Search for Cosmic-Ray Antideuteron with the BESS Spectrometer

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Abstract

Cosmic-ray antideuterons ($\bar{D}$'s), which have never been detected, are considered to be a unique probe to investigate novel "primary" origins of cosmic-ray antiparticles, especially in a low energy region below 1 GeV/nucleon. We performed a search for low-energy $\bar{D}$ with the BESS superconducting spectrometer. No candidate was found in the data obtained from four balloon flights at Lynn Lake, Canada during 1997 to 2000. We obtained, for the first time, at the 95% confidence level an upper limit of 1.9×10^{-4} (m^{2}s sr GeV/n)$^{-1}$ for the differential flux of the cosmic ray $\bar{D}$ in the energy region between 0.17 and 1.15 GeV/n.

1. Introduction

While recent results of successive BESS experiments confirmed that most of cosmic-ray antiprotons ($\bar{p}$'s) are probably "secondary" products [5], there remains room for $\bar{p}$'s from "primary" sources such as annihilating neutralino dark matter [6] and/or evaporating primoridial black holes (PBHs) [7,11].

Cosmic-ray antideuterons ($\bar{D}$'s) are considered to be a sensitive probe of those "primary" origins, especially in the low energy region below ~ 1 GeV/n. This is because the "secondary $\bar{D}$ spectrum" would be suppressed and shifted to higher energy than that of $\bar{p}$'s [8], whereas "primary" sources could produce "softer" spectra peaked in the low energy region [7,9,10] (Fig. 1b). Consequently, detection of even a single $\bar{D}$ at the low energy region will strongly suggest the existence of novel "primary" sources. However, the amount of the

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cosmic-ray $\bar{D}$, which has never been detected, is predicted to be very small. Note that "secondary" and "primary" production probabilities of heavier antinuclei ($^3\bar{T}$, $^3\overline{\mathrm{He}}$, $^4\overline{\mathrm{He}}$, $\ldots$) would be even more suppressed than that of $\bar{D}$ [3,8].

Here, we report a search for cosmic-ray $\bar{D}$ using the data obtained from four balloon flights of the BESS spectrometer.

2. Experiment and Analysis

The BESS detector is a magnetic-rigidity ($R \equiv pc/Ze$) spectrometer with a large geometrical acceptance. It employs a thin superconducting solenoidal magnet, a high-resolution drift-chamber tracking system, a plastic scintillator time-of-flight (TOF) counter system, and a silica-aerogel Čerenkov counter. Details of the spectrometer are described elsewhere [1,4,15].

The balloon flights were carried out in northern Canada, from Lynn Lake to Peace River. Data for $\bar{D}$ search were taken during the live-time periods (T_{live}) of 5.7, 6.0, 9.9 and 9.3 $\times 10^4$ seconds at altitudes around 36 km (residual air of 5.4, 5.2, 3.9 and 5.4 g/cm^2 on average) in 1997, 1998, 1999 and 2000, respectively.

The concept of the off-line analysis is similar to that used for $\bar{p}$'s [5]. First, we select events with a single downward going track which is fully contained inside the fiducial volume. Next, in order to ensure the quality of β (velocity) and R measurements, we apply cuts on several tracking quality parameters. All $\mathrm{d}E/\mathrm{d}x$ measurements in the TOF counters and in the central chamber are required to be consistent with $\bar{D}$ or D (deuteron) as a function of R. In addition, the Čerenkov veto is applied to reduce the e^-/μ^- background contamination.

Figure 1a shows the $1/\beta$ versus R plot for the surviving single-charge events among the 1998 data; events of p's and $\bar{p}$'s are also plotted. Clean bands of p's, D's, tritiums and $\bar{p}$'s can be seen. However, no $\bar{D}$ candidate exists within the expected selection band, which is defined by the mirror position of D's where the $\bar{p}$ band does not overlap. No $\bar{D}$ candidate was found in the data set.

The resultant upper limit on the differential flux of cosmic-ray $\bar{D}$, $\Phi_{\bar{D}}$, is given by: $\Phi_{\bar{D}} = \frac{N_{\mathrm{obs}}}{\left|S\Omega\ \bar{\varepsilon}_{\mathrm{total}}\right|_{\mathrm{min}}\ T_{\mathrm{live}}\ (E_2 - E_1)}$, $\bar{\varepsilon}_{\mathrm{total}} = \bar{\varepsilon}_{\mathrm{sngl}}\ \bar{\varepsilon}_{\mathrm{trig}}\ \bar{\varepsilon}_{\mathrm{d}E/\mathrm{d}x}\ \bar{\varepsilon}_{\beta}\ \bar{\varepsilon}_{\mathrm{acc}}\ \bar{\varepsilon}_{\mathrm{TQ}}\ \bar{\eta}$; where $\bar{\varepsilon}_{\mathrm{acc}}$ denotes the aerogel Čerenkov cut efficiency, and the meanings of the other parameters are similiar to those described in [14]. In order to obtain the most conservative limit, the minimum value of ($S\Omega\ \bar{\varepsilon}_{\mathrm{total}}$) is used. To determine $S\Omega$, $\bar{\varepsilon}_{\mathrm{sngl}}$ and $\bar{\eta}$, we have developed a simulation model of the BESS instrument based on the GEANT/GHEISHA code. Nuclear interactions of $\bar{D}$ were implemented in the code with the following assumptions similar to those in $\overline{\mathrm{He}}$ analysis [14]: (1) The inelastic cross sections of $\bar{D}$ can be estimated by scaling those of $\bar{p}$ using an empirical model of hard spheres with overlaps, which is described as $\sigma(A_i, A_t) \propto [A_i^{1/3} + A_t^{1/3} - 0.71 \times (A_i^{-1/3} + A_t^{-1/3})]^2$; where $\sigma(A_i, A_t)$ is the cross section of an incident particle with atomic weight A_i to a target with atomic

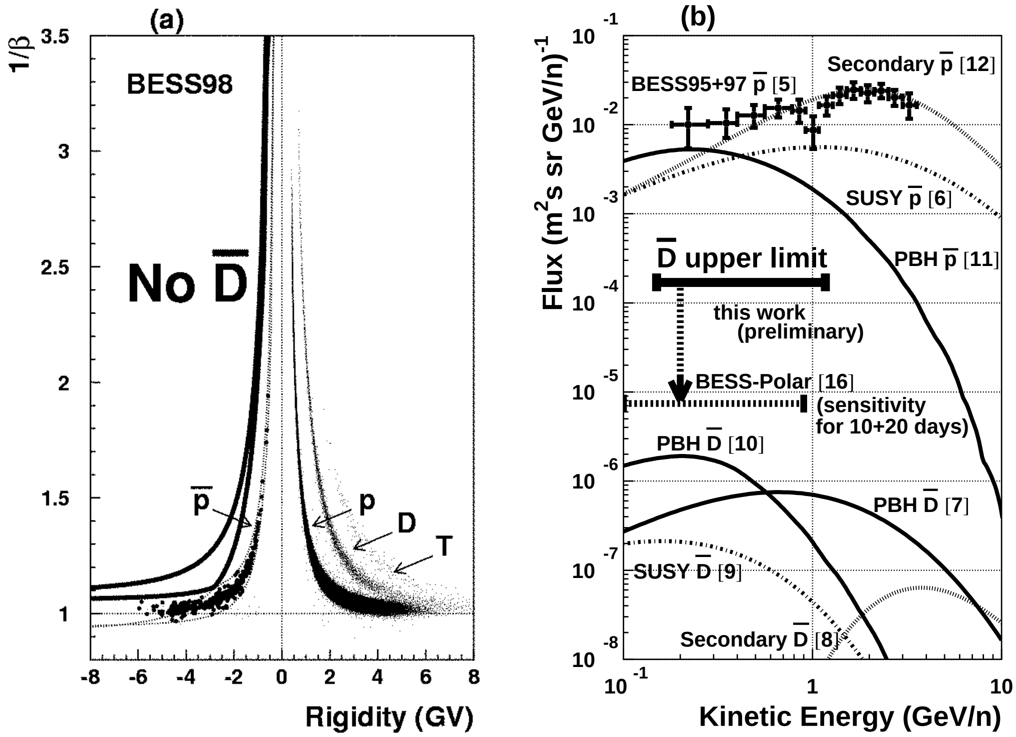

Fig. 1. (a): The identification plot of single-charge particles for '98 data. (b): Obtained upper limit on the differential cosmic-ray $\bar{D}$ flux and the expected $\bar{D}$ sensitivity for BESS-Polar. The calculated energy spectra of $\bar{p}$'s and $\bar{D}$'s from each origin at the solar minimum phase are also compared. The number density of PBHs in [10,11] was chosen to fit the BESS95+97 $\bar{p}$ data using the secondary $\bar{p}$ spectrum in [12].

weight A_t. (2) When an inelastic interaction occurs, $\bar{D}$ is always fragmented or annihilated. (3) The elastic cross sections of $\bar{D}$ are the same as those of D.

The other selection efficiencies among $\bar{\varepsilon}_{\rm total}$ were derived from D events in the flight data, under the assumption that noninteracting $\bar{D}$'s behave similar to D's except for deflection in the symmetrical configuration of BESS. The combined systematic error of these efficiencies were estimated to be less than 10%.

The energy range (E_1, E_2) was determined to be from 0.17 GeV/n to 1.15 GeV/n (at the top of the atmosphere) where $\bar{D}$'s can be well separated from $\bar{p}$'s with high $S\Omega$ $\bar{\varepsilon}_{\rm total}$ (typically $S\Omega \geq 0.22$ m^{2}sr and $\bar{\varepsilon}_{\rm total} \geq 27\%$ with less energy dependence). Since no $\bar{D}$ candidate was found, we took 3.1 as $N_{\rm obs}$ for the calculation of the 95% confidence level (C.L.) upper limit (U.L.).

3. Result and Discussions

We have searched for cosmic-ray $\bar{D}$ with the BESS spectrometer flown during 1997 - 2000. No candidate was detected. As a preliminary result, the upper limit (U.L.) on the $\bar{D}$ flux in an energy range 0.17 - 1.15 GeV/n at the top of the atmosphere was obtained to be 1.9×10^{-4} (m^{2}s sr GeV/n)$^{-1}$ (95% C.L.), which includes the systematic error of 10% (Fig.1b). Based on the discussion given in Ref. [10], this leads to an U.L. 2.3×10^0 pc^{-3}yr^{-1} (95% C.L.) for the explosion rate of local PBHs, which is five orders of magnitute more stringent than the sensitivity for 50-TeV γ-ray bursts [2] but two orders of magnitude more loose than that on the $\bar{p}$ flux [11]. The sensitivity to detect $\bar{D}$ is to be greatly improved in our next project, BESS-Polar [16], subsequently by AMS-02 and GAPS [7,9,13].

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References

1. Ajima Y. et al. 2000, Nucl. Instr. Methods A443, 71.
2. Alexandreas D. E. et al. 1993, Phys. Rev. Lett. 71, 2524.
3. Allkofer O. C., Brockhausen D. 1985, Astrophys. and Space Sci. 109, 145.
4. Asaoka Y. et al. 1998, Nucl. Instr. Methods A416, 236.
5. Asaoka Y. et al. 2002, Phys. Rev. Lett. 88, 051101; and references therein.
6. Bergström L. et al. 1999, Astrophys. J. 52, 6215.
7. Barrau A. et al. 2002, A&A 388, 676; 2003, A&A 398, 403.
8. Chardonnet P. et al. 1997, Phys. Lett. B 409, 313.
9. Donato F., Fornengo N. and Salati P. 2000, Phys. Rev. D 62, 043003.
10. Maeno T. and Orito S. (internal note BESS-19Feb2000-4): The $\bar{D}$'s emission from PBHs, the propagation, the source distribution, and the solar modulation are considered in the similar way to [7], [11], [11], and [5], respectively.
11. Maki K., Mitsui T., Orito S. 1996, Phys. Rev. Lett. 76, 3474.
12. Mitsui T., Maki K., Orito S. 1996, Phys. Lett. B 389, 169.
13. Mori K. et al. 2002, Astrophys. J. 566, 604.
14. Sasaki M. et al. 2002, Nucl. Phys. B (Proc. Suppl.) 113, 202; and references therein.
15. Shikaze Y. et al. 2000, Nucl. Instr. Methods A455, 596.
16. Yamamoto A. et al. 2002, Adv. Space Res. 30, 1253.