

## BESS-polar experiment

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Received 19 October 2002; received in revised form 28 April 2003; accepted 2 May 2003

### Abstract

In order to investigate elementary particle phenomena in the early Universe, the BESS-polar experiment is proposed. It will study low-energy antiprotons and search for antinuclei in the galactic cosmic rays at the constant altitude maintained by a scientific balloon. A new superconducting spectrometer is being developed for long-duration balloon flights. In order to extend the detectable energy range of antiprotons down to 100 MeV, the thickness of materials along the trajectory of the incident particle is minimized. The spectrometer will be completed in 2003, and the first long-duration flight is planned in 2004.

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**Keywords:** Scientific ballooning; BESS-polar experiment; Superconducting spectrometer; Low-energy antiprotons

### 1. Introduction

The balloon-borne experiment with a superconducting spectrometer (BESS) has now been conducted for 10 years. Before this, observations of anomalous excess of antiproton flux (Bogomolov et al., 1979; Golden et al., 1979; Buffington et al., 1981), as compared to predictions made by secondary production models, had already suggested the existence of novel processes of antiproton production. To search for low-energy antiprotons of cosmic origin, BESS was proposed in 1987 (Orito, 1987), and begun in 1993.

Since then, by 2000, seven successful flights have been carried out at Lynn Lake, Canada. More than 2000

antiprotons have definitely been identified in a kinetic energy range between 150 MeV and 4.2 GeV (Yoshimura et al., 1995; Moiseev et al., 1997; Matsunaga et al., 1998; Orito et al., 2000; Maeno et al., 2001; Asaoka et al., 2002). As shown in Fig. 1, a characteristic peak of the antiproton spectrum around 2 GeV has clearly been measured. The results show that the cosmic antiprotons are predominantly produced by collisions of high-energy primary cosmic rays with interstellar gas. They also show that propagation models in the galaxy are basically consistent. However, the spectrum below 1 GeV in the solar-minimum period seems to be softer than that predicted by the secondary production models. Although we still have insufficient statistics, and propagation models are very uncertain, we cannot rule out the possible existence of some exotic processes of antiproton production, such as evaporation of primordial black

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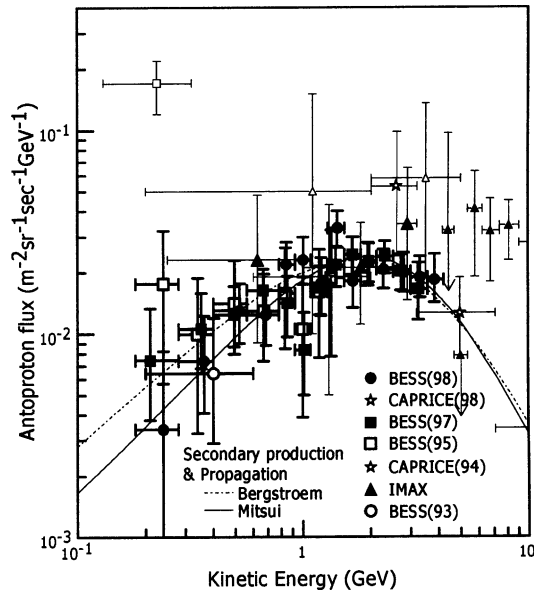


Fig. 1. Cosmic-ray antiproton spectra measured by BESS and other experiments.

holes (Turner, 1982; Maki et al., 1996) or annihilation of supersymmetric dark matter (Stecker et al., 1985; Bergström et al., 1999) in the Universe.

The flux of the primary antiprotons, if they exist in the cosmic radiation, should be strongly affected by solar modulation (Mitsui et al., 1996), because models of primary antiproton production predicted flat spectra in the low energy region. Thus, it is very important to estimate solar modulation effects on the low-energy antiprotons. Charge-dependent solar modulation effects have been pointed out (Bieber et al., 1999), predicting that positive and negative charged particles should be affected differently. Such effects have been studied by comparing the effects of modulation on protons and on electrons. Recent BESS results confirm the charge dependence using high statistical samples of protons and antiprotons (Asaoka et al., 2002).

Various searches for cosmic antimatter have been conducted in order to investigate matter/antimatter asymmetry in the Universe. The attempt to detect the boundary between matter and antimatter domains by observing  $\gamma$ -rays requires many assumptions. Direct observation of potential antimatter in the cosmic radiation, such as that attempted by BESS, requires fewer assumptions. Even if BESS detects only a single instance of antimatter, the existence of antimatter domains can be proved. In the BESS flights, no antihelium candidate was found (Ormes et al., 1997; Saeki et al., 1998; Sasaki et al., 2001). Sasaki et al. (2001) placed an upper limit on a ratio of antihelium to helium nuclei of  $6.8 \times 10^{-7}$  (95% C.L.) in a rigidity range between 1 and 14 GV, which is the most stringent upper limit ever achieved (Fig. 2). Since uncertainties in the models of cosmic-ray propagation between galaxies are very large, we cannot rule

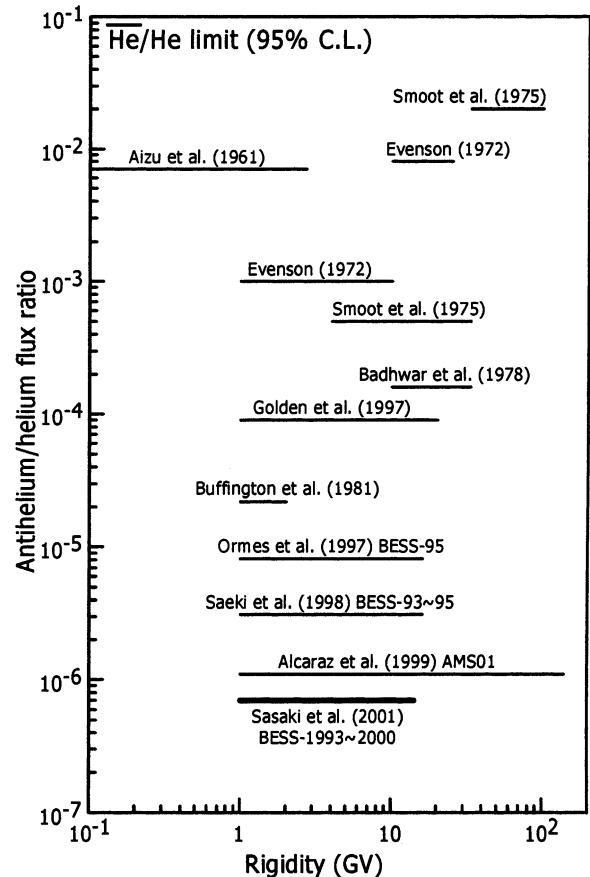


Fig. 2. Upper limits on the ratio of antihelium to helium nuclei.

out the existence of antimatter domains in the Universe merely from this null result. But this result is the most direct evidence that our galaxy and its nearby neighbors consist of matter.

Based on these results from the BESS experiments so far, we are preparing a new balloon-borne experiment to carry out further study of low energy antiprotons (Yamamoto et al., 2001; Yamamoto et al., 2002a). The primary purpose of this “BESS-polar” experiment is to probe the early Universe by searching intensively for antiprotons of cosmic origin. Since the flux of primary antiprotons is strongly suppressed by the solar wind, we must estimate the effect of solar modulation precisely. High precision measurement enables us to search for cosmic antiprotons with very high sensitivity, and the precise antiproton spectrum observed will provide basic data to check propagation models, and to study solar modulation processes.

## 2. BESS-polar spectrometer

As shown in Fig. 3, the design concept of the BESS-polar spectrometer is basically the same as that of the current BESS spectrometer (Ajima et al., 2000; Shikaze

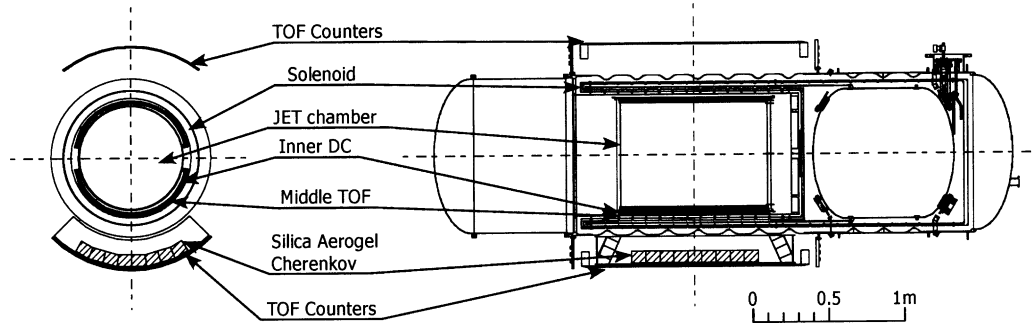


Fig. 3. Cross-sectional view of the BESS-polar spectrometer.

et al., 2000; Asaoka et al., 1998). A thin superconducting solenoid provides a strong magnetic field of 0.8 T. A tracking system, consisting of a jet-type drift chamber (JET) and two cell-type drift chambers (Inner DC), measures the curvature of the trajectory of the incident particle. At the top and the bottom of the spectrometer, time-of-flight (TOF) plastic scintillator paddles will be mounted to measure the velocity and the energy deposit of the incident particle. A silica-aerogel Čerenkov counter will also be installed as a redundant particle identifier.

We have to reduce the weight of the payload to meet the requirements of long duration flights over Antarctica, and must also reduce material thickness in the payload, in order to measure antiprotons at the lowest possible energy. In order to reduce weight and material thickness there will be no pressure vessel outside the detector, so that photomultipliers and high voltage supplies can work in vacuum. The silica-aerogel Čerenkov counter will be placed beneath the magnet, in order to reduce the thickness of materials in the upper half of the spectrometer, since the counter is used to identify antiprotons in the high energy region. To maintain high trigger efficiencies for very low energy particles, an additional trigger scintillation counter system (Middle-TOF) is installed inside the magnet bore. Comparisons between the BESS and the BESS-polar spectrometer are given in Table 1.

In order to study very low energy antiprotons down to 100 MeV through long duration flights, it is necessary to minimize material thickness along the trajectory of the incident particles. To meet this challenge, we have developed an ultra-thin superconducting solenoid.

It has also been essential to develop a new power supply system to enable long duration flights.

### 2.1. Ultra-thin superconducting solenoid

The key technology necessary to realize an ultra-thin superconducting solenoid is the development of high strength superconductor (Yamamoto et al., 1999). Recently, a new aluminum stabilizer has been developed using micro alloying of 0.5% nickel followed by cold-

Table 1

Comparison between the BESS and the BESS-polar spectrometer

	BESS	BESS-polar
Acceptance (m <sup>2</sup> str)	0.3	0.3
Magnetic field (T)	1.0	0.8
Superconducting coil diameter (m)	1.0	0.9
Cryogen life (days)	5.5	20
JET/IDC diameter (m)	0.83	0.76
Weight (kg)	2400	1500
Power source	Primary batteries	Solar cells
Minimum thickness for trigger generation (g/cm <sup>2</sup> )	18	4.5
Detectable antiproton energy (GeV)	0.18–4.2	0.1–4.2
MDR (GV)	200	150

work hardening. Fig. 4 shows a scanning electron microscope (SEM) image of the cross-section of the aluminum stabilizer (Wada et al., 2000). In the superconductor's aluminum stabilizer, the pure aluminum domain acts as a conductor, and the aluminum–nickel composite domain acts as reinforcement. When the current BESS solenoid was manufactured in 1986, the yield strength of this type of superconductor was around 100 MPa, but now, as shown in Fig. 5, overall yield

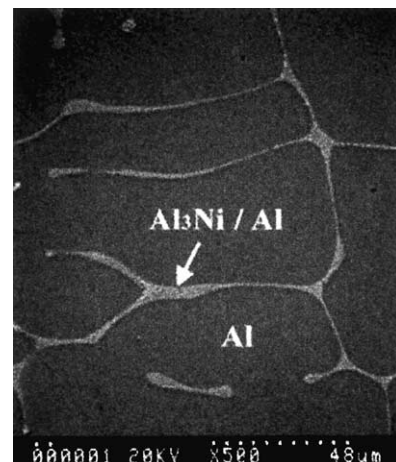


Fig. 4. SEM image of high strength aluminum-nickel alloy.

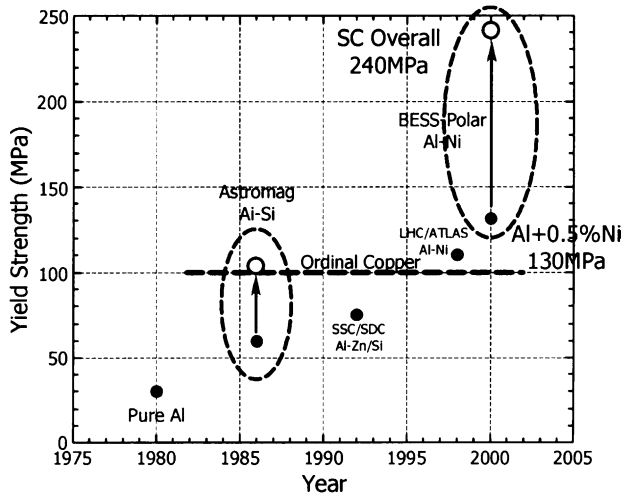


Fig. 5. History of the development of high strength aluminum-stabilized superconductor.

strength of up to 240 MPa can be reached by adopting a high strength aluminum stabilizer.

The equivalent stress of the two-layer solenoid (Fig. 6) calculated as 174 MPa at 1.2 T is well below the yield strength of the high strength superconductor, so we could eliminate the thick structural cylinder from the solenoid which is traditionally required to give it sufficient mechanical strength. Thus the solenoid’s material was reduced down to 1.0 g/cm<sup>2</sup> and the total thickness of the magnet, including cryostat, will be about 2.0 g/cm<sup>2</sup> (Yamamoto et al., 2002b).

The superconducting solenoidal coil itself has already been wound, and successfully tested up to 1.05 T, and is presently being assembled into its cryostat. In the new cryostat, a large reservoir tank for 400 L of liquid helium will also be incorporated, enabling the magnet to operate for 20 days.

2.2. Solar-cell power supply system

To supply electric power to the electronics onboard the payload, a new power supply system using solar cells

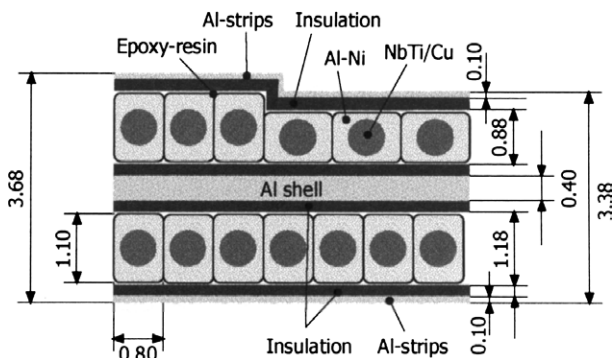


Fig. 6. Cross-section of the superconducting solenoid.

is also being developed. The power consumption of the BESS-polar payload is estimated to be around 600 W, so taking into account inefficiencies of the DC–DC converters, losses in cables, and so on, solar cells should provide about 900 W continuously. In order to limit the total weight of the payload less than 1500 kg, the weight of the power supply system should be less than 300 kg.

We have designed an omni-directional solar-cell array-structure, as shown in Fig. 7, to achieve the high reliability of power production. Each side is designed to have the same area so that no orientation control is required. Moreover, it is not presently planned to use a re-chargeable battery system, in order to realize the simplest system. Table 2 summarizes the specifications of the Sharp NT3436BD solar-cell module (Sharp Corp., 1991), which will be used because of its high efficiency, inclusion of a bypass diode, and its light weight.

The solar-cell array-structure needed to produce 900 W becomes quite large. In order to confirm the mechanical strength of the structure of the array, and also

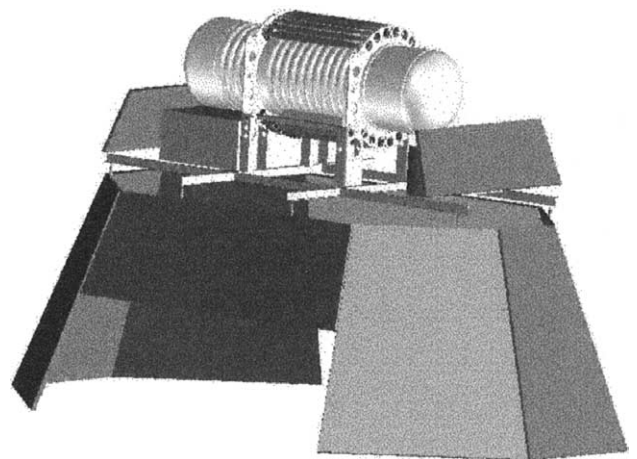


Fig. 7. Conceptual design of solar-cell array-structure for the BESS-polar experiment.

Table 2  
Specifications of the sharp NT3436BD solar-cell module, under the conditions of 1000 W/m<sup>2</sup> direct normal irradiance and 25 °C cell temperature

Cell	Multi-crystal silicon solar cells, 97.5 × 75 mm
No. of cells and connection	36 in series
Dimensions	703 × 399 × 1.5 mm
Weight	660 g
Electro-optical characteristics	Typical
Open circuit voltage (V)	22.1
Maximum power voltage (V)	17.8
Short circuit current (A)	2.70
Maximum power current (A)	2.53
Maximum power (W)	45.0
Encapsulated solar cell efficiency (%)	17.1
Module efficiency (%)	16.0

to justify the simulation results of temperature and power generation during flight, a technical flight was performed at the Sanriku Balloon Center in Japan in May 2002.

The total weight of the payload (Fig. 8) was about 380 kg including the house-keeping system, which monitored temperatures of the panels, output voltages and currents, and solar inputs.

During the flight, the solar-cell array-structure was monitored by a video camera installed at the lower end of the parachute. Appropriate performance was found on launching and termination. House keeping data were transmitted to the ground by the telemetry system and were analyzed to check consistency between data and simulation results. In Fig. 9, dots indicate the temperature on the panel structure measured during the flight. Two envelopes show the simulated maximum and minimum temperatures on the entire structure. In Fig. 10, dots and circles indicate measured and simulated output voltages, respectively, of the solar-cell array. Both figures show close agreement between measured and simulated results, and it was concluded that our basic design of the solar cell power supply system was suitable for the purpose.

### 2.3. Particle detectors

Particle detectors are also being developed. Construction of drift chambers for tracking incident particles has already been completed. These chambers had already been installed into the conventional BESS payload, and were carried on a scientific flight in the summer of 2002. The expected spatial resolution below 200  $\mu\text{m}$  was confirmed by data taken during the flight. Since the flow of the drift gas should be maintained, during the BESS-polar flights, in order to maintain its purity without a complex gas mixing system, the system has to

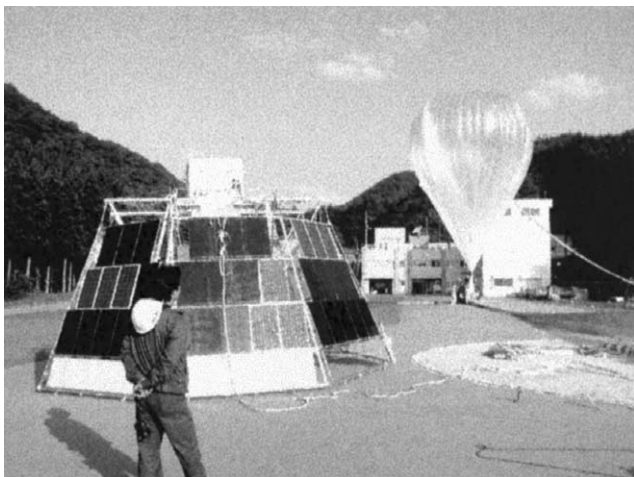


Fig. 8. Dummy structure for the Sanriku technical flight.

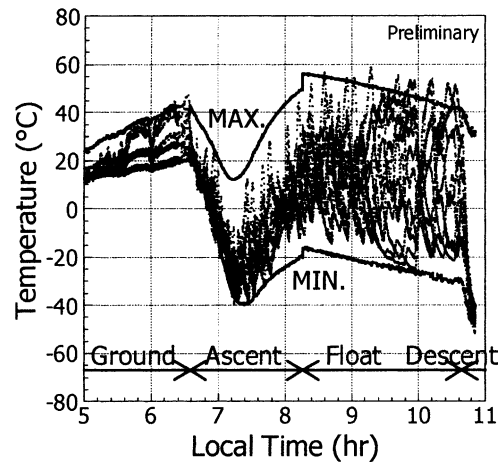


Fig. 9. Temperatures on the solar-cell array panels during the Sanriku technical flight. Maximum and minimum lines are calculated from measured irradiances, air temperature, etc.

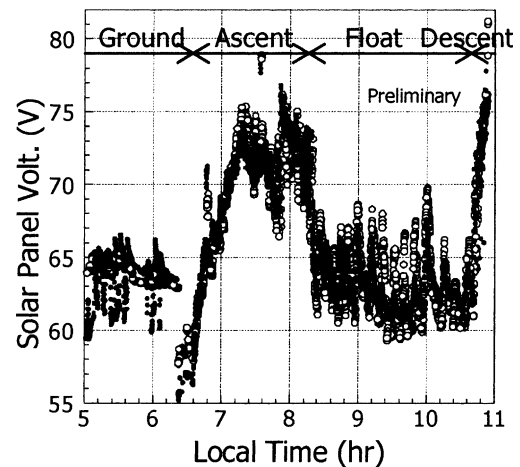


Fig. 10. Measured and calculated output voltage of the solar-cell arrays.

be operated under pure  $\text{CO}_2$  gas instead of the mixture of  $\text{CO}_2$  and argon used in the BESS experiment. An operational test using pure  $\text{CO}_2$  was successfully performed, and the gas flow control system is presently under development.

The time-of-flight scintillation counter system was designed with 10 and 12 scintillator paddles installed at the top and the bottom, respectively, of the spectrometer. Each paddle has a dimension of approximately  $100^{\text{W}} \times 950^{\text{L}} \times 10^{\text{t}}$  mm. To reduce material along the trajectory of the incident particle, thinner scintillation paddles than those of the BESS detector are used. On both ends of each paddle, Hamamatsu R6504 2.5-in. fine-mesh photomultipliers will be mounted. A time-of-flight resolution of 100 ps is expected.

A Čerenkov radiator consisting of silica aerogel blocks is being produced by Matsushita Electric Works. The refractive index of the block is 1.020, so antiprotons

up to 4 GeV will be distinguished from the enormous electron background. Čerenkov light will be collected by R6504 photomultipliers.

Production of the photomultipliers for the time-of-flight counters and the aerogel Čerenkov counter is already finished. The high voltage supply modules are in production.

A new Middle-TOF counter system consisting of 64 rods of plastic scintillator will be installed inside the bore of the solenoid. Each rod has a cross-section of  $5 \times 10$  mm and a length of 1 m. The light emitted will be transferred to newly developed 2.5-in. fine-mesh 8-anode photomultipliers (Hamamatsu R6504MODX-M8) through bundles of clear plastic fibers. The Middle-TOF counters will generate trigger signals for low energy particles which cannot penetrate the lower half of the magnet. Time-of-flight information will also be provided. A time resolution around 500 ps will be obtained, which is enough to distinguish antiprotons below 150 MeV from the background.

Low-power electronics for the photomultipliers, based on the ACE electronics, are now being developed (Yamato et al., 2002). On each front-end module, in order to reduce dead-time in the data acquisition system, an onboard data signal processor (DSP) will be installed for parallel processing. A low power flash ADC system now being developed will read the signals from the drift chambers. Signals over 500 channels will be digitized at 40 MHz. Data from the front-end will be transferred to the event-building system via USB 2.0 serial connections.

The event-building system consists of an online event-reduction subsystem and a storage subsystem. Though we intend to carry onboard a large storage system of up to several terabytes, in the form of a hard disk drive complex, strong online event reduction will be required in order to reduce the quantity of event data. A new online event reduction system is now being developed, based on the Hitachi SH4 CPU and the Linux operation system.

The house-keeping system is being developed on an Echelon Lon Works platform. The Lon Works network consists of modules of Neuron integrated circuits dis-

tributed over the payload. They communicate with each other by a message-based protocol called LonTalks. Each Neuron integrated circuit will control one of the command interpretations, telemetry coding, environment monitoring, and so on.

### 3. Comparison with other space experiments

Two other space-based experiments are being developed to investigate similar objectives in physics. One is the Alpha Magnet Spectrometer (AMS) and the other is a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA). Table 3 summarizes a comparison between BESS-polar, PAMELA and AMS. PAMELA is a compact detector for a polar-orbital satellite. The polar-orbital satellite passes the area of very low rigidity cut-off, so that it can cover down to 80 MeV antiprotons (Adriani et al., 1995). AMS has a large exposure factor and a strong particle identification capability (Ahlen et al., 1994). It can provide very precise cosmic-ray measurements above several hundred MeV. PAMELA will be launched in 2003 by a Russian rocket for 3 years observation and AMS will be launched by the space shuttle in October 2005 and will stay at the International Space Station for 3 years.

Fig. 11 shows relative sensitivities for the antiprotons of three experiments as a function of kinetic energy. “Sensitivity” is defined as a combination of the following: a product of the exposure factor; observation time; and efficiency in staying at the cut-off rigidity region where antiprotons of specific kinetic energy can be observed. Long Duration Ballooning at high latitude is ideal for low energy antiproton measurements since such LDB flights remain at the lowest cutoff rigidity region.

Between 300 MeV and 4 GeV, the energy range of BESS-polar and AMS overlap, and PAMELA will cover the overall energy range, so in the near future we will have a very precise measurement of the spectrum of the cosmic-ray antiprotons provided by three independent and complementary experiments.

Table 3  
Comparison between PAMELA, BESS-polar and AMS

Project	PAMELA	BESS-polar	AMS02
Flight vehicle	Satellite	LDB	ISS
Flight duration	3 years	10–20 days	3–5 years
Altitude	300–600 km	37 km ( $5 \text{ g/cm}^2$ )	320–390 km
Orbit	$70.4^\circ$	$>70^\circ\text{S Lat.}$	$51.7^\circ$
Acceptance	$0.0021 \text{ m}^2 \text{ str}$	$0.3 \text{ m}^2 \text{ str}$	$0.3 \text{ m}^2 \text{ str}$
MDR(GV)	740	150	$\sim 1000$
Particle identification	TOF/TRD/CAL	TOF/ACC	TOF/TRD/RICH/CAL
Number of helium	$4 \times 10^7$	$(1-2) \times 10^7$	$2 \times 10^9$
Launch	2003	2004	October 2005

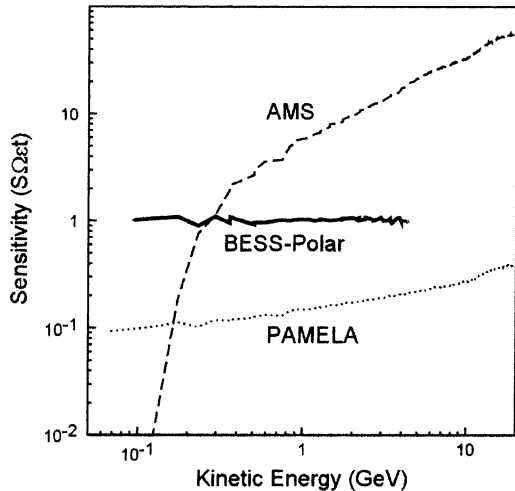


Fig. 11. Relative sensitivities for low energy antiprotons.

#### 4. Flight plan

All components of the BESS-polar spectrometer are expected to be ready by March, 2003. Assembly of the spectrometer will then take 3 months in KEK, Japan, and will be completed by June, 2003. It is planned to have a technical flight at Fort Sumner, New Mexico, USA, in autumn 2003.

Though we expect to carry out the first long-duration flight in 2004, it is not clear that this can be in Antarctica. We are therefore considering an alternative option: a long-duration flight in the northern hemisphere. If the balloon flies from Fairbanks, Alaska, additional primary batteries would have to be carried in order to provide sufficient power during the nights. A larger solar-cell array might be required for a flight in lower latitude than Antarctica.

In the 2006/2007 Antarctic summer, when solar activity will become minimum, we are eager to conduct a second long-duration flight over Antarctica in order to optimize the search for the existence of antiprotons of cosmic origin.

#### 5. Summary

The BESS was carried out to investigate elementary particle phenomena in the early Universe. In seven successful flights from 1993 to 2000, 2000 low-energy antiprotons were definitively identified in a kinetic energy range between 150 MeV and 4.2 GeV. A characteristic peak of the antiproton spectrum around 2 GeV was clearly measured. This result shows that the cosmic antiprotons are predominantly produced by collisions of high-energy primary cosmic-rays with interstellar gas. The spectrum below 1 GeV, however, seems to be softer than that predicted by secondary production models.

We still cannot rule out the possible existence of some novel processes of antiproton production, such as evaporation of primordial black holes, or annihilation of supersymmetric dark matter in the Universe. For antinuclei searches, an upper limit of  $6.8 \times 10^{-7}$  has been placed on the ratio of antihelium nuclei to helium nuclei.

For extended studies of low-energy antiprotons and extensive searches for antinuclei in cosmic rays, the BESS-polar experiment has been proposed. In order to extend the detectable energy range of antiprotons down to 100 MeV at the top of the atmosphere, a new superconducting spectrometer is now being developed. The recent development of a high-strength aluminum-stabilized superconductor enables us to make an ultra-thin superconducting solenoid, with a transverse material thickness of  $2 \text{ g/cm}^2$ . With further efforts to minimize material thickness along the trajectory of the incident particles, such as adopting a thinner scintillation counter for time-of-flight measurement, and avoiding thick walls in the pressure vessel, the thickness of the upper half of the detector becomes  $4.5 \text{ g/cm}^2$ , equivalent to half that of the BESS detector. A new scintillation counter hodoscope will be placed inside the bore of the solenoid to trigger low energy particles which cannot pass through the lower half of the detector.

The BESS-polar detector is designed to meet the requirements of long duration balloon flights over Antarctica. The total weight of the payload will be about 1500 kg. A dedicated solar battery system providing 600 W electric power is also being developed for the front-end electronics and the data acquisition system.

A technical flight of the solar-cell array-structure was carried out at Sanriku Balloon Center in Japan in May 2002. The BESS-polar spectrometer will be available by June 2003. The first BESS-polar flight in Antarctica is planned to take place in December 2004, and the second one during the period of the solar minimum in the 2006/2007 Antarctic summer.

#### Acknowledgements

The authors thank Dr. W.V. Jones of NASA Headquarters for his continuous encouragement in this US–Japan cooperative project. Sincere thanks are expressed to the NASA Balloon Project Office at GSFC/WFF and the National Scientific Balloon Facility (NSBF) for their experienced support. We also thank ISAS and KEK for their continuous support and encouragement. This experiment is supported by the Grant-in-Aid for Specially Promoted Research (1300 1004) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan, and by NASA Grants RTOP 188-05-10-01 for NASA/GSFC, and NAG5-5347 for the University of Maryland, in the USA. Development of the thin superconducting solenoid has been carried out as a

part of “Ground Research Announcement for Space Utilization” promoted by the Japan Space Forum.

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