Energy Spectra of Cosmic-Ray Hydrogen and Helium Isotopes during the 2000 Solar Maximum

K. C. Kim[1], K. Abe[2,a] H. Fuke[3], S. Haino[4,b], T. Hams[5], Y. Makida[4], S. Matsuda[6], J. W. Mitchell[5], A. A. Moiseev[5], J. Nishimura[6], M. Nozaki[2], S. Orito[6,c], J. F. Ormes[5,d], T. Sanuki[6], M. Sasaki[5], E. S. Seo[1], Y. Shikaze[2,e], R. E. Streitmatter[5], J. Suzuki[4], K. Tanaka[4], T. Yamagami[3], A. Yamamoto[4], T. Yoshida[5], K. Yoshimura[4]
[1] *Institute for Physical Science and Technology, University of Maryland at College Park, MD 20742, USA.*
[2] *Kobe University, Kobe, Hyogo, 657-8501 Japan.*
[3] *Institute of Space and Astronautical Science (ISAS/JAXA), Sagamihara, Kanagawa, 229-8510 Japan*
[4] *High Energy Accelerator Research Organization, Tsukuba, Ibaraki, 305-0801 Japan.*
[5] *NASA's Goddard Space Flight Center, Greenbelt, MD 20771 USA.*
[6] *The University of Tokyo, Bunkyo, Tokyo, 113-0033 Japan.*
[a] *Present address: Kamioka Observatory, ICRR, The University of Tokyo, Kamiok, Gifu 506-1205, Japan.*
[b] *Present address: Instituto Nazionale di Fisica Nucleare (INFN), Universita degli Studi di Perugia, Perugia 06123, Italy.*
[c] *Deceased.*
[d] *Present address: Denver University, Denver, CO 80208, USA.*
[e] *Present address: Japan Atomic Energy Agency (JAEA), Tokai, Ibaraki 391-1195, Japan.*
seo@umd.edu

Abstract: The Balloon-borne Experiment with a Superconducting Spectrometer (BESS) was flown eight times from Lynn Lake, Manitoba, Canada between 1993 and 2002. The performance of the instrument was improved with essentially each successive flight, and precise spectral measurements of cosmic-ray hydrogen and helium isotopes were made during different phases of the solar modulation. This paper presents the measured isotopic spectra for the most recent solar maximum in 2000 and compares the results with previous measurements and with the theoretical prediction from the Reacceleration model. Both ^{1}H and ^{2}H spectra are consistent with the propagation calculation with the solar modulation parameter 1500 MV. The total He (^{3}He + ^{4}He) flux is in good agreement with the same modulation parameter. Fluxes of ^{3}He and ^{4}He require slightly higher modulation parameter.

Introduction

Precise measurements of the isotopic composition of hydrogen and helium nuclei can provide information on the cosmic-ray origin and propagation history in interstellar space. The Balloon-borne Experiment with a Superconducting Spectrometer (BESS), which has been flown annually since 1993, has measured both the primary cosmic-ray hydrogen, helium and their secondary particles as well as antiparticles [1] [2]. BESS-2000 was flown in northern Canada from Lynn Lake to Peace River where the geomagnetic cuttoff rigidity ranges from 0.3 to 0.5 GV at altitude about 4.3 g/cm^2 from August 10th to 12th in 2000.

In this paper, we present the absolute fluxes of primary proton, helium, and their isotopes with the energy range 0.23 GeV/n - 2.37 GeV/n as measured during the most recent solar maximum with the BESS-2000 flight. We compared these fluxes to the previous measurements BESS and other instruments as well as the theoretical prediction from the Reacceleration model [3].

The BESS Instrument

The BESS spectrometer was designed and constructed to search for antimatter in cosmic rays, and to make precise measurements of other cosmic ray components [4]. All of the detector's components are assembled in a cylindrical configuration with a superconducting solenoidal magnet. The solenoid provides a uniform magnetic field of 1 Tesla. The particle's trajectory is measured by a tracking system composed of several detectors in the instrument. The TOF hodoscopes consist of ten plastic scintillation counter paddles at the top and twelve at the bottom of instrument. The hodoscopes provide the velocity ($\beta \equiv v/c$) and energy loss ($\mathrm{d}E/\mathrm{d}x$) measurements. The time resolution of each counter is 55 ps, which yields a 1/β resolution of 1.4$\%$ [5]. The data acquisition sequence is initiated by a first level TOF trigger, which is a coincidence of signals in the top and bottom scintillators. The tracking system consists of a central jet-type (JET) chamber and two inner drift chambers (IDC), which are used to determine a particle's rigidity. The track positions in the r-ϕ plane and along the z-axis are measured by all three independent detectors: JET, IDC, and TOF. The plastic scintillators, a lead plate and the Acrylic Čerenkov Counter were placed at the bottom of the BESS-99 to improve accurate measurements for highly-charged particles and the μ/e separation, but the plastic scintillators were removed for BESS-2000. The Čerenkov counter with the silica aerogel radiator was not used in the current isotope analysis.

Data Analysis

The countdown data are unbiased data sets that are used in our data analysis to obtain the cosmic-ray particles with positive charge and positive velocity [6]. One of every 30 events passing the trigger system were processed and saved in the countdown data set for BESS-2000. After removing the events with negative velocity and negative rigidity, single-track cuts were used to remove events either not passing the fiducial region of the JET chamber or having nuclear interactions within the instrument. The charge identification was based on the ionization signals in both the top and bottom TOF scintillation counters. From the data set passing the single-track cuts, we selected the Z = +1 and Z = +2 particle candidates by applying $\mathrm{d}E/\mathrm{d}x$ cuts to select good events. Note that the dE/dx cut in this analysis is more loose than that of paper [7]. A narrower dE/dx band cut was used to remove recoil protons in our previous work [7]. However, this cut also removes deuterium. The proton fluxes below 1 GeV reported in this paper are slightly higher than those presented in paper [7]. The efficiencies of the single-track cuts for each particle were estimated by the Monte Carlo simulations using GEANT 3.21.

In order to achieve good measurements of the rigidity, track-quality and consistency cuts were applied to the Z =+1 and Z = $+2$ candidates. Track-quality cuts ensure particle's passing through the center of JET chamber, and the number of hits for trajectory fitting. The consistency cuts ensure the consistency of hitting in the TOF and IDC with JET track in both the r-ϕ and r-z planes. Mass histograms were made for the selected events to effectively separate ^{2}H from ^{1}H and ^{3}He from ^{4}He and the plots were presented at prvious paper [8].

In balloon experiments, secondary particles produced by nuclear interactions in the atmosphere are measured along with the primary cosmic-ray events. The ^{1}H spectrum was corrected for atmospheric secondaries as described in paper [7]. The ^{2}H, ^{3}He, and ^{4}He spectra were also corrected for atmospheric secondaries as described in paper [9]. The absolute flux was determined by the following:

$$F_{TOA}(E) =$$

$$\{\frac{N(E)C_d}{\varepsilon_{gf}(E)\varepsilon_c T\Delta E_{in}} - f_{sec}(E)\}\frac{\Delta E_{in}}{\eta(E)\Delta E_{TOA}}$$

where C_d is the inverse of the countdown rate (30), ε_{gf} is the effective geometry factor (calculated to be 0.193 for ^{1}H, 0.211 for ^{2}H, 0.172 for ^{3}He, and 0.180m^2sr for ^{4}He), ε_c is the efficiency of the data selection cuts (85.5 $\%$), The efficiencies of track-quality and consistency cuts were obtained from the average of the particles which passed the high energy limit of the each particle in which the efficiencies were constants with repect to the energies. T is the live time (28.7 hours), ΔE_{in} is the energy bin size at the BESS float altitude and corresponds to ΔE_{TOA} at the top of the atmosphere, f_{sec} is the atmospheric secondary spectra, and $\eta(E)$ is the correction factor for the attenuation loss.

Results and Conclusions

The absolute fluxes of hydrogen, helium and their isotopes,^{1}H, ^{2}H, ^{3}He and ^{4}He, obtained by analyzing the BESS-2000 data are shown in Fig. Only statistical uncertainties are included in the error bars. IMAX-92 data [10] (open diamond) and MASS-89 data [11] (snow symbol) are also shown to compare with the BESS data. The solid curves represent calculated spectra using the Reacceleration model with solar modulation parameters of 500, 600, 700, 800, 900 and 1500 MV from top to bottom. Stochastic reacceleration of the cosmic rays in the turbulence which supposedly exists in the interstellar medium was considered in the Reacceleration model [3]. For each isotope, the local interstellar spectrum obtained from the galactic propagation calculation was subjected to solar modulation based on a numerical solution for a spherically symmetric model [12].

A successive evolution of fluxes along with the solar modulation are clearly shown in the energy spectra measured by BESS-2000 and earlier BESS flights, BESS-93, 94, 95, 97 and 98 [13] [14]. Our resulting spectra are consistent with the theoretical calculations with 1500 MV and with previous observation from MASS-89, which was flown at the previous solar maximum. The absolute fluxes of ^{1}H and ^{2}H measured by BESS during the 93, 94, 95, 97, 98, and 2000 flights agree well with the predictions of the Reacceleration moldel with solar modulation parameter values of 800, 700, 600, 500, 600, and 1500 MV, respectively. The total He (^{3}He + ^{4}He) fluxes are in good agreement with the same modulation parameters of ^{1}H and ^{2}H. The ^{3}He and ^{4}He fluxes measured by BESS during the same flights agree with the Reacceleration model, albeit with slightly higher modulation parameter values.

In conclusion, we present the absolute fluxes of ^{1}H, ^{2}H, ^{3}He and ^{4}He, obtained from the BESS-2000 data. The BESS-2000 fluxes, which are much lower than those of previous BESS flights due to maximum solar activity in 2000, are consistent

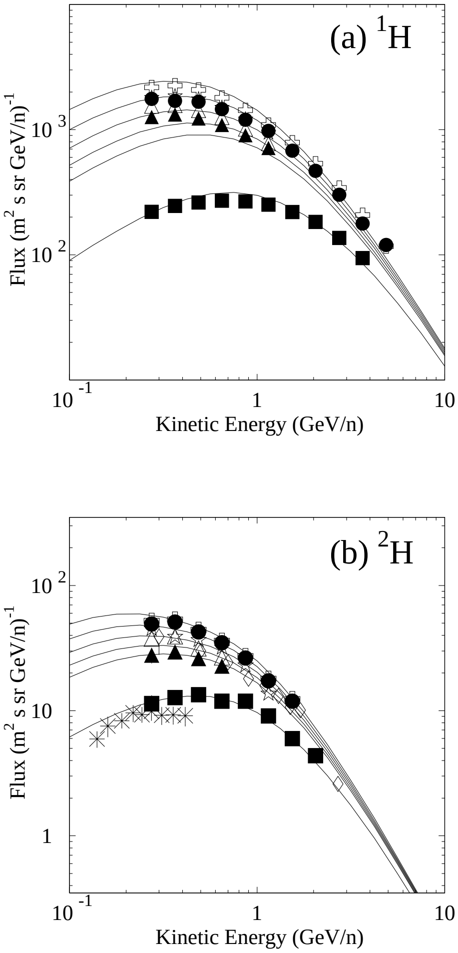

Figure 1: The absolute fluxes of ^{1}H and ^{2}H The solid lines are theoretical predictions of the Reacceleration model. Modulation parameters are 500, 600, 700, 800, 900 and 1500 MV from top to bottom. (a) ^{1}H fluxes from BESS (93(solid triangle), 94(open triangle), 95(open star), 97(open cross), 98(solid circle), and 2000(solid square)) and IMAX-92(open diamond) data. (b) The absolute flux of ^{2}H from BESS and MASS-89(snow) data.

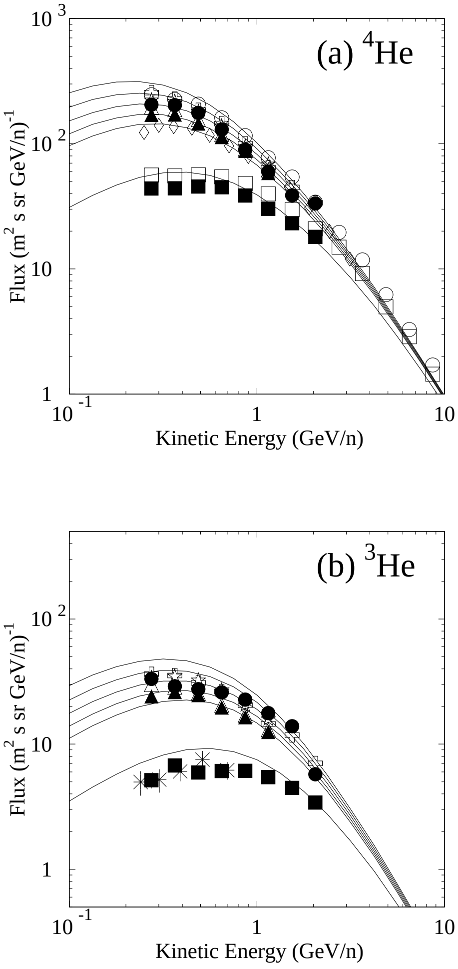

Figure 2: The absolute fluxes of ^{4}He and ^{3}He Open circle and open square are for total He of 98, and 2000, respectively, and all other symbols are the same as Fig.1. (a) The absolute flux of ^{4}He from BESS-2000 and from previous BESS (93, 94, 95, 97 and 98) data. (b) The absolute flux of ^{3}He from BESS-2000, previous BESS (93, 94, 95, 97 and 98) and from MASS-89. The solid lines are the Reacceleration model with modulation parameters of 500, 600, 700, 800, 900 and 1500 MV from top to bottom.

with those previous BESS measurements after accounting for the relevant values of the modulation parameter.

Acknowledgments

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