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An Upper Limit on Cosmic-ray $\overline{p}/p$ Flux Ratio Estimated by the Moon's Shadow with the Tibet III Air Shower Array

The Tibet ASγ Collaboration

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The Tibet air shower array has been in operation since 1999 as Tibet III (22,050 m^2) with energy threshold of a few TeV. As primary cosmic rays are shielded by the Moon having the finite size of 0.5 degree in diameter, we observe a deficit in cosmic rays called the Moon's shadow with sufficient statistical significance. The center of the Moon's shadow shifts westwardly due to the geomagnetic field. By analyzing this energy-dependent westward displacement carefully, we set an upper limit of about 5% at 90% confidence level on the cosmic-ray antiproton/proton ratio at multi-TeV energies.

1. Introduction

Cosmic antiprotons are mainly produced by collisions of cosmic-ray protons with interstellar hydrogen gas: $p + p \longrightarrow \overline{p} + p + p + p$. Accelerator experiments measured the antiproton/proton ratio ($R(\overline{p}/p)$) to be about $10^{-3} \sim 10^{-4}$ in this process. The energy spectrum of the parent cosmic-ray protons has a power-law index ~ -2.7 above 10 GeV and the power-law index of $\overline{p}$ should also be ~ -2.7. According to a pure secondary production model during the propagation of cosmic rays in the galaxy, $R(\overline{p}/p)$ decreases as $E^{-0.6}$ above 10 GeV. Various experimental groups have measured $R(\overline{p}/p)$ below 10 GeV. However, $R(\overline{p}/p)$ is still controversial and its decrease at energies above 10 GeV has not been established due to technical difficulties in satellite or balloon-borne observations. For example, CAPRICE[1] reported on $R(\overline{p}/p)$ increasing above 10 GeV, though statistically not significant. Therefore, it is meaningful to measure $R(\overline{p}/p)$ in the TeV energy region. $R(\overline{p}/p)$ at multi-TeV energies can be directly measured by using the Moon's shadow in cosmic rays as anti-beam and the geomagnetic field as a charge spectrometer. This is qualitatively different from the ones[2] obtained by indirect measurements of the cosmic-ray μ^+/μ^- ratio. The Tibet air shower array has been in operation since 1999 until 2004 as Tibet III ($22,050\ \mathrm{m}^2$) with energy threshold of a few TeV and angular resolution of $0.9°$ at a few TeV. The details of Tibet III is described elsewhere[3]. In this paper, we will report on $R(\overline{p}/p)$ at multi-TeV energies measured by the Moon's shadow observed by Tibet III.

2. Simulation

Full Monte Carlo (MC) simulation has done for the Moon's shadow analysis. This simulator consisted of the CORSIKA Ver 6.200 code[4] for air shower event generation and Epics uv8.00 code[5] for the response of each scintillation counter. The primary cosmic-ray flux model was based on direct observational data [6]. The MC events were generated on the top of the atmosphere randomly along the Moon's orbit around the Earth. The primary charge of the MC event was assumed the opposite charge and injected into back toward the Moon along the first trial direction, where the first trial direction was randomly on the $\pm 10° \times \pm 10°$ angular window centered at the Moon direction and determined the final trial direction by smearing the difference between the Moon direction and the estimated air shower direction. In addition, the geomagnetic field was given by the Virtual Dipole Moment model ($8.07 \times 10^{25}\ \mathrm{G} \cdot \mathrm{cm}^3$) at altitude > 600 km. To trace back each parent particle's trajectory between the Earth and the Moon in the magnetic field for each primary particle, the events of first trial direction hitting the Moon are collected and their final trial direction is used for the cosmic-ray direction. In this way, the Moon shadow, which is equivalent to the observed one, was simulated.

3. Data Selection

Total number of 6.1×10^{10} events were triggered and recorded during 1041 live days of Tibet III during the period from November, 1999 until October, 2004. Then, air shower events were selected by imposing the following requirements; (1)Each shower must fire 4 or more counters recording 1.25 or more particles; (2)Among 9 hottest counters in each event, 8 must be inside the fiducial area; (3)zenith angle of the arrival direction must be less than $40°$. After the selections, 1.5×10^{10} events remained for further analysis.

4. Results and Discussions

As shown in Fig. 1, Tibet III observes the Moon's shadow shifting westwardly by $0.23°$ at mode energy ~ 3 TeV. The deficit events are equivalent to about 40 statistical significance on two-dimensional analysis. The MC

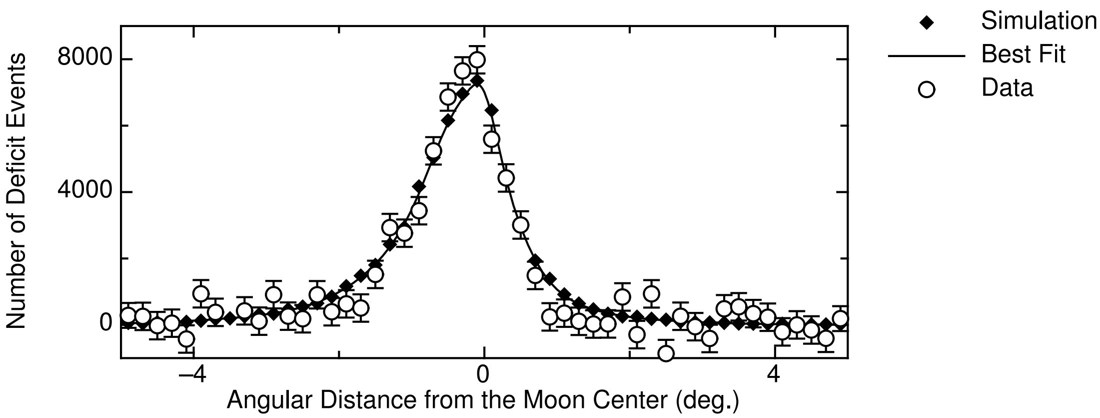

Figure 1. Deficit events around the Moon's shadow. Data is shown within the range of $\pm 5^{\circ}$ for the east-west direction and $\pm 1^{\circ}$ for the south-north direction. Thier plots are indicated as follows; open circle: experimental data,filled diamond: simulation data, solid line: best fit of $f_3(\theta)$. Each error bar indicates $\pm 1\sigma$.

simulation is also shown in Fig. 1. The data is in good agreement with the MC simulation within statistics. In order to estimated the flux of antiprotons, the MC simulation data decomposes to primary cosmic rays and protons, and each distribution is expressed by a function. They are fitted by superimposing four Gaussian formula:

$$f_1(\theta) = \sum_{i=1}^{4} C_{all,i} exp(-4 \times ln(2) \times \frac{(\theta - M_{all,i})^2}{\sigma_{all,i}^2}) \quad \text{(for primary cosmic ray without antiproton)} \tag{1}$$

$$f_2(\theta) = \sum_{i=1}^{4} C_{p,i} exp(-4 \times ln(2) \times \frac{(\theta - M_{p,i})^2}{\sigma_{p,i}^2}) \quad \text{(for primary proton)} \tag{2}$$

where θ is the angular distance from the Moon direction in the west-east direction. Then, the observed deficit events are expressed by the function $f_3(\theta)$ as

$$f_3(\theta) = af_1(\theta) + bf_2(-\theta) \tag{3}$$

where the first term represents the deficit in cosmic rays and second term represents the deficit in antiprotons. From our simulation, protons are estimated to be 63.1% of cosmic rays, so the ratio $b/0.631a$ indicates $R(\overline{p}/p)$. The observed Moon's shadow is fitted by the function $f_3(\theta)$. The best fit curve is shown in Fig. 1 as a solid curve with parameters of $a = 1.75 \pm 0.09$ and $b = -0.30 \pm 0.14$. There is no evidence for excess of antiprotons around $\theta = +0.23$. To calculate an upper limit, the confidence interval of the parameter b is estimated by the goodness-of-fit probability[12], because the parameter b is negative. Finally, an upper limit on $R(\overline{p}/p)$ at the 90% confidence level is calculated to be 0.05. However, this value might have ambiguity due to depending on statistical treatments. Figure 2 shows the present result with the upper limits set by other experimental groups.

There are 3 results at multi-TeV energies so far, as shown in Fig. 2. Two of them are our experiment by using the Moon's shadow (this work) and the Sun's shadow (Tibet-I [7]). Our results are consistent with other experiment.

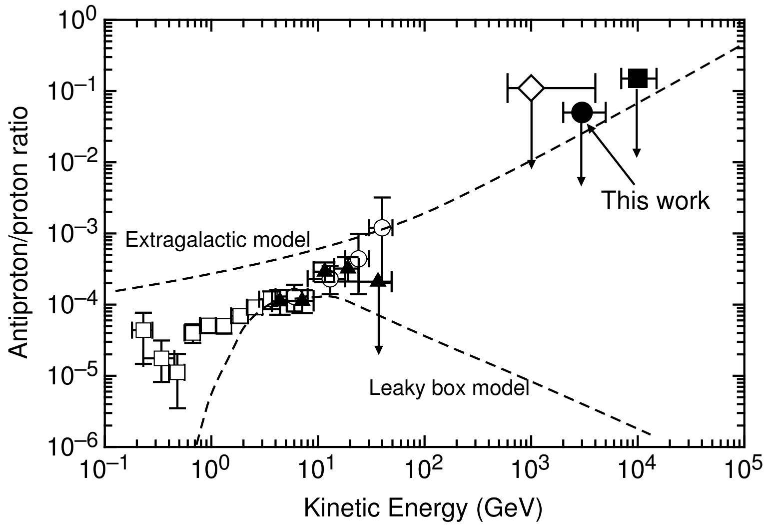

Figure 2. The $\overline{p}/p$ ratio obtained in this work compared with previous measurements (open square: BESS(2002)[8], open circle: CAPRICE(2001)[1], filled triangle: HEAT(2001)[10] diamond: L3+C(2005)[9], filled square: Tibet I(1995)[7], and filled circle: this work). The dash lines are the calculations asumming the leaky box model and the antimatter-galaxy model, respectively[11].

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