32ND INTERNATIONAL COSMIC RAY CONFERENCE, BEIJING 2011

BESS-Polar: Search for Antihelium

M. SASAKI[a,1], K. ABE[b,2], H. FUKE[c], S. HAINO[d,3], T. HAMS[a,4], M. HASEGAWA[d], A. HORIKOSHI[d], A. ITAZAKI[b], K. C. KIM[e], T. KUMAZAWA[d], A. KUSUMOTO[b], M. H. LEE[e], Y. MAKIDA[d], S. MATSUDA[d], Y. MATSUKAWA[b], K. MATSUMOTO[d], J. W. MITCHELL[a], Z. MYERS[e,5], J. NISHIMURA[f], M. NOZAKI[d], R. ORITO[b,6], J. F. ORMES[g], K. SAKAI[f], E. S. SEO[e], Y. SHIKAZE[b,7], R. SHINODA[f], R. E. STREITMATTER[a], J. SUZUKI[d], Y. TAKASUGI[b], K. TAKEUCHI[b], K. TANAKA[d], N. THAKUR[g], T. YAMAGAMI[c], A. YAMAMOTO[d,f], T. YOSHIDA[c], AND K. YOSHIMURA[d]

[a] *NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA.*
[b] *Kobe University, Kobe, Hyogo 657-8501, Japan.*
[c] *Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA), Sagamihara, Kanagawa 252-5210, Japan.*
[d] *High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan.*
[e] *University of Maryland, College Park, MD 20742, USA.*
[f] *The University of Tokyo, Bunkyo, Tokyo 113-0033 Japan.*
[g] *University of Denver, Denver, CO 80208, USA.*
Makoto.Sasaki@nasa.gov

Abstract: We have searched for antihelium in cosmic-rays since 1993 using a series of nine conventional BESS northern latitude balloon flights and two long-duration BESS-Polar Antarctic balloon flights. The BESS-Polar spectrometer is an evolutionary development of the previous BESS instruments, adapted to long duration flight. No antihelium candidate was found in the rigidity ranges of 0.6-20 GV among 8×10^6 helium nuclei events for BESS-Polar I and in the rigidity range of 0.6-14 GV among 4×10^7 events for BESS-Polar II, respectively. A resultant upper limit of 6.9×10^{-8} for the abundance ratio of antihelium/helium at the top of the atmosphere in the rigidity range of 1-14 GV was set by combining all the BESS and BESS-Polar flight data. This is the most stringent limit obtained to date.

Keywords: Antimatter, Antihelium, BESS, BESS-Polar, cosmic-rays

1 Introduction

The existence of antiparticles was predicted by Dirac as a consequence of the Dirac equation [1] and confirmed by Anderson through the discovery of the positron, antiparticle of the electron, in the cosmic radiation [2]. It was followed by the experimental confirmation of the existence of antiprotons in the laboratory [3] and also in the cosmic radiation [4]. At present, the production of antiparticles in the laboratory with $|Z| = 2$ has been confirmed [5]. However, in spite of many efforts to find them, there is no evidence that antiparticles with $|Z| \geq 2$ exist in the cosmic radiation [6], and by implication in the universe at large.

This apparent asymmetry of particle and antiparticle is one of the fundamental questions in cosmology. Many cosmologists consider that this asymmetry was caused by the symmetry-breaking between particles and antiparticles just after the Big Bang, with cosmological antiparticles vanishing at an early stage of the universe. However, the existence of $|Z| \geq 2$ antiparticles is not excluded by theory. There might be remnant antiparticle domains from the Big Bang.

We have searched for those antinuclei in cosmic radiation since 1993 using the BESS spectrometer and set the most stringent upper limit obtained to date. From 1993 to 2000, we had seven conventional one day balloon flights from northern Canada. In 2002, we upgraded the central tracker and installed a new detector (ODC) to obtain higher rigidity

1. Also University of Maryland, College Park, MD 20742, USA

2. Present address: ICRR, The University of Tokyo, Kamioka, Gifu, 506-1205, Japan

3. Present address: Instituto Nazionale di Fisica Nucleare (INFN), Perugia, Italy

4. Also University of Maryland, Baltimore County, Baltimore, MD 21250, USA

5. Present address: Physics Department, Technion Israel Institute of Technology, Technion City, Haifa, Israel

6. Present address: Tokushima University, Tokushima, Japan

7. Present address: Japan Atomic Energy Agency (JAEA), Tokai, Ibaraki, Japan

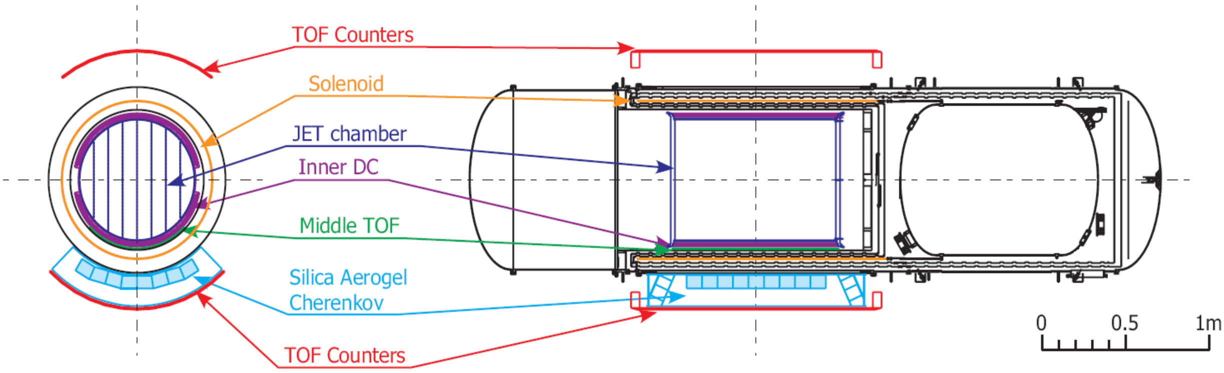

Figure 1: The cross-sectional view and the side view of the BESS-Polar II Spectrometer.

resolution, so that we could search for antihelium up to 500 GV (BESS-TeV).

In order to search for antihelium with more sensitivity, we realized long-duration balloon flights over Antarctica in the 2004-2005 season (BESS-Polar I) and 2007-2008 season (BESS-Polar II).

2 The BESS-Polar Spectrometer

The BESS-Polar spectrometer is an evolutionary development of the previous BESS experiments improved to adapt to a long duration flight in Antarctica [7]. There was no pressure vessel outside the detector to reduce the material thickness along the incident particle trajectories and total suspended weight. The time-of-flight (TOF) counters and aerogel Cherenkov counter (ACC) as well as their related front-end electronics were operated in vacuum. The cryostat of the solenoid magnet was used as the pressure vessel for the central tracker, which worked successfully in the BESS-TeV experiment [8]. The basic spectrometer configuration was the same for the BESS-Polar I and BESS-Polar II flight. For the BESS-Polar II flight, the spectrometer was improved in performance and achieved an extended lifetime during the flight. A newly constructed magnet with a larger liquid helium reservoir tank and a data storage system with larger capacity of hard disk drives (HDDs) enabled longer observation time.

Figure 1 shows the cross-sectional view and the side view of the BESS-Polar II spectrometer. All the detector components are arranged in a cylindrical configuration. The time-of-flight detector is placed at the outmost location of the spectrometer and provided the incident particle velocity, $\beta = v/c$, with a time resolution of 120 ps and two independent dE/dx measurements. The TOF detector consists of the 10 scintillator paddles for the top and the 12 scintillator paddles for the bottom. Photomultiplier tubes (PMTs) are attached to both sides of the scintillator paddles through acrylic light guides. The Z-position of an incident particle is roughly determined by the time difference between the two PMT signals. The superconducting solenoid provided a uniform field of 0.8 Tesla for over 11 days continuous operation for the BESS-Polar I and over 24 days for the BESS-Polar II. Two inner drift chambers (IDCs) and a JET-cell type drift chamber (JET) are located inside of the warm bore (0.80 m in diameter and 1.4 m in length) and measure the particle trajectories by fitting up to 52 hit-points with 150 μm resolution for each wire. The resulting magnetic-rigidity (R $\equiv$ pc/Ze, momentum divided by electric charge) resolution is 0.4% at 1 GV, with a maximum detectable rigidity (MDR) of 240 GV for the BESS-Polar I and 280 GV for the BESS-Polar II. The JET also provides dE/dx information from the truncated mean of the integrated charges of the hit-pulses. The JET and IDCs are filled with CO_2 gas and fresh gas is circulated during the flight. The additional TOF detecter (MTOF) was installed between the bottom IDC and warm bore to observe low energy particles which can not penetrate the magnet. The Aerogel Cherenkov Counter (ACC) was located between the magnet and the bottom TOF as a veto counter to separate antiproton events from background e^-/μ^- events. The middle TOF and ACC was not used for the antihelium search.

3 Flight Conditions

The BESS-Polar spectrometer was successfully flown over Antarctica twice. The first BESS-Polar flight was launched on December 13th, 2004 from Williams Field near McMurdo Station. The spectrometer was flown 8.5 days around Antarctica successfully recording 900 million cosmic-ray events, then terminated on December 21, landing at the south end of the Ross Ice Shelf. The averaged floating altitude was 38.5 km (residual atmosphere of 4.3 $\mathrm{g/cm^2}$). During the flight, several PMTs of the TOF hodoscopes showed extremely high count rates and drew excessive current, ultimately having to be turned off. However, 66% of the full geometric acceptance could be sustained by controlling the trigger algorithm through telemetry. The second BESS-Polar flight was launched on December 22nd, 2007 from Williams Field. The spectrometer was flown for 29.5 days over Antarctica and observed cosmic-ray events for about 24.5 days at float altitude with the magnet energized, recording 4.7 billion events on the

HDD. The full geometric acceptance was maintained during the entire flight, though two TOF PMTs had to be turned off due to a HV control issue. The drift chamber HV system had an issue, and we could not apply full HV for the JET chamber. We adjusted the gas pressure and HV value to compensate.

4 Data Analysis

4.1 Event Selection

During the flights, we recorded all events which penetrated the spectrometer. It is possible that more than one particle passed through the spectrometer simultaneously. Hence, we first have chosen events with a single good track. The criterion is that there be only one track in the drift chamber, and one track each passing thorough the upper and lower TOF counters. Then, we have applied track quality selection such as hit data consistency between TOF and drift chambers, small χ^2 in trajectory fitting, fiducial selection, etc. None of these selections depend on the sign of the particle charge.

4.2 Particle identification

As with the BESS spectrometer, the BESS-Polar spectrometers were designed as general purpose detectors. So we have measured not only the helium (antihelium) nuclei but also measured the protons, deuterons, etc. during the flights. After selecting the events as mentioned above, we identified the helium (antihelium) nuclei from selected events by their mass. Particle mass M is related to rigidity R, velocity β and charge Z (dE/dx) as

$$M^2 = R^2 Z^2 (\frac{1}{\beta^2} - 1). \quad (1)$$

The β, dE/dx and rigidity were measured by the TOF counter and the drift chamber. We applied a $1/\beta$ band cut and dE/dx band cut instead of selecting particle mass directly. Figure 2 shows the $1/\beta$ band cut and dE/dx band cuts for the TOF counters.

5 Results

Figure 3 shows the 1/rigidity distribution of the BESS-Polar II flight data after all selections are applied. No antihelium candidates were found in the rigidity region 1-20 GV, among 8×10^6 helium nuclei events for the BESS-Polar I, and in the rigidity region 1-14 GV, among 4×10^7 helium nuclei events for the BESS-Polar II. Since there are no antihelium events in the data, we can only set an upper limit for the abundance ratio of antihelium/helium at the top of the atmosphere. The upper limit is given by the following formula:

$$R_{\overline{\mathrm{He}}/\mathrm{He}} = \frac{\int N_{Obs,\overline{\mathrm{He}}}/(S\Omega \times \overline{\eta} \times \overline{\epsilon}_{sngl} \times \overline{\epsilon}_{dE/dx} \times \overline{\epsilon}_{\beta} \times \overline{\epsilon}_{DQ})dE}{\int N_{Obs,\mathrm{He}}/(S\Omega \times \eta \times \epsilon_{sngl} \times \epsilon_{dE/dx} \times \epsilon_{\beta} \times \epsilon_{DQ})dE}, \quad (2)$$

where the $N_{obs,He(\overline{\mathrm{He}})}$ is the number of observed He ($\overline{\mathrm{He}}$) event, the SΩ is the geometric acceptance of the spectrometer, and η ($\overline{\eta}$) is a survival probability of He ($\overline{\mathrm{He}}$) to traverse the atmosphere above the spectrometer, ϵ_{sngl} ($\overline{\epsilon}_{sngl}$) is single track efficiency for He ($\overline{\mathrm{He}}$), $\epsilon_{dE/dx}$ ($\overline{\epsilon}_{dE/dx}$) is the d$E$/d$x$ selection efficiency for He ($\overline{\mathrm{He}}$), ϵ_{β} ($\overline{\epsilon}_{\beta}$) is the β selection efficiency for He ($\overline{\mathrm{He}}$), and ϵ_{DQ} ($\overline{\epsilon}_{DQ}$) is the data quality selection efficiency for He ($\overline{\mathrm{He}}$). The numerator in the equation is the number of antihelium at the top of the atmosphere (TOA) and the denominator is the number of helium at the TOA.

In order to calculate the upper limit, we have to assume an energy spectrum of antihelium since the efficiencies are function of energy. If we assume that the hypothetical energy spectrum of antihelium was same as the energy spectrum of helium, we can simplify the previous formula as

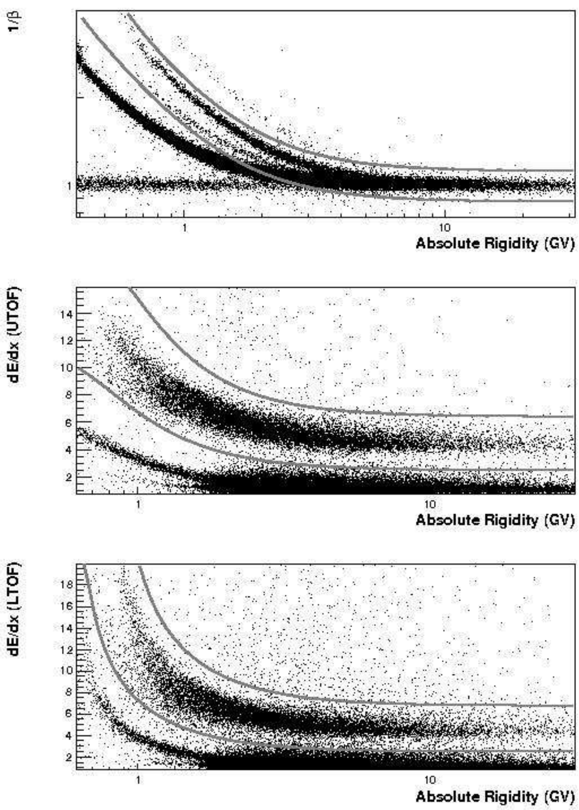

Figure 2: The upper figure shows the β^{-1} vs absolute rigidity of the BESS-Polar II flight data. The lower two figures show the dE/dx vs absolute rigidity measured by top and bottom TOF counters. The event candidates are between the lines.

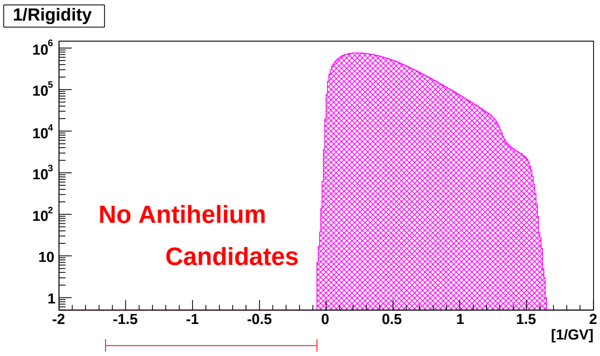

Figure 3: R^{-1} distribution of $|Z| = 2$ events of the BESS-Polar II flight data.

follows:

$$R_{\overline{\mathrm{He}}/\mathrm{He}} < \int \frac{3.1\,\mathrm{d}E}{N_{Obs,\mathrm{He}} \times \overline{\eta} \times \overline{\epsilon}_{sngl}/(\eta \times \epsilon_{sngl})}. \quad (3)$$

Here, we take 3.1 as the number of antiheliums ($N_{Obs,\overline{\mathrm{He}}}$) for the calculation of the 95 % confidence level upper limit ([9]). The η ($\overline{\eta}$) and ϵ_{sngl} ($\overline{\epsilon}_{sngl}$) are determined by the Monte Carlo simulation which has been developed based on the GEANT/GHEISHA code for the spectrometers. By using the BESS-Polar I flight data, we set the upper limit for the antihelium to helium ratio of 4.4×10^{-7} in the 1-20 GV rigidity range, and by using the BESS-Polar II flight data, we set the upper limit of 9.4×10^{-8} in the 1-14 GV rigidity range, respectively. The resultant upper limit of 6.9×10^{-8} was set by combining all the BESS data and the data of the two BESS-Polar flights. This is the most stringent upper limit obtained to date. The result is shown in Figure 4 with previous experimental results.

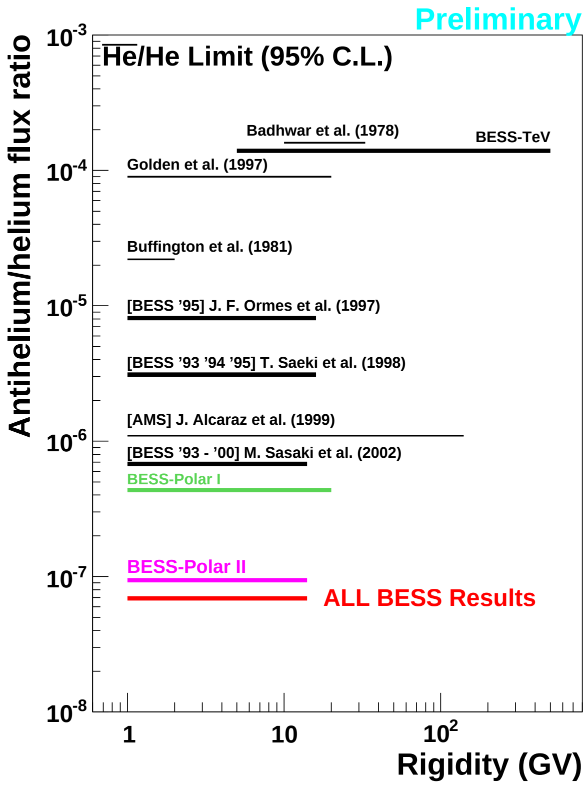

Figure 4: The new upper limit of $\overline{\mathrm{He}}$/He with previous experimental results.([10],[11],[12],[13],[14],[15])

Acknowledgements

The authors thank NASA Headquarters for the continuous encouragement in this U.S.-Japan cooperative project. Sincere thanks are expressed to the NASA Balloon Program Office at GSFC/WFF and CSBF for their experienced support. They also thank ISAS/JAXA and KEK for their continuous support and encouragement. Special thanks go to the National Science Foundation (NSF), U.S.A., and Raytheon Polar Service Company for their professional support in U.S.A. and in Antarctica. The BESS-Polar experiment is being carried out as a Japan-U.S. collaboration, and is supported by a KAKENHI(13001004 and 18104006) in Japan, and by NASA in U.S.A.

References

[1] P. A. M. Dirac, Proc. R. Soc. Lond. A, 1928, **117**: 610-624
[2] C. D. Anderson, Phys. Rev., 1933, **43**: 491-494
[3] O. Chamberlain, E. Segrè, C. Wiegand, and T. Ypsilantis, Phys. Rev., 1955, **100**: 947-950
[4] R. L. Golden *et al.* , Phys. Rev. Lett., 1979, **43**(16): 1196-1199
[5] H. Agakishiev *et al.* , Nature, 2011, **473**: 353-356
[6] M. Sasaki *et al.* , Adv. Space Res. 2008, **42**: 450-454
[7] A. Yamamoto *et al.* , Adv. Space Res. 2002, **30**(5): 1253-1262
[8] S. Haino *et al.* , Phys. Lett. B., 2004, **594**: 35-46
[9] G. J. Feldman, R. D. Cousins, Phys. Rev. D, 1998, **57**: 3873-3889
[10] G. D. Badhwar, R. L. Golden *et al.* , Nature, 1978, **274**: 137-139
[11] R. L. Golden *et al.* , Astrophys. J., 1997, **479**: 992-996
[12] A. Buffington *et al.* , Astrophys. J., 1981, **248**: 1179-1193
[13] J. F. Ormes *et al.* , Astrophys. J., 1997, **482**: 187-190
[14] T. Saeki *et al.* , Phys. Lett. B, 1998, **422**: 319-324
[15] J. Alcaraz *et al.* , Phys. Lett. B., 1999, **461**: 387-396