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# Moon shadow by cosmic rays under the influence of geomagnetic field and search for antiprotons at multi-TeV energies

Tibet AS$\gamma$ Collaboration

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**Abstract**

We have observed the shadowing of galactic cosmic ray flux in the direction of the moon, the so-called moon shadow, using the Tibet-III air shower array operating at Yangbajing (4300 m a.s.l.) in Tibet since 1999. Almost all cosmic rays are positively charged; for that reason, they are bent by the geomagnetic field, thereby shifting the moon shadow westward. The cosmic rays will also produce an additional shadow in the eastward direction of the moon if cosmic rays contain negatively charged particles, such as antiprotons, with some fraction. We selected $1.5 \times 10^{10}$ air shower events with energy beyond about 3 TeV from the dataset observed by the Tibet-III air shower array and detected the moon shadow at $\sim 40\sigma$ level. The center of the moon was detected in the direction away from the apparent center of the moon by 0.23° to the west. Based on these data and a full Monte Carlo simulation, we searched for the existence of the shadow produced by antiprotons at the multi-TeV energy region. No evidence of the existence of antiprotons was found in this energy region. We obtained the 90% confidence level upper limit of the flux ratio of antiprotons to protons as 7% at multi-TeV energies.


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## 1. Introduction

Observation of antiproton abundance in cosmic ray flux raises the possibility of a baryon-symmetric universe and the propagation of cosmic rays in interstellar space. Recent measurements of antiproton flux, however, appear to be almost within the conventional cosmic ray physics in which antiprotons are produced as secondary particles of cosmic ray interactions with interstellar gas. For example, antiprotons are produced mainly by collisions of cosmic ray protons with interstellar hydrogen gas as $p + p \rightarrow \bar{p} + p + p + p$. Accelerator experiments measured the production rate ($\bar{p}/p$) of antiprotons to protons to be on the order of $10^{-3}$ at energies greater than 10 GeV.

Recently, measurements of absolute flux of antiprotons below a few GeV were carried out using the magnet spectrometer equipped with a track detector to identify the charge and momentum of each incident particle [1–4]. Among these, the CAPRICE2 experiment extended the energy range of the spectrum up to about 50 GeV. It is obvious that accurate measurements of $\bar{p}$ flux are key to testing current propagation models of cosmic rays in the Galaxy. Of course, a $\bar{p}$ "excess" from the reliable propagation model may lead to discover possible sources of primary antiprotons such as dark matter annihilation and evaporation of primordial black holes. Strong et al. [5] made a detailed calculation of the antiproton flux, diffuse gamma rays and other cosmic ray fluxes and compared it with the recent BESS results available in the energy region below a few GeV [4]. They found that the conventional local cosmic ray measurements, simple energy dependence of the diffusion coefficient, and uniform cosmic ray source spectra through the Galaxy fail to reproduce simultaneously both the secondary to primary nuclei ratio and antiproton flux in this energy region.

The experiments mentioned above also present the flux ratio, $\bar{p}/p$, of antiprotons to protons in the cosmic rays. It seems that the observed results are within the scope of the prediction of the standard leaky box model [6]. Some results [1,3], however, show a tendency that the $\bar{p}/p$ ratio increases with increasing primary energy, although the amount of data is insufficient.

In the simple leaky box model [7], the ratio of antiproton flux $f_{\bar{p}}(E_{\bar{p}})$ to proton flux $f_p(E_p)$ is calculated as [8]

$$\bar{p}/p \equiv f_{\bar{p}}(E_{\bar{p}})/f_p(E_p) \propto \frac{\lambda_{\rm esc}(E_p)}{\lambda_{\rm N}} Z_{\rm N\bar{N}}, \quad (1)$$

where $\lambda_{\rm esc} \equiv \rho\beta c\tau_{\rm esc}$ ($c$ is the light velocity) is the mean amount of matter (density $\rho$) traversed by a nucleon of velocity $\beta c$, $\tau_{\rm esc}$ is the mean time spent by the cosmic rays in the confinement space, and $\lambda_{\rm N}$ is the mean free path of the nucleon in the interstellar matter. In addition, $Z_{\rm N\bar{N}}$ is the production rate of antinucleons by nucleon–nucleon (hydrogen atom) interactions, which is almost constant when Feynman scaling holds, while weakly depending on the spectral index of cosmic rays. According to the HEAO-3 data on the $B/C$ ratio in the primary cosmic rays up to about 50 GeV/n, $\lambda_{\rm esc} \propto E^{-\delta}$ and $\delta \sim 0.6$ [9]. Because

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