Solar modulation effect on the cosmic-ray proton spectra measured by BESS

Y. Shikaze,[1] K. Abe, [1] K. Anraku,[2,a] Y. Asaoka,[2,b] H. Fuke,[2] S. Haino,[2] M. Imori,[2] K. Izumi,[2] T. Maeno,[1,c] Y. Makida,[3] S. Matsuda,[2] N. Matsui,[2] H. Matsumoto,[2] J.W. Mitchell,[5] A.A. Moiseev,[5] J. Nishimura,[2,4] M. Nozaki,[1] S. Orito,[2,*] J.F. Ormes,[5] T. Sanuki,[2] M. Sasaki,[3,d] E.S. Seo,[6] R.E. Streitmatter,[5] J. Suzuki,[2] K. Tanaka,[2] K. Tanizaki,[1] T. Yamagami,[4] A. Yamamoto,[3] Y. Yamamoto,[2] K. Yamato,[1] T. Yoshida[3] and K. Yoshimura[3]
(1) Kobe University, Kobe, Hyogo 657-8501,Japan
(2) The University of Tokyo, Tokyo 113-0033, Japan
(3) High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
(4) The Institute of Space and Astronautical Science (ISAS), Sagamihara, Kanagawa 229-8510, Japan
(5) NASA/GSFC, Greenbelt, MD 20771, USA
(6) University of Maryland, College Park, MD 20742, USA

Abstract

We have measured cosmic-ray proton and helium fluxes under the residual atmospheric depth of 5 g/cm^2 by the BESS spectrometer launched from Lynn Lake, Manitoba, Canada from 1997 to 2000. By using realistic estimation of the atmospheric secondary protons, we obtained the precise primary fluxes at the top of the atmosphere (TOA) in a kinetic energy region of 0.2 – 20 GeV/nucleon. The solar modulation effects were observed in the obtained fluxes.

1. Introduction

The energy spectra and absolute fluxes of cosmic-ray proton and helium constitute the most fundamental data in cosmic-ray physics. Their interstellar spectra carry the information on the origin and propagation history of the cosmic rays in the Galaxy. However, observable spectra in the heliosphere are deformed by the solar modulation effect, and balloon data are also affected by the atmospheric interactions. In order to obtain the interstellar spectra, understanding of the solar modulation and precise estimation of the atmospheric effects are important. We report here measurements of low energy cosmic-ray proton and helium spectra by the BESS spectrometer and discuss the solar modulation effects using the observed data between 1997 to 2000.

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2. Balloon Flights

The BESS [2,3,8,10,12,13] flights were performed in northern Canada from Lynn Lake (cutoff rigidity is 0.4 GV), Manitoba to Peace River, Alberta in summer of '97, '98, '99 and 2000. During these flights, the BESS reached at a float altitude of 36 km ($\sim$ 5 g/cm^2 of residual atmosphere). During the four years, solar activity have changed from minimum to maximum as known from the sunspot numbers and neutron monitor [6]. We also obtained the ascending data of cosmic rays in '99 and 2000 and the descending data at Ft. Sumner (cutoff rigidity is 4.2 GV), New Mexico, USA in 2001 [1]. Particularly, use of the BESS-2001 data enables to compare with pure secondary proton in low energy region below the cutoff. By using these data, we have improved the parameters of elementary processes in Papini et al. [9] to reproduce better the observed data at various altitudes (Tail of the recoil generation function in higher energy region has been increased).

3. Results and Discussions

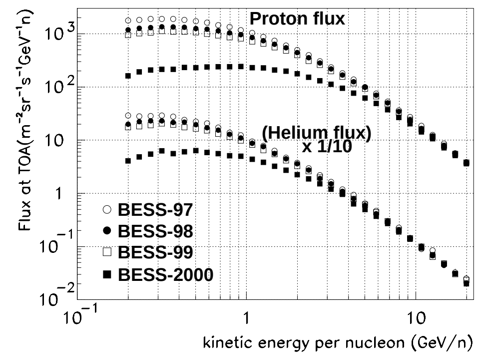

Fig. 1. Proton and helium fluxes at the top of the atmosphere (TOA) from 1997 to 2000.

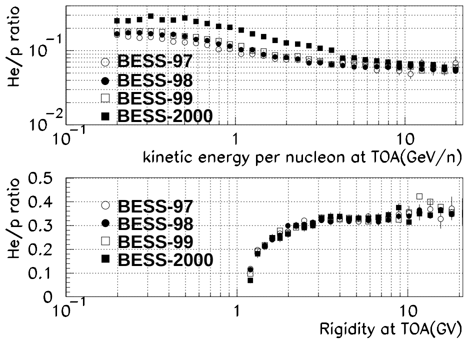

Fig. 2. Time variation of He/p ratio as a function of kinetic energy per nucleon (top) and rigidity (bottom).

By using the revised calculation of the atmospheric secondary particles, proton and helium fluxes at TOA were obtained [11]. Fig. 1. shows proton and helium fluxes at TOA from '97 to 2000. Note that helium fluxes are plotted after being divided by 10. In Fig. 1., the sudden decrease from '99 to 2000 were observed for both fluxes. Fig. 2. shows the ratio of helium to proton (He/p) fluxes observed by BESS from '97 to 2000. The top and bottom figures are the ratio as a function of kinetic energy per nucleon and rigidity, respectively. The latter ratio does not change during the period. This indicates that solar modulation is mainly ruled by rigidity. Fig. 3. shows the ratio of proton fluxes to those flux at BESS-98. The ratio of the Climax neutron intensity [6] (vertical cutoff rigidity is 3 GV) at the BESS flight date are shown by the lines. It should be noted that the time variation of the Climax neutron data corresponds to those of the proton flux at about 10 GeV/n as seen from their correlation in Fig. 3.. This is consistent with the previous reports on the primary protons at about 10.7 GV [4].

Taking the value of "modulation parameter" ϕ at the flight date, we can estimate the interstellar (IS) proton flux by assuming the Force Field approximation [5]. The approximation for the proton flux is clearly seen in Fig. 4., where IS proton flux is determined by assuming ϕ ∼600 MV for BESS-98 (estimated in Myers et al. [7]) and to be described by : $A\beta^{P_1}R^{-P_2}$, where β is the particle to the light velocity ratio, R is the rigidity, A, P_1 and P_2 are the fitting parameters (The results are noted in Fig. 4.. The P_2, power of R depends on the assumption of ϕ.). Other curves and the value of ϕ noted in Fig. 4. are obtained by fitting the BESS data using the approximation and the IS proton flux.

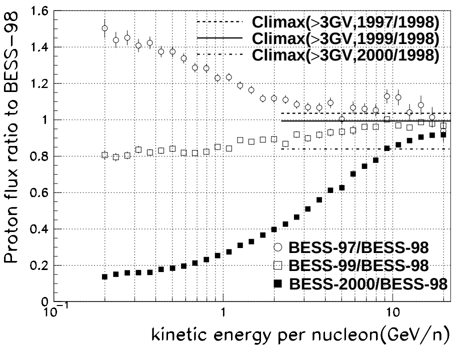

Fig. 3. Ratio of the proton fluxes to the proton flux at BESS-98. Ratio of the Climax neutron intensity data at BESS flight date to those at BESS-98 flight date are also shown by the dashed ('97/'98), solid ('99/'98) and dashed-dotted (2000/'98) lines.

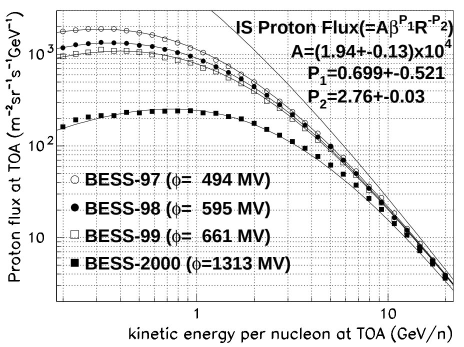

Fig. 4. Force Field approximation for protons. The interstellar (IS) proton flux is determined by assuming ϕ∼600 MV for BESS-98. Other curves and the value of ϕ are obtained by fitting the BESS data using the approximation and the IS proton flux.

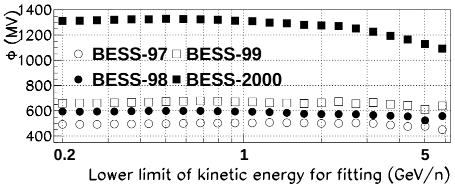

Fig. 5. The ϕ versus lower limit of kinetic energy per nucleon for fitting range. Upper limit is fixed at 20 GeV/n.

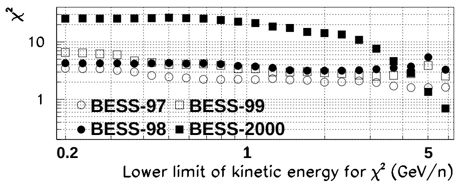

Fig. 6. The χ^2 versus lower limit of kinetic energy per nucleon for χ^2 calculation ragne. Upper limit is fixed at 20 GeV/n.

The value of χ^2 for the fitting in Fig. 4. are 3.44, 4.26, 6.58 and 25.5 , for '97, '98, '99 and 2000, respectively. Fig. 5. and Fig. 6. show the ϕ and the χ^2 versus lower limit of kinetic energy per nucleon for fitting and χ^2 calculation, respectively. In all case in Fig. 5. and Fig. 6., upper limit is fixed at 20 GeV/n. The results for 2000 show different tendency from others, which depends on the region to use. Though the results for '97, '98 and '99 in Fig. 4., Fig. 5. and Fig. 6. show that the Force Field approximation follows the time variation of proton flux well up to low energy of 0.2 GeV/n, the large modulation effect in 2000 is difficult to be described by the simple approximation with single ϕ for the same energy region.

4. Summary

Low energy cosmic-ray proton and helium spectra from solar minimum to maximum were obtained by using the calculation of atmospheric protons revised to agree with the secondary protons observed at Ft. Sumner (cutoff rigidity is 4.2 GV). Though the sudden decrease of the low energy fluxes in 2000 was observed, the He/p ratio as a function of rigidity hardly changed and the proton flux at about 10 GeV/n had good correlation with the Climax neutron intensity from '97 to 2000. The result on the He/p ratio indicates that solar modulation is mainly ruled by rigidity. The fitting result of our proton spectra by the Force Field approximation indicates the difficulty to describe precisely the large modulation effect at the solar maximum in 2000.

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a Present address: Kanagawa University, Yokohama, Kanagawa 221-8686, Japan
b Present address: ICRR, University of Tokyo, Kashiwa, Chiba 227-8582, Japan
c Present address: CERN, CH-1211 Geneva 23, Switzerland
d Present address: NASA/GSFC, Greenbelt, MD 20771, USA
∗ deceased

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