lower than the listed numbers at low energies. As an example, the BESS 93 geometry factors are shown as a function of energy in Fig. 2. Delta rays generated in the ionization process can produce additional tracks in the Jet chamber and TOF counters. An example of a helium event that has an additional hit in the bottom TOF due to a delta ray is shown in Fig. 3.

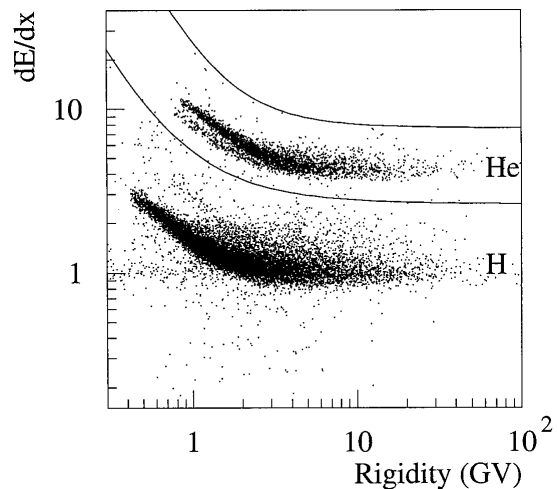


Fig. 1. Ionization energy loss in top TOF scintillator vs. rigidity. Lines represent the dE/dx selection criteria.

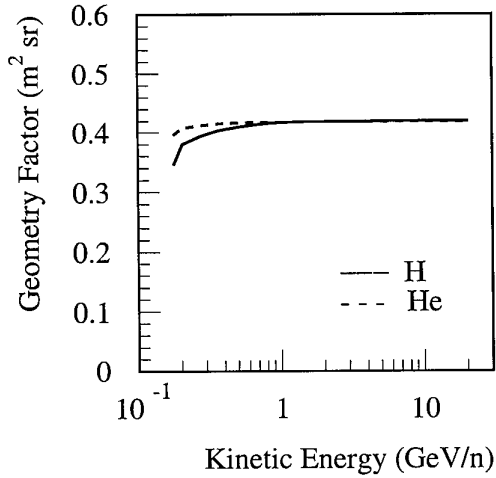


Fig. 2 BESS 93 geometry factors for H and He as a function of energy.

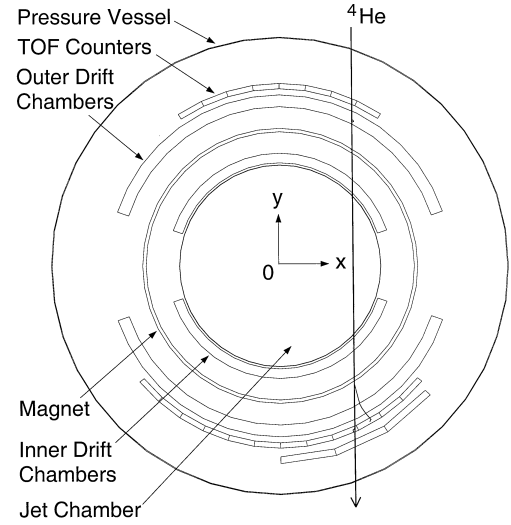


Fig. 3. Cross sectional view of BESS detector system and an example of He event that has two hits in the bottom TOF counter due to a delta ray.

Those events with multiple tracks due to delta rays could not be distinguished from the events with multiple tracks due to nuclear interactions inside the BESS instrument, and they were removed by single track cuts. The higher the energy and the higher the charge of the incident particles, the more serious this effect is. Events were simulated with delta rays generated explicitly in the ionization process to study this effect, and the resulting energy dependent efficiency was used to correct the measured spectra.

In order to obtain the efficiency for the single track cuts applied to remove the events with nuclear interaction inside BESS, simulations with all the physical processes turned on were carried out for the kinetic energy range from 150 MeV/n to 100 GeV/n. For BESS 93 the “efficiency” (fraction of particles not rejected) due to nuclear interactions is about 87% for protons and about 77% for helium. It is a bit lower for BESS 95 due to slight modification in the configuration, i.e., a thicker pressure vessel and finer segmentation and shorter length of TOF counters.

ATMOSPHERIC CORRECTIONS AND FLUX DETERMINATION

The cosmic ray spectra measured at the altitude of balloon flights have to be corrected for background from secondaries produced in the 5 g/cm² of residual atmosphere overlying the payload. Secondary spectra and the regression function for different levels of solar modulation calculated by Rygg and Earl (1971) were used to correct our measured spectra. The spectra are also corrected for atmospheric attenuation using attenuation lengths of 90 g/cm² for protons and 45 g/cm² for He to calculate the correction factors. For protons, the results were confirmed with GEANT simulations.

The cosmic ray flux at the top of the atmosphere was obtained using the following formula:

$$F_{\text{TOA}} = (N_{\text{count}} \cdot k / (G(E) \cdot \epsilon_i(E) \cdot \epsilon_m \cdot \epsilon_c \cdot T \cdot dE_{\text{in}}) - f_{\text{sec}}(E)) / \eta \cdot (dE_{\text{in}} / dE_{\text{TOA}}),$$

where N_{count} is the number of particles in an energy bin, k is the inverse of the count down rate, $G(E)$ is the geometry factor, $\epsilon_i(E)$ is the correction factor for the inefficiency due to delta rays, ϵ_m accounts for the loss of particles due to nuclear interactions, ϵ_c is the efficiency of data selection cuts, T is the total measurement time corrected for the dead time, dE_{in} is the energy bin size inside the BESS instrument, dE_{TOA} is the corresponding energy bin at the top of atmosphere, η is the correction factor for attenuation in the air, which is ~ 0.95 for protons and ~ 0.9 for helium, and $f_{\text{sec}}(E)$ is the atmospheric secondary spectra.

RESULTS AND DISCUSSIONS

Figures 4a and 4b show the H and He spectra obtained by analyzing the BESS data. The Interplanetary Monitoring Platform - 8 (IMP-8) data obtained during the time period that overlapped the BESS flight and the calculated spectra are shown for comparison. Using a spherically symmetric model of solar modulation and assuming that the local interstellar spectra of H and He at the heliospheric boundary are described by the rigidity power law spectra,

$\sim AR^{-2.74}$ and $\sim BR^{-2.68}$, respectively, we have calculated the expected spectra at 1 AU for different modulation levels (Seo et al. 1991). From the top, the curves represent the calculated spectra with solar modulation parameters 200, 400, 500, 600, 800, and 1000 MV. Each year the BESS data show good agreement with the IMP-8 satellite data. The measured fluxes have varied from the modulation level of about 700 MV for BESS-93 to about 500 MV for BESS-95. The Climax neutron monitor data also indicate a similar pattern of increasing flux from 1993 to 1995. The modulation level for BESS-95 is similar to that for the previous solar minimum measurement with the Low Energy Anti-Proton (LEAP) instrument (Seo et al. 1991). Only statistical uncertainties are shown with error bars in Figs. 4a and 4b. Considering uncertainties involved in various corrections including nuclear interactions in the instrument and attenuation in the air, etc., the uncertainty for the proton flux becomes about 10%, but it can be as high as 16% at the lowest energy due to the uncertainty involved in the atmospheric secondary correction. The uncertainty for the helium flux is dominated by the nuclear interaction correction, and it is about 13%.

This study was undertaken with the eventual goal of determining the unmodulated proton and helium spectra outside the heliosphere in interstellar space. Reaching this goal will require further study and a more accurate calibration of the momentum resolution of BESS. Meanwhile, we have shown that the low energy data are consistent with the results of IMP-8 and a simple spherically symmetric modulation pattern. The systematic errors are such that confidence is gained in using these spectra for the calculation of interstellar production of antiprotons (Orito et al. 1998).

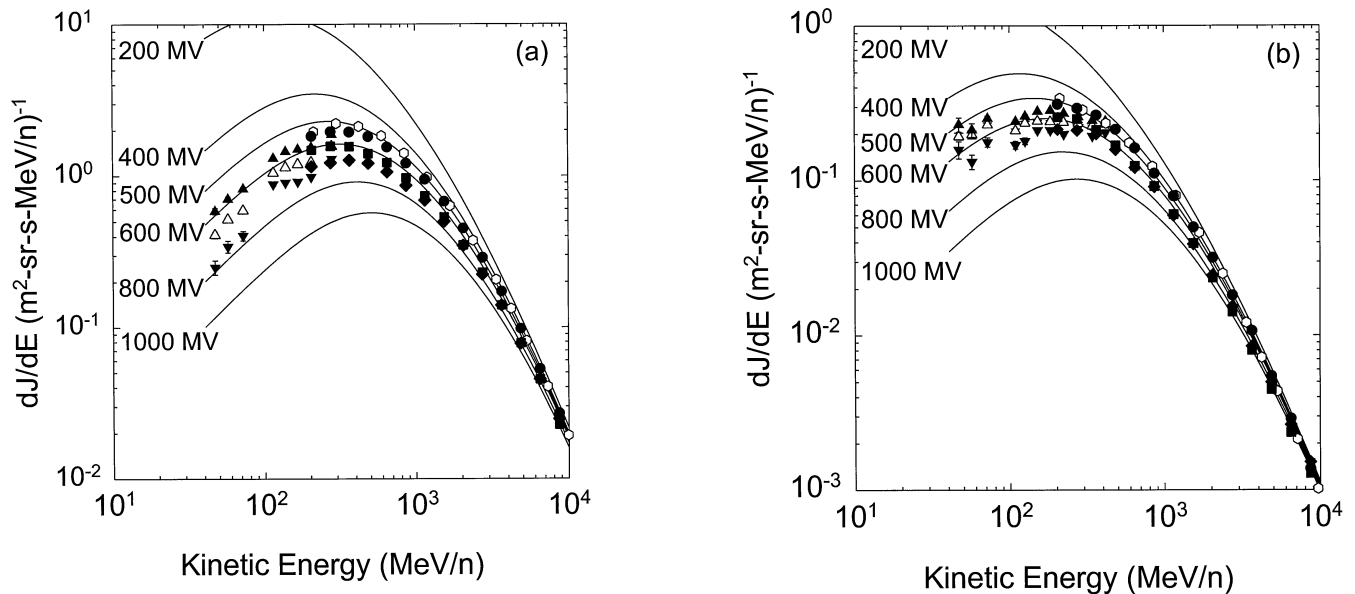


Fig. 4. Differential energy spectra of (a) protons and (b) helium from BESS-93 (filled diamonds) BESS-94 (filled squares) and BESS-95 (filled circles) along with the IMP-8 satellite data (downward filled triangles, 7/14/93 - 8/9/93; upward open triangles, 7/19/94 - 8/14/94; upward filled triangles, 7/14/95 - 8/9/95), LEAP data during 1987 solar minimum (open circles); and calculated spectra (curves).

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REFERENCES

- Moiseev, A. A., *et al.*, *Ap. J.*, **474**, 479 (1997).
 Orito, S. *et al.* this conference (1998).
 Rygg, T. A. and Earl, J. A., *J. Geophys. Res.*, **76**, No31, 7445 (1971).
 Seo, E. S., *et al.*, *Ap. J.*, **378**, 763 (1991).
 Yoshimura, K., *et al. Phys. Rev. Lett.*, **75**, 3792 (1995).