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BESS-Polar experiment: Progress and future prospects

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Abstract

The first scientific flight of the BESS-Polar balloon-borne experiment was successfully carried out in December 2004 from Antarctica with the primary scientific objectives of searching for primordial antiparticles from the universe and making precision measurements of primary cosmic-ray fluxes. During the 8.5 day flight, the newly developed BESS-Polar spectrometer worked well and gathered data from 9×10^8 cosmic-ray events, showing its capability for making long-duration science observations. We have already started hardware development for the second experiment, which is expected to be a flight of more than 20 days during the next solar minimum period with the upgraded spectrometer. In this manuscript, progress on and prospects for the BESS-Polar experiment are described.

Keywords: Superconducting spectrometer; BESS; Long-duration balloon flight; Antarctica

1. Introduction

Flights of the Balloon-borne experiment with a superconducting spectrometer (BESS) have been carried out since 1993. Its scientific objective is to investigate elementary particle phenomena in the early universe and to study the origin and propagation of galactic and atmospheric cosmic-rays, through precise measurements of various cosmic-rays species, especially very rare antiparticle components such as antiprotons, antideuterons, and antihelium. After nine successive science flights in North America from 1993 to 2002, the second phase of the BESS experiment was proposed and prepared as a long-duration balloon flight over Antarctica (BESS-Polar) (Yamamoto et al., 2001, 2002, 2003; Yoshida et al., 2003, 2004).

For the BESS-Polar experiment, most of the detectors were newly developed to meet the difficult requirements

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for a long-duration Antarctic balloon flight while keeping the primary advantages of previous BESS detectors, e.g., large geometrical acceptance, precise rigidity measurement and redundant particle identification. Preparations for BESS-Polar started in 2001 and the payload was constructed as illustrated in Fig. 1 in a two year period. A detailed description of the detectors was presented elsewhere (Nozaki, 2004). Here we describe the main features of BESS-Polar in comparison with the previous BESS detectors as summarized in Table 1.

1.1. New magnet and detector system

For the previous BESS, a pressure vessel was used to keep the whole detector system at ground atmospheric pressure. To reduce both weight and material traversed for the detected particles, we eliminated the pressure vessel for BESS-Polar and in flight all detectors except the three gas chambers were located in a near vacuum and cold environment. Accordingly, new photomultiplier tubes (PMTs) and high voltages for a time of flight scintillator hodoscope (TOF) and an aerogel Cherenkov counter (ACC) were developed to be operated in this environment (Hams et al., 2005).

A new ultra-thin superconducting magnet was developed for the longer duration flight of ~10 days (Makida et al., 2005). Its material thickness was reduced to 2 g/cm^2 by employing new high-strength superconductor with an aluminum stabilizer which has been developed using micro alloying nickel and cold-work hardening. The thickness of the TOF was also changed from 20 to 10 mm to decrease material at the expense of a tolerable degradation of timing resolution (50–85 ps). Total thickness of the detector wall was reduced from 18 to 9 g/cm^2, which reduced the minimum antiproton detectable energy from 0.18 to 0.15 GeV. Further, to detect low energy antiprotons that cannot penetrate all the detectors, we added a middle time of flight hodoscope (MTOF) between the jet-type central tracking chamber (JET) and the magnet wall. By using the MTOF for triggering, the minimum detectable energy range was extended down to 0.1 GeV.

1.2. Solar-cell power supply system

Since the primary lithium battery with 200 kg can only sustain a few-day flight, a solar-cell power system was necessary for long-duration flights. We used commercially available solar-cells (NT3436BD, Sharp) and arranged them in an omni-directional octagonal shape for reliable operation without pointing control. The maximum generated power was 1200 W and the total weight of the solar power system is ~300 kg.

Table 1
Main parameters of the BESS and BESS-Polar spectrometers

	BESS-2000	BESS-Polar
Geometrical acceptance	0.3 m^2 sr	0.3 m^2 s
Science flight time	1 day	~10 days
Central magnetic field	1.0 T	0.8 T
Diameter of central tracker	0.83 m	0.76 m
Tracker spatial resolution	160 μm (Ar–CO_2)	130 μm (CO_2)
TOF time resolution	50 ps ($t = 20$ mm)	85 ps ($t = 10$ mm)
Life for liquid He	5 days	>11 days
Weight of the payload	2400 kg	1950 kg
Power consumption	900 W	600 W → 420 W
Power supply system	Li primary battery	Solar battery
Minimum material for trigger	18 g/cm^2	4.5 g/cm^2
Detectable energy range	0.18–4.2 GeV	0.1–4.2 GeV
Maximum detectable rigidity	200 GeV	210 GeV

1.3. Data acquisition system

Maximum power consumption for the electronics was restricted to be 600 W, taking into account the efficiency of DC–DC converters and the safety margin of solar power. A fast data acquisition rate was also required to minimize trigger selection on board and to reduce dead time. We developed new readout electronics to reduce power consumption and to increase data throughput and capacity. This includes a low-power flash analog to digital converter (FADC) system for the chambers and a low-power charge to digital converter (QDC) and time to digital converter (TDC) for the TOF, ACC and MTOF. Event data were gathered concurrently into an event builder through a USB2 serial bus by an FPGA or DSP resident on each board. Data was recorded into an array of hard disks with a total capacity of 4 TB. Total power consumption was reduced from 900 to 420 W (Yamato et al., 2002; Sasaki et al., 2005).

2. Experiment – BESS-Polar I

After integration and pre-deployment tests of the BESS-Polar payload at NASA Goddard Space Flight Center (GSFC) and Columbia Scientific Balloon Facility (CSBF),

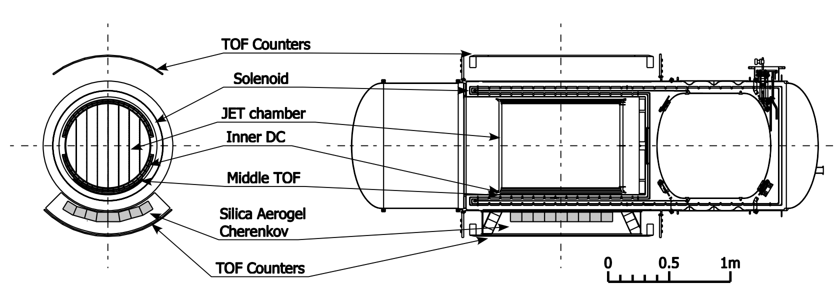

Fig. 1. The BESS-Polar spectrometer as it was in the first flight 2004.

the first BESS-Polar flight (BESS-Polar I) was successfully carried out in December 2004 in Antarctica. The payload was launched from the McMurdo station on December 13 and after more than 8 days of level flight it was landed at the south end of the Ross Ice Shelf on December 21 (Figs. 2 and 3). The whole instrument was recovered without anything left on the ice after 7 days of recovery work (Yoshida et al., 2005). During the flight, all of the detectors worked well except for several minor problems as follows:

2.1. PMT performance for TOF

Some of PMTs for TOF showed high voltage leakage in the cold and vacuum environment. This was found to be due to imperfections in the potted seal. As a result, high voltage of the PMTs had to be reduced or turned off inducing a 40% reduction of the acceptance. In addition, timing resolution was degraded for some of the counters because we needed to operate them with single-ended read out.

2.2. ACC performance

The ACC is used to enhance the rejection power against background for antiproton measurements. The performance was not as expected from the previous BESS flights. We collected less light output and resolution was degraded for two main reasons: (1) we used smaller aerogel blocks which resulted in a larger fraction of gap and wrap between them; (2) available space for the ACC counter was too restricted to optimize the counter geometry and PMT orientations along the magnetic field.

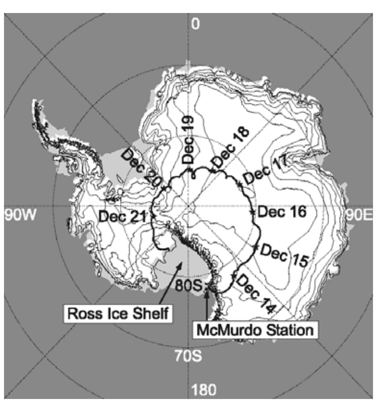

Fig. 2. Flight trajectory of BESS-Polar 2004 experiment.

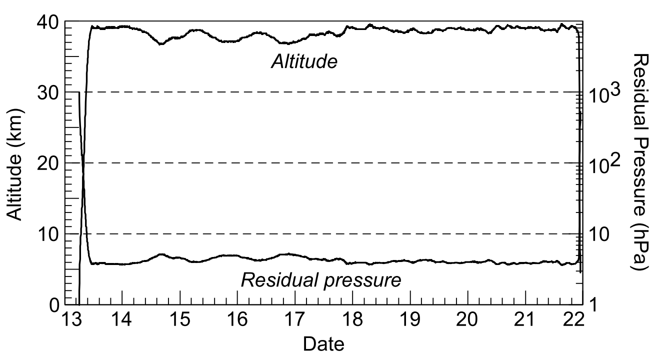

Fig. 3. Altitude and residual atmospheric pressure during the BESS-Polar flight.

2.3. Position resolution along axial direction

Resolution of axial position measurements with JET, was not as good as the previous flights. This is mainly due to noise induced by the DC–DC converters. As a result, some fraction of the data needed to be eliminated due to inconsistency between JET and TOF measurements.

2.4. Summary of results

More than 900 M events were gathered during the 8.5-day duration of the flight. Total statistics reached about 4 times as large as the previous one-day flight, which is consistent if we take into account inefficiency due to the above problems. Data analysis has been progressing. By using the newly developed MTOF counters, we have extended the antiproton identification range from 0.15 to 0.1 GeV. In the low-energy range between 0.1 and 1.28 GeV, 432 antiprotons were clearly identified and the antiproton flux was obtained. We have completed the antihelium search. Combined with the previous BESS data, we have placed a stringent upper limit on the antihelium/helium flux ratio, 2.7×10^{-7} (95% C.L.), which corresponds to a 100-fold improvement compared with the results before the BESS experiment. Preliminary results were presented in other articles in this proceedings (Yamamoto et al., 2007; Sasaki et al., 2007).

3. Future prospect – BESS-Polar II

The flight of the BESS-Polar I experiment was successfully completed, showing that a long-duration science observation is really feasible with BESS-Polar payloads. The second BESS-Polar flight (BESS-Polar II) is scheduled in 2007–2008 to measure the low-energy antiproton flux in the solar-minimum period with five times more statistics than the first BESS-Polar flight.

Repair, upgrades, redesign and construction of the new payload had already started in 2004. A beam test was performed at the KEK Proton Synchrotron test beam facility in 2005, aiming to improve performance of the particle ID devices; i.e., the TOF, MTOF, and ACC, as well as to check their post-flight performances.

Based on the feedback from data analysis of the first flight and on the beam test, most of the detector components have been upgraded to achieve better performances. Fig. 4 shows comparison of the BESS-Polar I and BESS-Polar II payloads. The main differences in general appearance are their length and height; the increase in length corresponds to the longer magnet cryostat and the decrease in height is achieved by optimizing the solar-cell rearrangement.

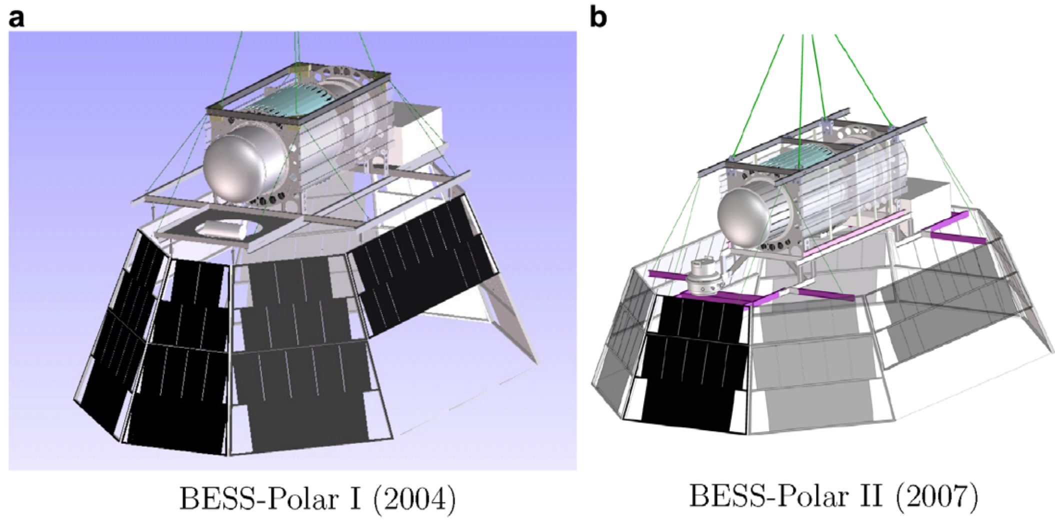

Fig. 4. Comparison of BESS-Polar I and BESS-Polar II configuration.

Individual improvements are listed as follows:

3.1. Magnet

A new superconducting magnet was constructed for the BESS-Polar II flight. The main improvement is its longer cryogen life up to 23 days, which is enough for more than 20 days flight (Fig. 5). The longer life is achieved by installing a larger He reservoir tank with a 520 ℓ capacity and an additional layer of radiation shield to improve the dewar's thermal insulation.

3.2. TOF

To protect the PMTs, a hermetic aluminum case has been developed to replace potting used in BESS-Polar I. The basic technique was adopted from the ACC PMT which was successfully operated in the BESS-Polar I flight. Fig. 6 shows a newly designed TOF PMT with a hermetic aluminum shell. The thickness of scintillator was also changed from 10 to 12.7 mm to compromise between material thickness, weight and performance.

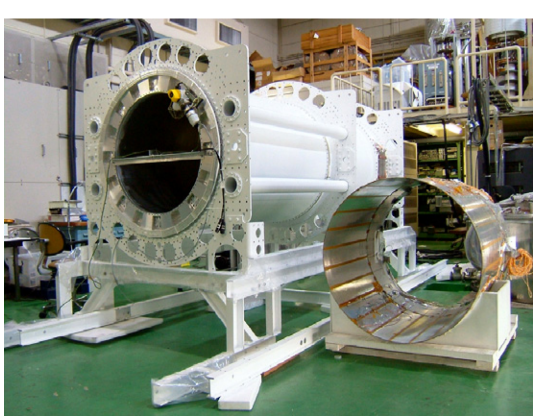

Fig. 5. New superconducting magnet for BESS-Polar II.

Fig. 6. TOF PMT with an aluminum hermetic housing.

3.3. New ACC counters

Design of ACC counter has been reviewed thoroughly based on the result from the flight and the beam tests. We have optimized various parameters, e.g., height, PMT angle, and size of blocks etc., using a Monte-Carlo simulation built with GEANT4 (http://geant4.cern.ch). We have finally employed new larger-sized aerogel blocks ($190 \times 280 \times 20$ mm^3) with refractive index of 1.03. (note that blocks with $100 \times 100 \times 10$ mm^3 were only available for the previous counter). Fig. 7 shows a tower made up from four tapered blocks wrapped with polyethylene film.

3.4. MTOF

The previous MTOF was only equipped with a single-ended readout, and consequently its performance was degraded according to axial position from the PMT end.

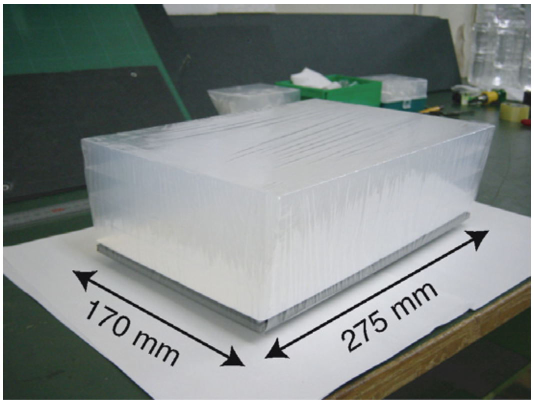

Fig. 7. Aerogel tower of four blocks wrapped with polyethylene film.

Fig. 8. Layout of MTOF with both-end readout using fiber-bundled light guide.

Both-end read out has been realized for the new MTOF system by employing clear fiber-bundled light guides as shown in Fig. 8. The new system enables axial position measurements by using timing and amplitude differences of both ends, in addition to improvement of performance and efficiency.

3.5. Data acquisition and storage

The data acquisition system has been upgraded to deal with the higher data rate and larger size in accordance with the higher event rate in a solar minimum period and a longer duration flight. FADC performance has been improved by changing the read out configuration, i.e., with a triple USB2 line. Capacity of data storage has been increased to 12 TB by using larger hard disk drives (from 350 GB to 1 TB).

Table 2 summarizes detector improvements and specifications in comparison with BESS-Polar I.

After the development and fabrication of the individual detector components, integration will start at NASA/GSFC in early 2007. The payload is scheduled to be launched in Antarctica in the December 2007.

Table 2
BESS-Polar II specifications as compared with BESS-Polar I

	BESS-Polar I	BESS-Polar II
Magnet cryogen life	~11 days	>22 days
Track detector (JET) gas quality	~10 days	>20 days
TOF-PMT housing	Resin potting	Pressurized housing
ACC particle ID	Rejection ~630	$\gg$1000
Solar-power gen.	4 stage 900 W	3 stage 700 W
Effective acceptance	0.1 m^2sr	0.3 m^2sr
Observation time	8.5 days	>20 days
Statistics	4 × BESS97	20 × BESS97
Data storage (recorded)	3.6 TB (2.14 TB)	12 TB

Meanwhile, PAMELA, a satellite mission launched in June of 2006, will observe various species of cosmic-ray radiation for several years. AMS, a payload built for operating on the ISS, has been waiting for a launch opportunity. They both are equipped with very sophisticated instruments for longer observation periods. Nonetheless, BESS-Polar II has still advantages over them, i.e., flight only in high geomagnetic latitude and 20 days steady state observation at solar minimum period. Thus BESS-Polar II is competitive and may provide unique science results especially in the very low energy range. These three experiments will be complementary in their ability to uncover low energy cosmic-ray phenomena and the results are crucial to understanding of cosmic-ray physics.

4. Summary

The BESS project has been successfully carried out experiments for long years, blessed with excellent flight opportunities. By taking full advantage of balloon payloads, the detectors have been upgraded year by year, and correspondingly data has been continuously improved both in quantity and quality. The BESS-Polar I experiment, among them, was the biggest step. Most of the components were newly redesigned and fabricated while keeping key features of BESS. After proof of the long duration science observation in the BESS-Polar I, we have been further upgrading the detector components for BESS-Polar II to realize an ultimate measurement for antiparticles from early universe at next solar minimum. We will expect to have the flight December 2007, at the end of the solar minimum period.

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