Measurement of Cosmic-Ray Proton, Antiproton and Muon Spectra at Mountain Altitude

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Abstract

Measurement of cosmic-ray proton, antiproton and muon spectra was carried out at mountain altitude. We observed 2×10^5 protons and 10^2 antiprotons in a kinetic energy region of 0.25 – 3.3 GeV. Zenith-angle dependence of proton fluxes was obtained. Atmospheric muon spectra were measured simultaneously. The observed antiproton spectrum showed some deviation from theoretical predictions particularly in a low energy region.

1. Introduction

Primary cosmic rays hit the Earth's atmosphere and produce baryons and mesons via hadronic interactions. Absolute fluxes of these "secondary cosmic rays" can be calculated by using the primary cosmic-ray intensity and interaction cross sections. Observation of the secondary cosmic rays is very important to verify, or to improve, theoretical calculations. It is essentially important to understand propagation process of the secondary particles inside the atmosphere. We report new measurement of secondary cosmic ray spectra at mountain altitude.

2. Observations

We performed cosmic-ray observation at Norikura Observatory, ICRR, University of Tokyo, Japan, in September 1999, with the BESS detector [1,2,11,17], which was the same apparatus as we utilized to measure the primary protons and antiprotons [3,9,12,13], as well as atmospheric muons at sea level [10]. The observatory is located at 2,770m above sea level. The vertical cutoff rigidities is 11.2 GV [16]. During the observation, the mean atmospheric depth was 742 g/cm^2.
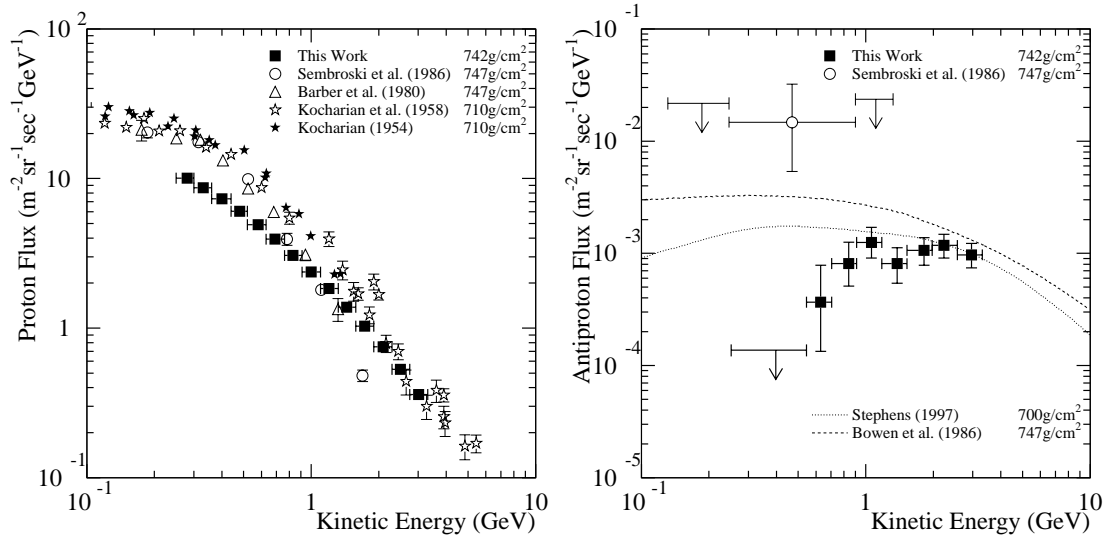
Fig. 1. Observed near-vertical flux of protons (left) and antiprotons (right). Calculated antiproton spectra are compared with the observed ones.

3. Results and Discussion

The measured energy spectra of protons and antiprotons are shown in Fig. 1, together with the previous measurements at mountain altitude [4,7,8,15]. The antiproton spectrum is compared with theoretical predictions [5,18]. In this analysis, the zenith angle (θ_z) was limited as $\cos\theta_z \geq 0.95$ for protons, and $\cos\theta_z \geq 0.84$ for antiprotons, thus the obtained fluxes are "near-vertical" fluxes. There is some disagreement among the proton fluxes shown in Fig. 1. According to simple Monte Carlo simulations, the deviations can be explained by the different altitudes and cutoff rigidities at their observation sites.

Fig. 2 shows zenith angle dependence of the observed proton flux in two kinetic energy regions. The zenith angle dependence can be expected in a simple one-dimensional approximation, $F(\cos\theta_z) = F_0 \exp(X/\lambda(1 - 1/\cos\theta_z))$, where X is the atmospheric depth and λ is the absorption mean free path of protons inside the atmosphere. Dotted lines in Fig. 2 show the expectation, in which $X/\lambda = 6$ was assumed. Relatively good agreement was found between the observed data and the calculation in the higher energy region. In the lower energy region, however, significant discrepancy was found between them. These facts are most likely due to the effect of angular spread of secondary protons produced via nuclear interactions. The solid lines shown in Fig. 2 give the results of the analytic calculation, in which the angular spread was taken into account. They reproduced the observed data better than one-dimensional calculation in the whole energy range.
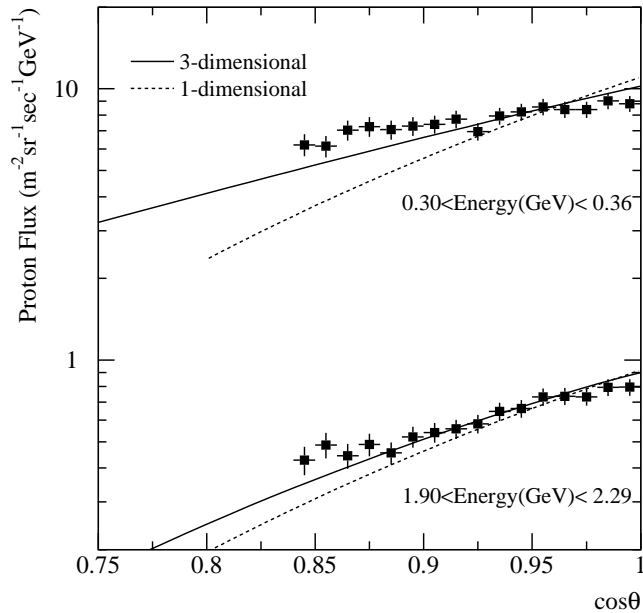
Fig. 2. Zenith angle dependence of proton flux. The dotted and solid lines show the expected dependence in simple one-dimensional and three-dimensional calculations, respectively.

The observed antiproton spectrum agrees with a theoretical calculation by Stephens [18] above 1 GeV as shown in Fig. 1. On the other hand, the flux below 1 GeV shows significant disagreement. In Ref. [18], production spectra of antiprotons are calculated, and the result shows a sharp peak around 2 GeV. This means that most antiprotons observed below 1 GeV are tertiary antiprotons, those which have been produced inside the atmosphere and then lost their energies during the propagations in the atmosphere. In this case, cross sections in $\bar{p} + A(nuclei)$ processes are to be precisely treated for an accurate evaluation of antiproton spectrum at mountain altitude. A recent work made with Monte Carlo simulation reported a preliminary result which shows better agreement with the observed spectrum [6].

The atmospheric muon spectra in a momentum range of 0.6 – 106 GeV/c have been measured simultaneously. The results are reported in Ref. [14]. The observed muon spectra showed much better agreement with theoretical prediction than that of antiprotons. It shows that secondary meson productions are treated rather properly in the theoretical calculations. However, secondary baryon interaction cross sections have to be modified so as to reproduce the observed antiproton spectrum.

4. Summary

We have measured proton, antiproton and muon spectra at Mt. Norikura, Japan, where the atmospheric depth was $742 \, \mathrm{g/cm^2}$. The zenith angle dependence in the proton flux was observed. It suggests an importance of three-dimensional effect of angular spread in secondary baryon productions. The calculated antiproton flux agrees with our antiproton flux above 1 GeV. In a lower energy region, however, our measurement gives much lower flux than that of the prediction.

Acknowledgment

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