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Search for cosmic-ray antiproton origins and for cosmological antimatter with BESS

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Abstract

The balloon-borne experiment with a superconducting spectrometer (BESS) has performed cosmic-ray observations as a US–Japan cooperative space science program, and has provided fundamental data on cosmic rays to study elementary particle phenomena in the early Universe. The BESS experiment has measured the energy spectra of cosmic-ray antiprotons to investigate signatures of possible exotic origins such as dark matter candidates or primordial black holes, and searched for heavier antinuclei that might reach Earth from antimatter domains formed in the early Universe. The apex of the BESS program was reached with the Antarctic flight of BESS-Polar II, during the 2007–2008 Austral Summer, that obtained over 4.7 billion cosmic-ray events from 24.5 days of observation. The flight took place at the expected solar minimum, when the sensitivity of the low-energy antiproton measurements to a primary source is greatest. Here, we report the scientific results, focusing on the long-duration flights of BESS-Polar I (2004) and BESS-Polar II (2007–2008).

Keywords: Cosmic rays; Antiproton; Antimatter; Primordial black hole; Solar modulation; Solar BESS

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1. Introduction

Progress in modern observational cosmology and astrophysics has shown that the material Universe is dominated by dark matter responsible for the formation of structure and for the dynamics of galaxies. The nature of the dark components, however, is unknown. Similarly, it is observed that cosmological antimatter is apparently absent in the present era, but the reason for this absence remains as a major problem for cosmology and particle physics. It has been suggested that one constituent of the dark matter may be primordial black holes (Hawking, 1975; Barrau et al., 2002) formed in the early Universe due to the collapse of dense regions formed by density fluctuations. The detection of PBH through antiparticles arising from the Hawking radiation emitted as they evaporate would probe the early Universe at very small scales (Maki et al., 1996). PBH evaporation might be detected by its effect on the measured antiproton spectrum. Addressing these issues are central scientific goals of the BESS program (Yoshimura, 2001; Yamamoto et al., 2008; Mitchell et al., 2009). The precise measurements of the low-energy cosmic-ray antiproton flux and the sensitive search for heavier antinuclei made by the BESS experiment are vital to constraining candidate models for dark matter, evaluating the possible density of primordial black holes, and seeking for the limits of cosmological antimatter. BESS also provides important fundamental data on the spectra of light cosmic-ray elements and isotopes and for studies of the effect of the out-flowing solar wind on the Galactic cosmic rays (Mitchell et al., 2009). The exceptionally large collecting power and precise particle identification capability of the BESS instruments enable a broad scientific reach.

BESS uses a superconducting magnetic-rigidity spectrometer with a time-of-flight (TOF) system and an aerogel Cherenkov counter (ACC) to fully identify incident particles by charge, charge sign, rigidity, and velocity (Ajima et al., 2000; Yoshida et al., 2004). The joint US–Japan BESS program, supported by NASA and ISAS–JAXA, carried out eleven successful balloon flights from 1993 to 2008, nine approximately one-day northern-latitude flights and two long-duration Antarctic flights, as summarized in Table 1. These have collectively recorded about 11,700 cosmic-ray low-energy antiprotons and set the most stringent upper limits to the existence of antihelium and antideuterium. BESS has also provided the reference standard for elemental and isotopic spectra of H and He over more than a full solar cycle. Together with the antiproton measurements, these provide strong constraints on models of cosmic-ray transport in the Galaxy and Solar System.

2. Progress of the BESS and BESS-Polar experiments

The BESS program began as an outgrowth of work toward the Astromag superconducting magnet facility that was planned for the International Space Station, ISS (Ormes, 1986). From the early 1980s, there was tremendous excitement over results from seminal balloon-borne experiments that reported detecting substantial excesses of antiprotons at both high and low energies using magnetic spectrometers or annihilation signature (Buffington et al., 1981). By the mid-1980s, the cosmic-ray community was fully engaged in an effort to measure cosmic ray matter and antimatter to unprecedented precision. During the Astromag study, a number of magnet configurations were proposed. BESS stemmed from a proposal to use a solenoidal superconducting magnet with a coil thin enough for particles to pass through with minimal interaction probability (Yamamoto et al., 1988). This configuration maximizes the opening angle of the instrument, and hence the geometric factor, making it ideal for rare-particle measurements. BESS began as a balloon-borne instrument to validate this concept, and rapidly evolved into an immensely capable scientific program in its own right (Orito, 1987).

The BESS instruments consist of thin superconducting solenoidal magnets and high-resolution detector systems. For energies between about 0.1 GeV and 4 GeV, referenced to the top of the atmosphere (TOA), the BESS instruments accurately identify incident particles by directly measuring their charge, charge-sign, magnetic rigidity, and velocity.

Table 1
Progress of the BESS and BESS-Polar balloon flights and observations.

	1993	1994	1995	1997	1998	1999	2000	2001	2002	2004	2007
Location	Canada	≫	≫	≫	≫	≫	≫	US	C.	Ant.	Ant.
Float time (h)	17.5	17	19.5	20.5	22.0	34.5	44.5	1.0	16.5	205	730
Observation time, float (h)	14	15	17.5	18.3	20.0	31.3	32.5	1	11.3	180	588
Observation time, asc./des. (h)						2.8	2.5	12.8	2.3	3.3	3.5
Recorded events ($\times 10^6$)	4.0	4.2	4.5	16.2	19.0	19.1	17.0	N/A	13.7	900	4700
Data volume (GB)	4.5	6.5	8.0	31	38	41	38	N/A	56	2,140	13,500
Event filtering	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Magnetic field (T)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.8	0.8
MDR (GV)	200	200	200	200	200	200	200	1,400	1,400	240	270
TOF resolution (ps)	300	300	100	75	75	75	75	75	75	160	120
ACC index	–	–	–	1.03	1.02	1.02	1.02	1.02	1.02	1.02	1.03
Antiproton events observed	6	2	43	415	384	668	558	N/A	147	1520	~8000
Antiproton's energy (GeV)	<0.5	<0.5	<3.6	<3.6	<3.6	<3.6	<4.2	N/A	<4.2	<4.2	<3.5
Anti-He/He upper limit ($\times 10^{-6}$)	22	4.3	2.4	1.4	1.0	0.8	0.68	N/A	0.65	0.27	0.07