Search for fractionally charged particles in cosmic rays with the BESS spectrometer

H. Fuke a,*, Y. Tasaki a, K. Abe b,1, S. Haino c,2, Y. Makida e, S. Matsuda c, J.W. Mitchell d, A.A. Moiseev d, J. Nishimura e, M. Nozaki c, S. Orito c,z, J.F. Ormes d,3, M. Sasaki d, E.S. Seo f, Y. Shikaze b,4, R.E. Streitmatter d, J. Suzuki c, K. Tanaka c, T. Yamagami a, A. Yamamoto c, T. Yoshida a, K. Yoshimura c

a Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA), Sagamihara, Kanagawa 229-8510, Japan
b Kobe University, Kobe, Hyogo 657-8501, Japan
c High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
d National Aeronautics and Space Administration, Goddard Space Flight Center (NASA/GSFC), Greenbelt, MD 20771, USA
e The University of Tokyo, Tokyo 113-0033, Japan
f University of Maryland, College Park, MD 20742, USA

Received 11 November 2006; received in revised form 24 January 2007; accepted 13 February 2007

Abstract

Historically, there have been many searches for fractionally charged particles in the cosmic radiation. However, few searches have been performed near the top of the atmosphere. We performed a search for relativistic $\frac{2}{3}e$ charged particles in cosmic rays using data collected during four BESS balloon flights from 1997 to 2000 carried out in northern Canada. The data were analyzed by examining energy deposition in the time-of-flight scintillator hodoscopes. No candidate was found. We derive an upper limit of $4.5 \times 10^{-7} \, \text{cm}^2 \, \text{s} \, \text{sr}^{-1}$ for the flux of $\frac{2}{3}e$ charged particles, at the 90% confidence level.

© 2007 COSPAR. Published by Elsevier Ltd. All rights reserved.

Keywords: Cosmic ray; Fractional charge; Quark search; Superconducting spectrometer; BESS

1. Introduction

The origin of the electric charge quantization is a fundamental question for elementary particle physics, but it remains unexplained within the Standard Model. Since the proposal of the quark model in 1964, many searches for fractionally charged particles have been carried out in the cosmic radiation without any evidence for their existence. However, most of these searches were performed on or under ground on the assumption that the objective particles are able to penetrate large amount of material (Table 1). Therefore, it is worthwhile to do a search near the top of the atmosphere where there is around 5 g/cm² of intervening material.

Here, we report a search for relativistic $\frac{2}{3}e$ charged particles in cosmic rays using the data collected during four BESS balloon flights from 1997 to 2000 carried out in northern Canada.

2. BESS spectrometer

The BESS detector (Fig. 1) was designed (Orito, 1987; Yamamoto et al., 1988) and developed (Ajima et al.,
2000; Makida et al., 1995; Shikaze et al., 2000; Asaoka et al., 1998) as a high-resolution spectrometer with the large geometrical acceptance and strong particle-identification capability. A uniform magnetic field of one Tesla is generated by a thin superconducting solenoid. The field region is filled with tracking detectors consisting of a jet-type drift chamber (JET) and two inner drift chambers (IDCs). Tracking is performed by fitting up to 28 hit points in these drift chambers, resulting in a rigidity ($R$) resolution of 0.5% at one GV. The upper and lower time-of-flight scintillator hodoscopes (TOFs) measure the velocity ($\beta$) and the energy loss ($dE/dx$). The time resolution of each counter is 55 ps, which yields a $1/\beta$ resolution of 1.4%.

3. Balloon flights

Four balloon flights were carried out in northern Canada, 1997 through 2000. They flew from Lynn Lake to Peace River where the geomagnetic cutoff rigidity ranges from 0.3 to 0.5 GV. Data for the search were taken for live times of 15.8, 16.8, 27.4, and 28.7 h in 1997, 1998, 1999, and 2000, respectively, at altitudes around 36 km, corresponding to ~5 g/cm$^2$ in residual atmospheric depth. The data acquisition sequence was initiated by a first-level trigger generated by a coincidence between hits of the upper and lower TOFs with a threshold set at $1/3$ of the pulse height from minimum ionizing particles (MIPs). In addition to biased trigger modes enriching negatively charged particles, one of every 60 (30 in 2000) first-level triggered events were recorded as unbiased samples (Ajima et al., 2000).

4. Data analysis

The unbiased samples were used to search for $2/3e$ charged particles. As described later, the “key” information to identify $2/3e$ particles is the energy deposit measured by the upper and lower TOFs. The typical energy loss of relativistic $2/3e$ particles should be $(2/3)^2 = 4/9$ in units of MIP's $dE/dx$. Therefore, an event which provides $dE/dx$ smaller than that of a MIP could be a candidate $2/3e$ particle.

At the first step of the analysis, we selected events with a single downward-going, passing-through track which is fully contained inside the fiducial volume with restricted number of TOF hits, in order to reject albedo particles as well as the events interacted elastically in the BESS apparatus.

The MIP samples were selected by using the relation between rigidity, $dE/dx$ in the upper and lower TOFs, and $1/\beta$ as shown by the heavy-line rectangles in Fig. 2. In further event selection, care must be exercised for those events

Table 1

<table>
<thead>
<tr>
<th>Reference</th>
<th>Objects</th>
<th>Upper limit (cm$^{-2}$ s$^{-1}$ sr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In primary cosmic rays</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sbarra et al. (2002)</td>
<td>$2/3e$</td>
<td>$3.0 \times 10^{-7}$ (95% C.L.) (preliminary)</td>
</tr>
<tr>
<td>On the mountain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DeLise and Bowen (2004)</td>
<td>$2/3e$, $2e$</td>
<td>$1.8 \times 10^{-8}$ (90% C.L.) ($2e$)</td>
</tr>
<tr>
<td>On or under ground</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ambrosio et al. (2004) and Ambrosio et al. (2000)</td>
<td>$2/3e$, $2e$</td>
<td>$6.1 \times 10^{-16}$ (90% C.L.) ($0.25 &lt; \beta &lt; 1$)</td>
</tr>
<tr>
<td>Aglietta et al. (1994)</td>
<td>$2/3e$, $2e$</td>
<td>$2.7 \times 10^{-13}$ (90% C.L.) ($2e$)</td>
</tr>
<tr>
<td>Mori et al. (1991)</td>
<td>$2/3e$, $2e$</td>
<td>$2.3 \times 10^{-15}$ (90% C.L.) ($2e$)</td>
</tr>
<tr>
<td>Mashimo et al. (1983) and Kawagoe et al. (1984)</td>
<td>$2/3e$, $2e$</td>
<td>$6 \times 10^{-13}$ (90% C.L.) ($2e$, $3.5 \times 10^{-4} &lt; \beta &lt; 0.4$)</td>
</tr>
</tbody>
</table>

Fig. 1. Cross sectional view of the BESS spectrometer in its 1999 configuration.
whose track is not fully contained inside the TOF counter and may thus yield small $dE/dx$ and “fake” $3\pi$ particles. At this step we also rejected those events that “grazed” the edge of the TOFs, by checking the intersection of the extrapolated chamber trajectory with the TOF position. The solid-line histogram in Fig. 3 shows the distribution of the distance, $|\Delta X|$, between this intersection and the center of the hit TOF counter paddle in the transverse, narrow, dimension. We fitted the error function to this $|\Delta X|$ histogram as shown by the dashed line in Fig. 3, and set the cut boundary for the $|\Delta X|$ as $4\sigma$ from the edge of TOF (dashed-dotted line). To confirm that this boundary is appropriate and effective to eliminate the “grazing” events, MIP events with $dE/dx$ smaller than 0.7 were selected from the whole MIP samples. The dotted-line histogram in Fig. 3 is the distribution of MIP events with small $dE/dx$. Most of the events show $|\Delta X|$ larger than the cut boundary; that is, it was confirmed that this $|\Delta X|$ cut can eliminate the “grazing” events effectively.

At the second step, in order to eliminate backgrounds such as large-angle scattered events by ensuring good quality of $R$ and $\beta$ measurements, we applied several cuts on tracking and timing measurement quality parameters such as: (i) the number of used hits and the reduced $\chi^2$ of the trajectory fitting, and (ii) the consistency between the JET track, hits in the IDCs, and the TOF timing information.

The solid-line histogram in Fig. 4 shows the $dE/dx$ distribution of MIP samples which survived both of the first and second step selections. We fitted this solid-line histogram by the Landau function as shown by the dashed line in Fig. 4; this line is same as the dashed line in Fig. 5 ($Z = e$).

At the last step, we searched for the $3\pi$ particles. In order to identify the objects, the $dE/dx$ distribution of $3\pi$ particles were estimated by scaling the Landau function for the MIP $dE/dx$ obtained above (the number of photoelectrons for MIP is typically 500 at the center of TOF). As denoted by the solid line in Fig. 5, most of the expected $dE/dx$ distribution of $3\pi$ particles is contained between the TOF trigger threshold (1/3 MIP) and the $dE/dx$ distribution of MIP events. To keep high detection efficiency of $3\pi$ particles and minimize the probability to misidentify single-charged particles as the objects of our search, the selection boundary was set to 0.7 MIP. The selection efficiency is above 80% as shown by the integrated Landau function in Fig. 5.

Fig. 6 shows the distribution of $dE/dx$ measured by the upper and lower TOFs in each flight. The events which yield either upper or lower TOF $dE/dx$ smaller than 0.8...
are emphasized by large points. No event can be seen in the searched area which is defined as the region where both of $dE/dx$’s are less than 0.7.

The large-pointed events are considered to be particles which scattered inside the BESS detector and “grazed” TOFs. These events cannot be quite eliminated by the first and second step selections in the present detector configuration. The number of these large-pointed events is consistent with the number estimated by a Monte Carlo simulation. According to the simulation, the probability that a particle is scattered both near upper and lower TOFs and grazed both the upper and lower TOFs is negligible with our event statistics.

5. Results

Since no $3e$ candidate was found, we calculated the resultant upper limit on the flux of cosmic-ray $3e$ particles, $\Phi_{3e}$, which is given by:
Table 2
The upper limits on the flux of cosmic-ray $\frac{3}{2}e$ charged particles for each four flights and their sum

<table>
<thead>
<tr>
<th>Year</th>
<th>Upper limit (90% C.L.) (cm$^2$ s sr)$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997 + 1998 + 1999 + 2000</td>
<td>$4.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>1997</td>
<td>$3.0 \times 10^{-6}$</td>
</tr>
<tr>
<td>1998</td>
<td>$2.9 \times 10^{-6}$</td>
</tr>
<tr>
<td>1999</td>
<td>$2.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>2000</td>
<td>$9.6 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

The upper limit is comparable to that obtained above the atmosphere by the AMS team (Sbarra et al., 2002) (see also Table 1). Although recent experiments on or under ground derive much more stringent results, as long as the penetration length of fractionally charged particles in the air is unknown, it is worthwhile using a balloon-borne platform. This environment is slightly different from that in free space because of the “thin target” of overlying atmosphere, so the experiment probes slightly different part of the possible phase space for fractionally charged particles.

We confirmed the ability of the BESS spectrometer to search for $\frac{3}{2}e$ particles, for the first time. More sensitive searches will be possible by combining other BESS flight data.

Acknowledgements

We thank NASA and the Columbia Scientific Balloon Facility (CSBF) for their professional and skillful work in carrying out the BESS flights. We also thank ISAS, KEK and ICEPP (the University of Tokyo) for their continuous support and encouragement for the BESS experiment. This experiment was supported by Grants-in-Aid, KAKENHI (9304033, 11440085, and 11694104) from the Ministry of Education, Culture, Sport, Science and Technology (MEXT), and by Heiwa Nakajima Foundation in Japan; and by NASA SR&T research grants in the USA.

References


