The BESS Program

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In nine flights between 1993 and 2002, the Balloon Borne Experiment with a Superconducting Spectrometer (BESS) has measured the energy spectrum of cosmic-ray antiprotons between 0.18 and 4.20 GeV, and the spectra of protons and helium to several hundred GeV. BESS has also placed stringent upper limits on the existence of antihelium and antiduterons. Above about 1 GeV, models in which antiprotons are secondary products of the interactions of primary cosmic rays with the ISM agree with the BESS spectrum. Below 1 GeV, BESS data suggest the presence of an additional source of antiprotons. The antiproton/proton ratios measured between 1993 and 1999, during the Sun's positive-polarity phase, are consistent with simple models of solar modulation. Results from the 2000 flight, following the solar magnetic field reversal, show a sudden increase in the antiproton/proton ratio and tend to favor a charge-sign-dependent drift model. To extend BESS measurements to lower energies, a new instrument, BESS-Polar, is under construction for a flight from Antarctica in 2004.

1. INTRODUCTION

Measurements of cosmic ray antiprotons and the search for heavier antinuclei address questions ranging from the origin and transport of cosmic rays to the apparent absence of cosmological antimatter and, perhaps, the nature of the dark matter. A comprehensive review of antimatter in the universe was given by Streitmatter [1]. Antiprotons are expected as secondary products of the interaction of primary cosmic ray nuclei (mainly protons) with the interstellar medium (ISM). Surprisingly, however, the first positive measurements [2-4] of cosmic ray antiprotons reported higher fluxes than predicted by contemporary secondary models. As reviewed by Stephens and Golden [5], this led to a great deal of excitement over the possibility that the reported excess might indicate the presence of an "exotic" source such as the decay of primordial black holes or the decay of dark matter.

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2. HISTORY: MAGNETIC SPECTROMETERS

From the early 1980s, excitement over the early antiproton measurements fueled an extensive experimental program using balloon-borne magnetic spectrometers. Orbiting spectrometers were also considered, and a large Space-Station-based facility, Astromag [6], reached a high degree of conceptual and engineering development.

At 1 GeV, the ratio of the antiproton to proton fluxes is about 10^{-5}. These rare particles must be uniquely identified in the presence of a large flux of cosmic-ray electrons, muons, and nuclei, requiring a careful application of instrumental and analysis techniques. Interpretation of the resulting measurements requires a clear understanding of the transport of cosmic ray nuclei in the galaxy and the heliosphere as well as an understanding of the interactions of primary cosmic rays with the ISM.

By the mid-1980s, the cosmic-ray community was fully engaged in an effort to measure cosmic ray matter and antimatter to unprecedented precision. The instrument of choice for this work was the superconducting magnetic-rigidity spectrometer

(rigidity = momentum/charge). Luis Alvarez of University of California Berkeley had recognized in the 1960s that a persistent-mode superconducting magnet could be successfully operated on a balloon or space platform. Early single-coil balloon-borne magnetic spectrometers were developed at Berkeley [7] and Johnson Space Flight Center [8,2], and a spectrometer with a near-Helmholtz magnet was developed at Goddard Space Flight Center [9]. The Berkeley group also formulated plans for a spectrometer to be flown onboard the HEAO-B mission. Although this instrument was not flown, a prototype was developed and tested. Together with advances in space cryogenics for IRAS, Spacelab-2, and COBE, this led to a proposal that NASA develop a Particle Astrophysics Magnet Facility for the Space Station, known as Astromag. A formal study for Astromag was begun in 1985 and the Report of the Astromag Study Team was released in May 1988 [10]. Astromag would have been a major facility with the ability to refill the cryostat on orbit and to change out experiments. The first round of experiments were, in fact, selected before work on Astromag and other attached payloads was terminated for budget reasons in 1990. An Astromag free-flyer option was studied, but not funded.

The influence of the Astromag study was immense. The community effort on Astromag bred a new generation of balloon-borne magnetic spectrometers with sophisticated instrumentation for studies of antimatter, nuclear spectra, and light isotopes (LEAP [11], PBAR [12], SMILI [13], MASS [14], IMAX [15], BESS [16,17], TS93 [18], CAPRICE [19,20], HEAT [21], and ISOMAX [22]). The satellite-based PAMELA [23] permanent magnet spectrometer, to launch in 2004, had its origin in the WiZard antimatter instrument selected for the first round of Astromag. Of recent antimatter instruments, only AMS [24] does not derive directly from Astromag work.

3. THE BESS INSTRUMENT

BESS is a magnetic-rigidity spectrometer with large geometrical acceptance, using a thin superconducting solenoidal magnet and a high-resolution drift-chamber tracking system [25-27]. This spectrometer is coupled to a state-of-the-art time-of-flight (TOF) system and a silica-aerogel Cherenkov counter (ACC). In its present configuration, the detectors and magnet are contained in an external pressure vessel maintained at 1 atmosphere and are arranged in a cylindrical configuration with a horizontal axis, as shown in Figure 1. The horizontal configuration enables the spectrometer to be compact and to have a wide opening angle, giving an acceptance of 0.3 m^2sr. The total mass of the instrument is currently ~2,300 kg.

The magnetic rigidity and charge-sign of incident particles are determined by measuring track curvature in the 1 Tesla axial field, which is uniform to 15% [28]. Curvature is measured using a central jet-type drift chamber (JET), which fills the warm-bore high-field region of the magnet. This chamber has a position resolution of 200 μm in the bending plane and provides up to 24 track positions. The most probable maximum-detectable-rigidity (MDR) of the system used for flights through 2000 is 200 GV, and 90% of the events have MDR>100 GV. Axial positions with a resolution of 1.5 cm for lZl>1 particles are given by charge-division readout on
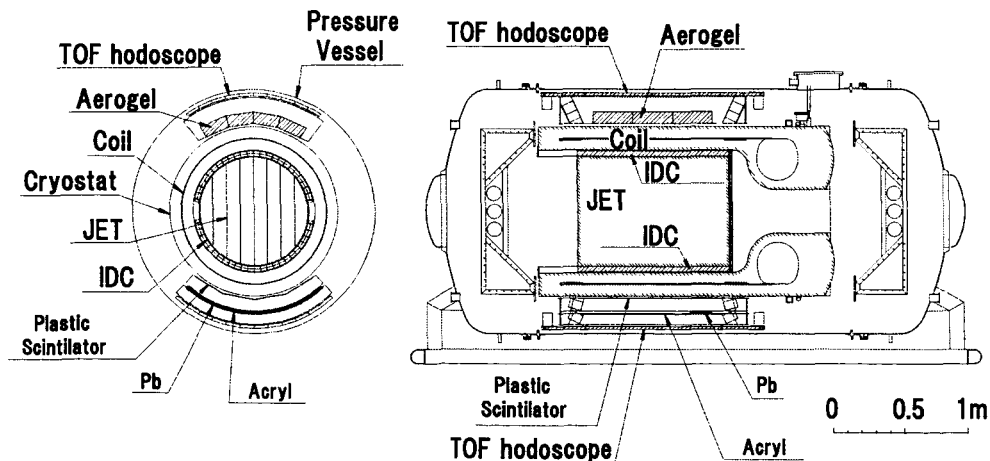

Fig. 1. Cross-sectional views of the BESS instrument.

both ends of the JET sense wires. Since the magnetic field is highly uniform inside the solenoid, a very sharp deflection resolution can be realized [29]. This enables the BESS experiment to provide very precise energy resolution and high statistics by allowing the full geometric acceptance to be used at all energies.

Inner drift chambers (IDC) are located just inside the cryostat. In combination with an outer hodoscope provided by a set of outer drift chambers (ODC) through 1995, and subsequently by the TOF system, they are used on-line by a second-level trigger system to select events rapidly for further processing. The BESS trigger detects negatively-charged particles with high efficiency, while sampling a fraction of the much more abundant positively-charged protons and helium. The IDC also provide 4 bending-plane points by drift-time measurement with a precision of 200 μm, and axial position by vernier pad readout with 500 μm precision.

In successive flights, the TOF measurement of BESS has regularly been improved [30]. Its resolution is now 75 ps, which yields a resolution for relativistic particles of 0.014 in $1/\beta$. This allows antiprotons to be clearly mass-resolved up to energies of 1.4 GeV. Upward-moving and downward-moving particles are cleanly separated with negligible chance of mistaking the direction of motion and consequently the charge-sign.

The aerogel Cherenkov counter (ACC), added in 1997 for rejection of light background particles (muons and electrons), initially used an optical index, n, of 1.032 to cover antiproton energies up to about 3.6 GeV at the top of the atmosphere (TOA) [31]. Currently, n=1.02 is used. This yields ~15 photoelectrons (Z=1, β=1) and extends measurements up to 4.2 GeV TOA. Figure 2, showing results from the 1999 and 2000 flights, illustrates the separation presently achieved between antiprotons and hydrogen isotopes using the β from the TOF and light-particle veto by the ACC. A

shower counter, using lead plates and acrylic Cherenkov detectors and covering about 20% of the geometric acceptance, was flown in 1999 and 2000 to improve rejection of electrons for measurements of atmospheric muons [32].
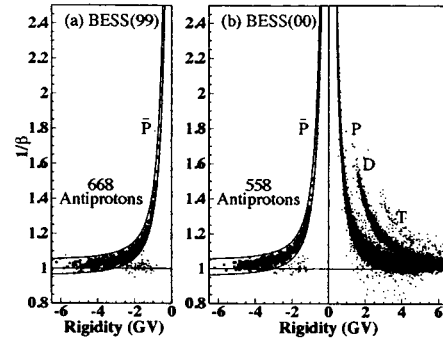

Fig. 2. Separation of antiprotons and hydrogen isotopes in the 1999 and 2000 BESS flights.

BESS is usually flown from a high-latitude site to access low magnetic-rigidity particles penetrating the Earth's magnetic field. BESS has been flown from Lynn Lake, Manitoba, Canada, eight times [33-35] with continuous improvement in the instrument live time and performance. Each flight reached a float altitude of about 36 km (residual pressure ~5 mbar). The high-latitude flights through 2002 are summarized in Table 1.

For 2001, the rigidity resolution of the spectrometer was greatly improved by the development of new JET, IDC, and ODC chambers. This resulted in a factor of five improvement in the momentum resolution, giving an MDR of 1.4 TV. Known as BESS-TeV [36,37] this version of the instrument was flown in 2001 from Ft. Sumner, NM, where the geomagnetic cutoff is about 4.3 GV, and in 2002 from Lynn Lake.

Table 1. Progress of the BESS balloon flights in Canada.

Year	unit	93	94	95	97	98	99	2000	2002
Float time	[hours]	17.5	17.0	19.5	20.5	22	34.5	44.5	16.5
Observation time	[hours]	14	15	17.5	18.3	20.0	31.3+(2.8*)	32.5+(2.5*)	11.3+(2.3*)
Events recorded	[10^6 events]	4.0	4.2	4.5	16.2	19.0	16.8+(2.3*)	15.0+(2.0*)	11.8+(1.9*)
Data volume	[GB]	4.5	6.5	8.0	31	38	41	38	56
TOF resolution (σ)	[ps]	300	300	100	75	75	75	75	75
Silica-aerogel index				1.032	1.020	1.020	1.020	1.020	1.020
Antiprotons observed		6	2	43	415	384	668	558	TBD
TOA Antiproton energy [GeV]		0.18~0.5		0.18~1.5	0.18~3.6	0.18~4.2	0.18~4.2	0.18~4.2	0.18~4.2

* Data taken during ascent.

4. BESS ANTIPROTON MEASUREMENTS

Antiprotons are a unique tool to probe the propagation process [38]. From the measured primary cosmic-ray flux and knowledge of the antiproton production mechanism, the flux of secondary antiprotons resulting from the interaction of primary cosmic rays with the ISM can be calculated using models of galactic and heliospheric transport.
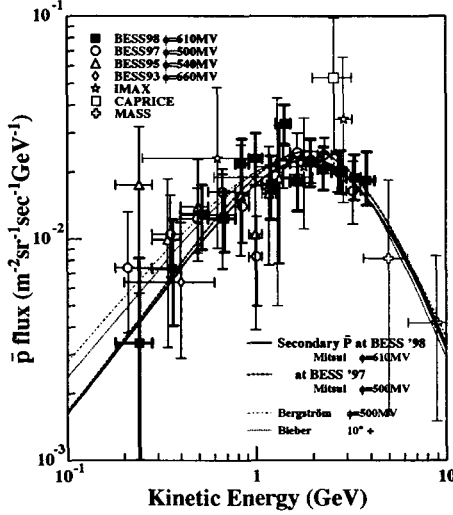

Fig. 3. BESS antiproton spectra (1993-1998) at the top of the atmosphere together with previous data and model calculations of secondary spectra.

That secondary production is the main source of cosmic ray antiprotons was clearly indicated by the first BESS [16,17] and IMAX [15] measurements of mass-resolved antiprotons. The low-energy antiproton spectrum in the energy range of 0.18 to 4.2 GeV has been measured with good statistics in subsequent BESS flights [39-41,35,42]. As summarized in Table 1, these flights, through 2002, total 160 hours of observation time and, through the 2000 flight, 2076 cosmic-ray antiprotons have been identified (2002 results TBD).

The secondary origin of most of the antiprotons is now well established [41]. This conclusion is supported by the measurements of IMAX [15] and CAPRICE94 [19] in energy ranges similar to BESS and by higher energy measurements from MASS91 [14], CAPRICE98 [20], and HEAT-pbar [21]. Figure 3 shows the energy spectrum measured by BESS in comparison with other experiments [35]. A

clear peak in the energy spectrum at 2 GeV, characteristic of secondary production, was first observed in BESS-97 data [41] and was confirmed in BESS-98 data [35]. Three calculations of the secondary antiproton flux [43-45] are shown in Figure 3. These reproduce the observed flux at the peak region around 2 GeV with 10-15% accuracy. This implies that most of the observed antiprotons are secondary and that the propagation models are basically correct.

In addition to secondary production, there could be other, more exotic, antiproton sources such as the annihilation of neutralinos or the evaporation of primordial black holes. Because the secondary antiproton spectrum has a sharp peak around 2 GeV, antiproton contributions well above or below this peak from other sources could cause an apparent flattening of the spectrum.

Neutralinos are among the possible candidates for dark matter in the universe [46,44], and their annihilation could produce antiprotons at energies well below the kinematic threshold for the production of antiprotons as nuclear secondaries. This might yield a feature, a flattening of the spectrum below ~500 MeV, that could be effectively used to search for dark matter signatures [43,47]. Similar flattening of the low-energy antiproton spectrum could be caused by evaporation of primordial black holes [48]. There are some indications of this flattening in the BESS low-energy data from 1995 and 1997 [41], as indicated in Figure 3, spurring efforts toward lowering the energy limit of BESS and increasing its sensitivity with the BESS-Polar instrument.

5. SOLAR MODULATION

At low energies, antiproton measurements are strongly affected by the outflowing solar wind. Thus, accurate measurements of the spectra of singly-charged particles, and the effects of solar modulation on those spectra, are critical to understanding the origin of cosmic-ray antiprotons and potential signatures of exotic matter in the measured antiproton spectra. Solar modulation could mimic or obscure the signature of an exotic source. The study of solar modulation is very complex, and ideally involves long-term (extending over much of the solar cycle) measurements of all charged components of the cosmic radiation. It is probable that the modulation effect depends on the particle charge-sign and solar magnetic field polarity [49,50]. Although the Sun has a complex magnetic field, the dipole term nearly always dominates in determining

the magnetic field of the solar wind. At each sunspot maximum, the dipole reverses direction, leading to alternating magnetic polarity in successive solar cycles. The charge-sign dependence of solar modulation has been studied with electron and helium data [51]. However, it is best studied using identical particles with opposite sign (e.g. positrons and electrons or antiprotons and protons). The antiproton to proton ratio is expected to strongly depend on the solar magnetic field polarity [45], and is an ideal tool for the study of charge-sign-dependent solar modulation. BESS, with its yearly flights, provides a unique opportunity to track this dependence. Figure 4 [42] shows the resulting antiproton to proton ratio from the BESS 1997, 1999, and 2000 flights. There was a reversal of the solar magnetic field before the 2000 BESS flight. Increasing solar activity suppresses the relatively soft primary proton spectrum, while the spectrum of the secondary antiprotons is less strongly affected. The increase in the antiproton/proton ratio with increasing solar modulation results mainly from the relatively greater suppression of the primary protons and is shown by both spherically-symmetric and drift-model calculations [45]. However, the rapid increase in this ratio in the 2000 data is better reproduced by the drift model. It is very important to continue this investigation into and through solar minimum. Future BESS flights can provide the antiproton spectrum from 100 MeV to 4.2 GeV with increased sensitivity and statistics.
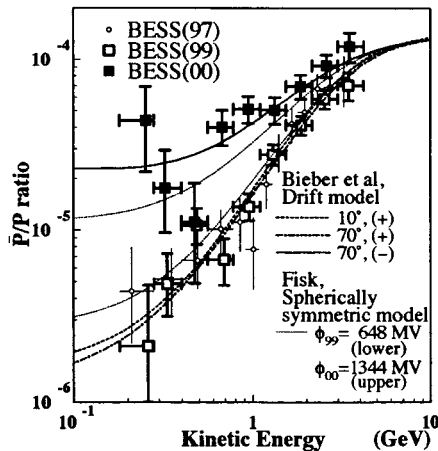

Fig. 4. The antiproton/proton ratio measured by BESS in 1997, 1999, and 2000 compared to model calculations.

6. HIGH-ENERGY PROTON SPECTRUM

BESS has measured the spectra of protons and helium nuclei in each of its flights. In 2002 BESS-TeV successfully measured the proton spectrum up to 540 GeV and the He spectrum up to 250 GeV/nucleon [37,52]. Figure 5 shows the BESS-TeV spectrum compared to previous experiments [52]. Between 50 GeV and 100 GeV the BESS-TeV results are consistent with the results obtained in 1998 by BESS [29] and AMS-01 [24]. The differences at low energy are the result of solar modulation [53].
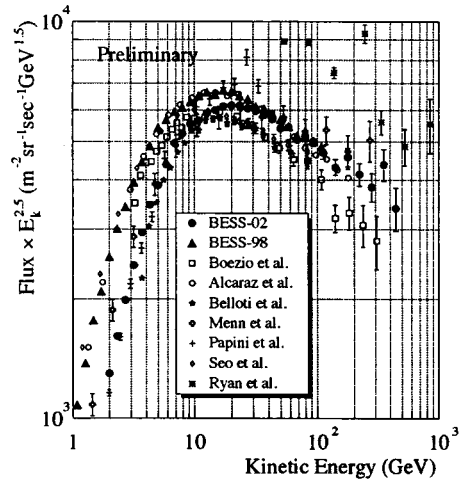

Fig. 5. Proton spectrum measured by BESS-TeV compared with previous experiments.

7. ANTIHELIUM AND ANTIDEUTERON

Beginning with the first BESS flight, a continuing search for antihelium has been carried out [54-57]. The unambiguous detection of even a single antihelium would provide conclusive evidence for the existence of primordial antimatter [1]. No antihelium candidate has been detected by BESS in >6.6 x 10^6 observed helium events in a rigidity range of 1 GV to 14 GV accumulated in seven flights. Figure 6 shows the upper limit of the antihelium/helium ratio derived from the BESS program in comparison with other experiments. The resultant upper limit of the antihelium/helium flux ratio at the top of the atmosphere has been decreased to 6.8 x 10^{-7} with a 95% confidence level under the assumption that antihelium and helium would have the same spectrum [57]. The sensitivity of the antihelium search has been pushed nearly two orders of magnitude by the BESS experiment. The search

for antihelium is to be extended to reach an upper limit ~ 10^{-7} in the future BESS long duration flights.

A search for antideutrons has been carried out using BESS data from the 1997-2000 flights [58]. No candidate has been found. The result is a 95% confidence level upper limit to the differential flux of cosmic ray antideuterons between 0.17 and 1.15 GeV/nucleon at the top of the atmosphere of 1.9 x 10^{-4} (m^2sr GeV/nucleon)$^{-1}$.
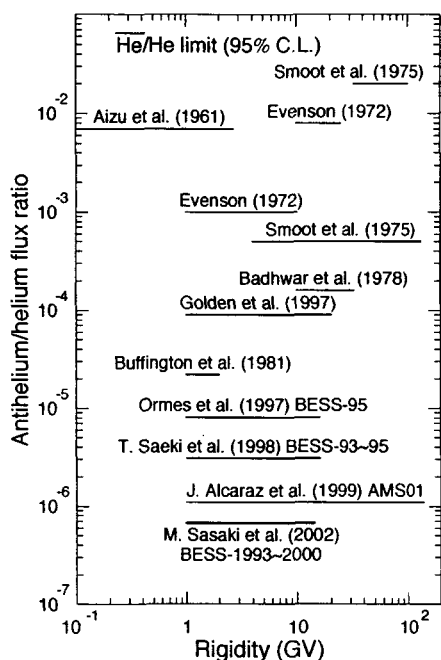

Fig. 6. The upper limit to the ratio of antihelium to helium obtained with BESS data through 2000.

8. THE BESS-POLAR INSTRUMENT

BESS-Polar is an entirely new lightweight version of the instrument under construction for an Antarctic long-duration balloon (LDB) flight in 2004. BESS-Polar is discussed in detail by Yamamoto et al. [59] and Yoshida et al. [60]. With the increased transparency of the instrument and the very low geomagnetic cutoff near the south pole, BESS-Polar will conduct extremely sensitive measurements of low-energy antiprotons, greatly improve the sensitivity of the antihelium search, and will have an improved ability to measure light cosmic-ray isotopes.

The detector system, shown in Figure 7, consists of a JET central tracker, with TOF, ACC, and IDC for triggering and particle identification. The JET, IDC, and a middle TOF layer (MTOF), below the lower IDC, are placed inside the warm bore of the solenoid, which also acts as a pressure vessel. The outer TOF layers and ACC are in vacuum. A very low instrumental energy cut-off for antiprotons is achieved with a new thin-walled superconducting magnet, using a new high-strength aluminum-stabilized superconductor, and by eliminating the pressure vessel, thinning the TOF, adding the MTOF, and moving the ACC below the magnet. Low-energy particles only have to reach the MTOF to be detected, traversing 4.5 g/cm^{2}of material, about four times less than in BESS-TeV. The lowest energy for antiproton detection is ~0.1 GeV at the top of the atmosphere (TOA). The cryogenic system of the magnet allows continuous operation for over 20 days and the instrument is powered by solar-cell arrays. The compact spectrometer design has a geometrical acceptance of 0.3 m^{2}sr, matching the acceptance of the current BESS instrument.
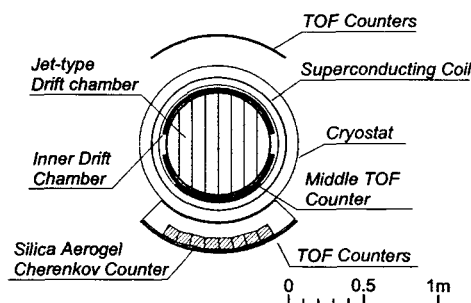

Fig. 7. Cross-section of BESS-Polar

BESS-Polar is unique and complementary to two space experiments, PAMELA and AMS, to be carried out in the same time period [23,24,61,60,59]. AMS and BESS-Polar have similar geometric acceptances and AMS has the advantage of a long planned exposure on the International Space Station. However, the access of low-energy particles to the Space Station orbit at ~52 degrees inclination is poor and BESS-Polar will exceed the sensitivity of AMS for antiproton energies below ~250 MeV. BESS-Polar and PAMELA, in a near-polar orbit, will sample similar ranges of geomagnetic cutoff, but because the geometry factor of PAMELA is ~21 cm^{2}sr BESS-Polar will have greater collecting power at low energies by about an order of magnitude. Both AMS and PAMELA will measure antiprotons to

much higher energy than BESS-Polar. All three instruments will measure the characteristic secondary antiproton peak with high precision, allowing accurate intercalibration of the absolute flux.

BESS-Polar carried out a technical flight in Ft. Sumner, NM, in October 2003. The instrument is currently undergoing integration at Goddard Space Flight Center in preparation for its first Antarctic flight planned for Winter 2004-2005. A second flight is planned for Winter 2006-2007 to nearly coincide with solar minimum and maximize the sensitivity of the antiproton measurements at low energies. In a 20-day flight, more than 10^3 antiprotons are expected to be observed below 1 GeV and $\sim 10^4$ over the full energy range from 0.1 to 4.2 GeV. Figure 8 shows simulated antiproton spectra from such a flight [62]. The solid curve indicates the expected secondary antiproton spectrum, and the dotted curve indicates the spectrum that might arise from primordial black hole evaporation under one model [48]. The dashed curve indicates the combined spectrum. The error bars represent the statistics that might be expected. This illustrates the potential of BESS-Polar to identify a low-energy primary antiproton component.
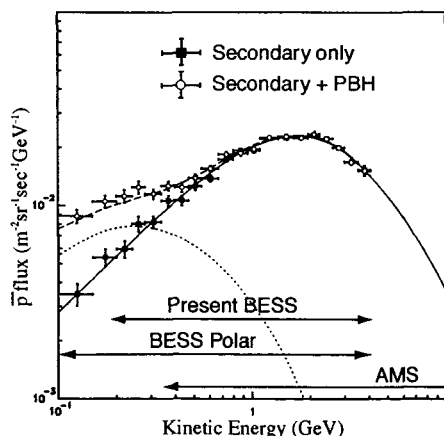

Fig. 8. Simulated antiproton spectra based on the spectrum measured in BESS-1995 –1997 with statistics from a 20 day flight.

BESS-Polar will also carry out the search for antihelium and antideuterons with tremendously enhanced sensitivity. The expected sensitivity of BESS-Polar in the ratio of antihelium to helium will reach $\sim 3 \times 10^{-8}$ for 30 days total observing time. The sensitivity of the antideuteron search over the same period will reach $\sim 1 \times 10^{-5}$ (m^2 sr GeV/nucleon)$^{-1}$

9. SUMMARY

BESS is very-large-geometry balloon payload with sophisticated instrumentation that is being fully exploited to understand the origin of cosmic-ray antiprotons, to probe galactic and heliospheric cosmic-ray transport processes, and to search for cosmic antimatter. BESS has measured the cosmic-ray antiproton spectrum between 0.18 and 4.20 GeV in eight flights between 1993 and 2002. These data show that most of the antiprotons originate as secondary products of interactions of the primary cosmic rays with the ISM. Below 1 GeV, however, BESS data suggest the presence of an additional source of antiprotons. BESS antiproton and proton spectra provide a unique tool to study charge-sign-dependent solar modulation. These data generally agree with a charge-sign-dependent drift model, and show the importance of a careful treatment of solar modulation for the interpretation of low-energy antiproton measurements. BESS has also carried out a sensitive search for antihelium and has set the most stringent current limit to the ratio of antihelium to helium. The antiproton measurements and antihelium search will be greatly extended by the BESS-Polar instrument. Flying for long periods at the low polar geomagnetic cutoff, BESS-Polar will make unique contributions to the search for antimatter, dark matter, and primordial black holes.

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