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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1. Abstract

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^o in diameter, we observe a deficit in cosmic rays called the Moon's shadow with statistical significance of 32σ. 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 11% at 90% confidence level on the cosmic-ray antiproton/proton ratio at multi-TeV energies.

2. 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

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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, recently, 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][3] obtained by indirect measurements of the cosmic-ray μ^+/μ^- ratio. The Tibet air shower array has been in operation since 1999 until 2002 as Tibet-III ($22,050$ m^2) with energy threshold of a few TeV and angular resolution of 0.9^o at a few TeV. The details of Tibet-III is described elsewhere[4]. 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.

3. Simulation

We develop a detailed Monte Carlo (MC) simulation code for the Moon's shadow analysis. We employ the CORSIKA Ver 6.004 code[5] for air shower event generation and Epics uv7.24 code[6] for the response of each scintillation counter, respectively. We adopt a primary cosmic-ray flux model based on direct observational data [7][8][9]. We generate MC events on the top of the atmosphere randomly along the Moon's orbit around the Earth. Then, we assign opposite charge to a primary particle and imaginarily shoot them back toward the Moon along the first trial direction, where we choose the first trial direction randomly on the $\pm 5^o \times \pm 5^o$ angular window centered at the Moon direction and determine the final trial direction by smearing the difference between the Moon direction and the estimated air shower direction. We make an assumption that the geomagnetic field is given by the IGRF model[10] under altitude 600 km, and by the Virtual Dipole Moment model (8.07×10^{25} $\mathrm{G} \cdot \mathrm{cm}^3$) at altitude > 600 km. We trace back each parent particle's trajectory to the Moon in the magnetic field for each primary particle. The events whose first trial direction hitting the Moon are collected and their final trial direction is used for the cosmic-ray direction. In this way, we obtain the expected Moon's peak which is equivalent to the observed Moon's shadow.

4. Data Selection

Total number of 3.99×10^{10} events are triggered and recorded during 682.9 live days of Tibet-III. Then, we select good air shower events 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^o; and some quality selection. After the selections, 7.9×10^9 events remained

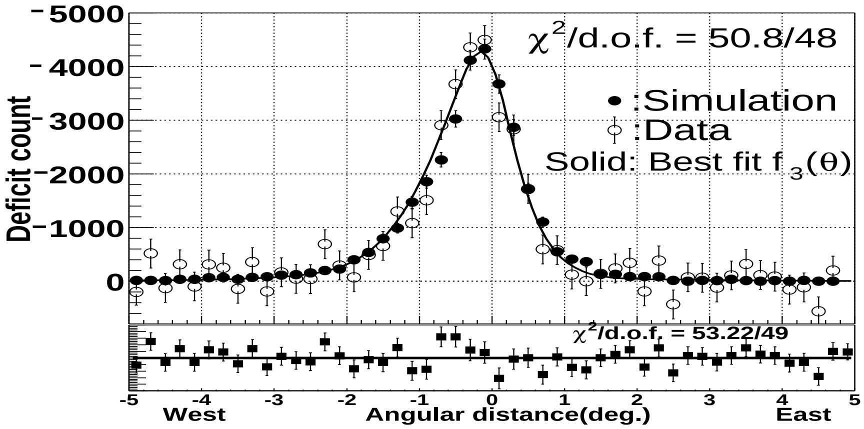

Fig. 1. Deficit count around the Moon's shadow

for further analysis.

5. Results and Discussion

As shown in Figure 1, Tibet-III observes the Moon's shadow at 32 statistical significance shifting westwardly by 0.23^o at mode energy $\sim$ 3 TeV. We show our MC simulation also in Fig. 1. Difference between the data and the MC simulation is demonstrated in Fig. 1 (lower panel). The data is in good agreement with the MC simulation within statistics. Subsequently we make up a function which successfully reproduce the MC simulation. The MC simulation data set are divided into seven data subsets according to the range of shower size. Each of the seven data subsets is fitted to a single Gaussian or dual Gaussian. Then, we add up all the seven functions which are eventually made of nine Gaussian to obtain the function:

$$f_1(\theta) = \sum_{i=1}^{9} C_{all,i} exp(-\frac{(\theta - M_{all,i})^2}{2\sigma^2_{all,i}}) \quad \text{(for primary cosmic rays)} \qquad (1)$$

$$f_2(\theta) = \sum_{i=1}^{9} C_{p,i} exp(-\frac{(\theta - M_{p,i})^2}{2\sigma^2_{p,i}}) \quad \text{(for antiproton)} \qquad (2)$$

where θ is the angular distance from the Moon direction in the west-east direction. Then we create the function $f_3(\theta)$ as

$$f_3(\theta) = af_1(\theta) + bf_2(-\theta) \qquad (3)$$

where the first term represents the deficit in cosmic rays and second term represents the deficit in antiprotons. From our simulation, 63.2% of cosmic rays are protons, so the ratio $b/0.632a$ indicates $R(\overline{p}/p)$. We fit the observed Moon's shadow to the function $f_3(\theta)$. The best fit curve is shown in Fig. 1 as a solid curve. The best fit values are: $a = 9.21 \pm 0.5$, $b = -0.93 \pm 0.5$, $\chi^2/d.o.f. = 50.8/48$. There is no evidence for excess of antiprotons around $\theta = +0.23$ Accordingly, an upper limit on $R(\overline{p}/p)$ at the 90% confidence level is calculated to be 0.11. Figure

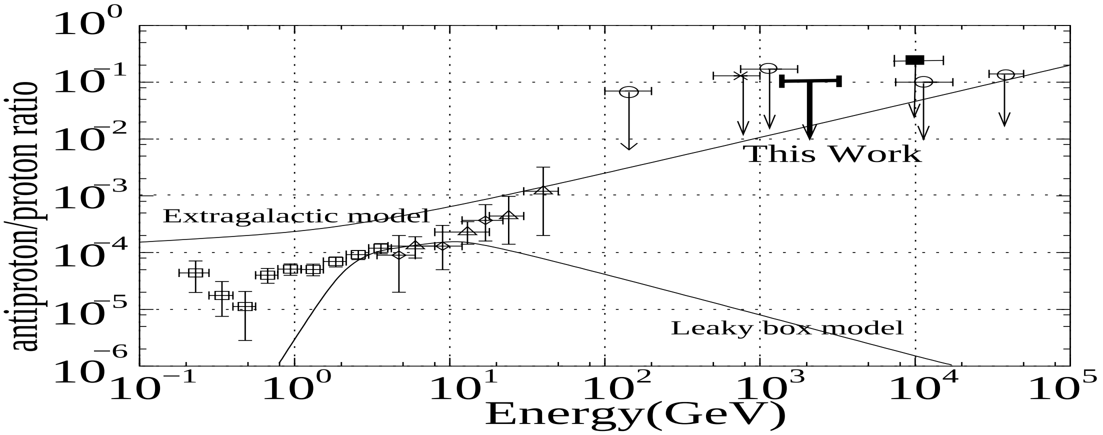

Fig. 2. Square: BESS(2002)[11], Triangle: CAPRICE(2001)[1], Diamond: Other experiment from [1], Circle: Stephens,S.A.(1985)[2], Cross: L3+C(2002)[3], Filled square: Tibet-I(1995)[12]

2 shows the present result together with the upper limits set by other experimental groups. Although there are 4 experiments at multi-TeV energies so far, as shown in Fig. 2, it should be noted that two of them belong to spectroscopic direct measurement, using the Moon's shadow (this work) and the Sun's shadow (Tibet-I [12]), that the other two belong to indirect measurement estimated by means of the cosmic-ray μ^+/μ^- ratio.

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References

1. Boezio, M., et al. 2001, ApJ, 561, 787
2. Stephens, S.A., 1985, Astron. Astophys. 149, 1.
3. Parriaud, J., 2002, Proc. of XIVth Rencontres de Blois, arXiv:astro-ph/0210334
4. Amenomori, M., et al. 2001, Proc. of 27th ICRC., HE2, 573-576
5. Heck, D., et al. 1998, Report FZKA, 6019, Forschungszentrum Karlsruhe
6. Kasahara, K., web site
7. Asakimori, K., et al. 1998, ApJ, 502, 278
8. Kamioka, E., et al. 2001, Adv. Space Res., 26, 1839
9. Sanuki, T., et al. 2000, ApJ, 545, 1135
10. National Geophysical Data Center web site
11. Asaoka, Y., et al. 2002, Phys. Rev. Lett., 88, 5
12. Amenomori, M., et al. 1995, Proc. of ICRC OG vol.3 84