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Overview of the Scientific Results of the BESS-Polar Program

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Abstract: With its high-precision measurement of the cosmic-ray antiproton spectrum and sensitive search for cosmological antihelium using BESS-Polar II, the US-Japan BESS-Polar Collaboration (Balloon-borne Experiment with a Superconducting Spectrometer Polar) has finalized its core study of the early Universe using elementary particle measurements. The antiproton spectrum probes possible exotic sources, such as dark-matter candidates. The search for antihelium or heavier antinuclei examines the possibility that antimatter domains remain in the cosmological neighborhood from symmetry breaking processes in the early Universe. Since1993, BESS has carried out eleven high-latitude balloon flights, including two long-duration Antarctic flights, that together have defined the study of antiprotons below 4 GeV, provided standard references for light element and isotope spectra, and set the most sensitive reported limits on the existence of antideuterons and antihelium. BESS-Polar II recorded over 4.7 billion cosmic-ray events in 24.5 days of flight over Antarctica during the 20072008 Austral Summer, identifying about 8000 antiprotons. These data more than doubled all earlier BESS flights combined and were obtained at very low, near minimum, Solar activity when the low-energy antiproton measurements are most sensitive to a primary source. Depending on energy range, the BESS-Polar II antiproton measurements have 10-20 times the statistics of BESS95+97 data from the previous Solar minimum. Here, we give an overview the scientific results of the long-duration flights of BESS-Polar I (2004) and BESS-Polar II, including antiproton spectra, the energy-dependent ratios of antiprotons to protons, and the limits on the relative abundance of antihelium. We also discuss the future of the BESS-Polar program. Complementing this presentation, details of additional BESS-Polar measurements including the interstellar proton and helium spectra, time dependence of the spectra, and light isotope abundances will be discussed in other papers at this conference.

Keywords: Cosmic-ray antiproton, Antihelium, Superconducting spectrometer, Solar modulation

1 Introduction

It is well established that dark matter (DM) is responsible for the formation of structure and for the dynamics of galaxies. However its nature is still unknown. It is also observed that cosmological antimatter is apparently absent in the present era, but fully explaining this remains a significant problem for both cosmology and particle physics. The BESS program was developed specifically to address these issues. The exceptional collecting power and particle identification capability of the BESS instrument enable a broad scientific reach. The BESS collaboration has carried out eleven successful balloon flights from 1993 through 2008, nine conventional northern-latitude flights and two long-duration-balloon (LDB) flights over Antarctica that have recorded more than 13,000 cosmic-ray antiprotons and set the most stringent upper limits to the existence of antihelium and antideuterium. In addition, BESS has 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. The precise measurements of the low-energy cosmic-ray antiproton $\overline{\mathrm{p}}$ flux and the sensitive search for antihelium $\overline{\mathrm{He}}$ and heavier antinuclei made by the BESS collaboration are vital to constraining candidate DM models, placing limits on the possible density of primordial black holes (PBH) and defining the limits of cosmological antimatter. BESS also measures the spectra of light Galactic cosmic-ray (GCR) elements and isotopes to probe GCR propagation, study of the effect of the outflowing Solar wind, and provide data for calculations of atmospheric secondary particle production.

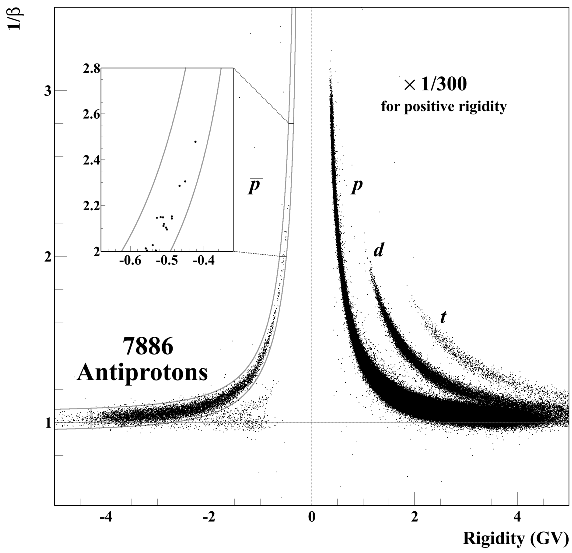

Figure 1: Particle identification capability of the BESS-Polar instrument. The isotopes of hydrogen well separated and the antiproton band clearly visible.

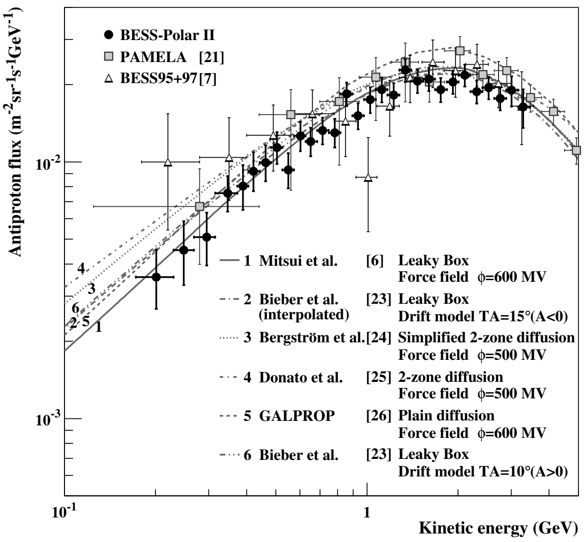

Figure 2: Spectra of antiprotons measured by BESS-Polar II at solar minimum compared with BESS95+97 and PAMELA measurements and with secondary model calculations.

2 The BESS Program

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. The instrument and experimental program are discussed in detail in[1, 2] and references therein. Between ~0.1 GeV - 4 GeV, referenced to the top of the atmosphere (TOA), BESS instruments directly measuring charge (Z), charge-sign, magnetic rigidity ($R = p/Ze$ and velocity (β) to derive their momentum (p), mass (m), and kinetic energy (E_k). A central JET-type drift chamber and inner drift chambers (IDC), give 52 trajectory points in the bending direction with a characteristic resolution of $\sim 140\mu$m. R is determined by fitting the particle track and charge-sign by the direction of curvature. Arrays of time-of-flight (TOF) scintillators are at the top (UTOF) and bottom (LTOF) of the instrument, with a middle TOF scintillator array (MTOF) inside the magnet bore below the lower IDC. The TOF scintillators trigger events and measure Z and β. m resolution is illustrated in Figure 1. At higher β, an aerogel Cherenkov counter (ACC) identifies low m, high β, background particles. Additional background rejection is supplied by multiple measurements of ionization energy loss (dE/dx) from the JET. The horizontal cylindrical configuration of the BESS instrument allows a full opening angle of ~90 degrees with a geometric acceptance of 0.3 m^{2}sr. The thin solenoid coil and MTOF allows particles to be measured with only ~4.5 g/cm^2 encountered and gives an effective energy threshold to well below 100 MeV TOA. The uniform magnetic field gives nearly constant R resolution for all trajectories. The maximum detectable rigidity (MDR) for BESS-Polar is 270 GV.

BESS-Polar I was flown in 2004, acquiring data for 8.5 days, measuring 9×10^8 cosmic ray events including 1512 antiprotons from 0.1–4.2 GeV. For BESS-Polar II, flown in 2007–2008, cryogen lifetime was increased to >25 days, the TOF resolution was improved to ~120 ps, the rejection power of the ACC was increased to >12000. In 24.5 days with the magnet energized, BESS-Polar II recorded over 4.7×10^9 cosmic ray events and detected 3996 antiprotons. After about one and two-thirds orbits of Antarctica, the BESS-Polar II flight was terminated over the West Antarctic Ice Sheet. The instrument was recovered during the 2009–2010 Austral Summer.

3 Antiprotons

Most cosmic-ray $\overline{\mathrm{p}}$ are produced by interactions of GCR nuclei with the ISM. Due to production kinematics and to the energy spectra of the primary GCR, the energy spectrum of secondary $\overline{\mathrm{p}}$ peaks at around 2 GeV and decreases sharply below and above the peak. Their mainly secondary origin makes $\overline{\mathrm{p}}$ important tools to probe GCR transport and the peaked spectral shape gives the possibility of detecting superimposed primary contributions from DM candidates. For example, primordial black holes (PBH) may have formed in the early Universe in the collapse of dense regions formed by density fluctuations and could be detected through antiparticles arising from Hawking radiation emitted as they evaporate. PBH evaporation should yield an $\overline{\mathrm{p}}$ spectrum with a peak well below 1 GeV. Superimposed on the steeply decreasing secondary $\overline{\mathrm{p}}$ spectrum, this could cause a flattening. Because of the low-energy spectral peak predicted from PBH evaporation, solar modulation is expected to affect such a $\overline{\mathrm{p}}$ component more than the secondary$\overline{\mathrm{p}}$ spectrum and measurements at solar minimum are critical. BESS (95+97) $\overline{\mathrm{p}}$ flux measurements at solar minimum hinted at an excess at low energy and motivated the BESS-Polar program.

At 1 GeV, the $\overline{\mathrm{p}}/\mathrm{p}$ ratio is about 10^{-5}. At balloon altitude there are also significant fluxes of electrons and muons. Thus careful application of instrumental and analysis techniques is required, and interpreting the resulting measurements requires a clear understanding of GCR transport in the galaxy and the heliosphere, and of the interaction physics of primary cosmic rays with the interstellar gas. Fig. 2 from [3] (c.f. references therein) shows the $\overline{\mathrm{p}}$ spectrum measured by BESS-Polar II compared to results from the BESS95+97 flights, PAMELA and model calculations. Curve 1 uses Mitsui et al. data with force-field modulation of 600 MV from the best fit to the BESS-Polar II proton spectrum. Curve 2 was generated by interpolating model calculations supplied by Bieber et al. for negative solar magnetic field polarity (A<0). The tilt angle of 15°(A<0) is

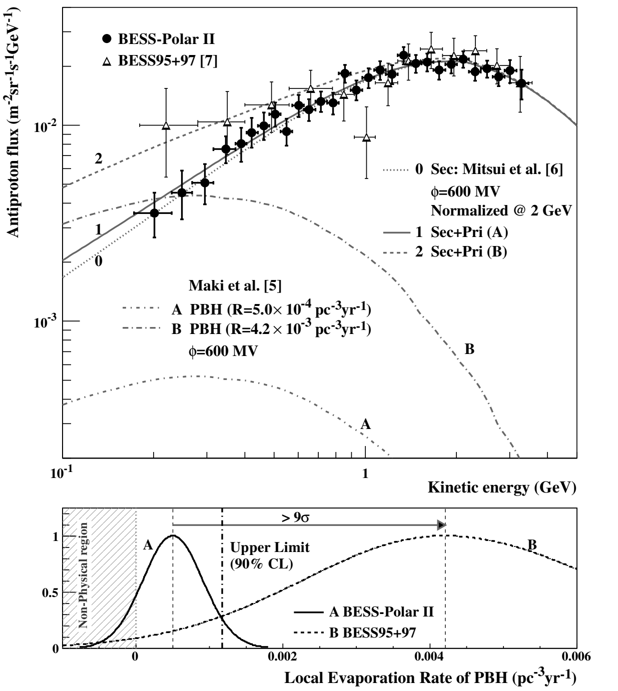

Figure 3: (Top) Possible primary $\bar{p}$ fluxes from PBH evaporation calculated for BESS-Polar II (A) and BESS95+97 (B) by fitting differences of the measured spectra from the Mitsui secondary $\bar{p}$ spectrum. (Bottom) PBH evaporation rate (R) distributions. Values of R $<$ 0 are non-physical.

the best fit to the BESS-Polar II proton data. Curve 6 is the published Bieber et al. A>0 solar-minimum calculation for comparison to the BESS95+97 measurements. Curves 3 and 4 are also published solar-minimum calculations. Curve 5 was generated using the GALPROP model with 600 MV force-field modulation. Improved statistical precision of the measured $\bar{p}$ flux results from 14 and 30 times more events below 1 GeV than BESS95+97 and PAMELA, respectively. The BESS-Polar II and PAMELA spectra generally agree in shape, but differ in absolute flux. Both are consistent with solar-minimum secondary calculations and neither exhibits the flattening at low energies found by BESS95+97.

The likelihood of primary $\bar{p}$ from PBH evaporation is represented by a model-dependent evaporation rate (R) determined by fitting a PBH model spectrum to the difference of a secondary calculation from the measured flux. R is positive (physical) only if the measured flux exceeds the secondary prediction. To avoid bias from uncertainties in the predicted absolute flux, the secondary calculation is normalized to the measurements at the spectral peak (2 GeV). Comparing the models to the measurements, only 1 and 5 give a significant, and almost identical, excess. Using the Maki et al. PBH model with force-field modulation gives R = 5.0+4.1 104pc3 yr1 , as shown in Fig. 3 . This excludes by more than 9 sigma the slight possibility of primary pbars suggested by $R = 4.2(+1.8, -1.9) \times 10^3 pc^3 yr^1$ from BESS95+97 data with the same models and modulation. The 90% confidence level upper limit of $R \sim 1.2 \times 10^3 pc^3 yr^1$ is almost insensitive to modulation. Thus, within statistics, the BESS-Polar II data show no evidence of primary $\bar{p}$ from PBH evaporation.

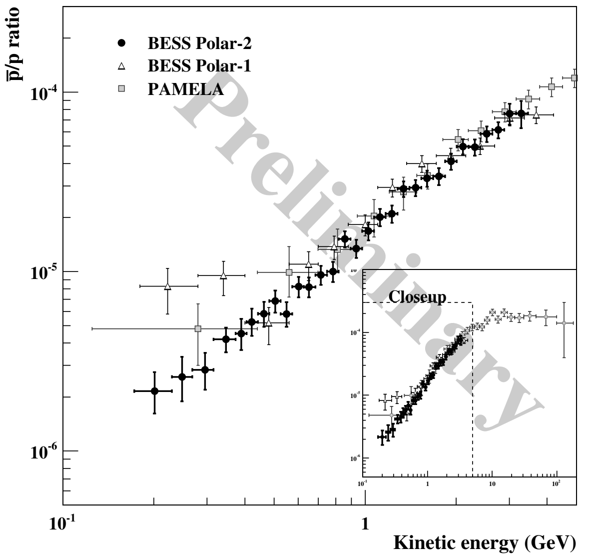

Figure 4: Preliminary antiproton/proton ratio measured by BESS-Polar II compared with measurements from BESS-Polar I and PAMELA.

4 Charge-sign-dependent Solar Modulation

The affect of the solar wind and its entrained magnetic fields on the GCR depends on both the *R* and charge-sign of the particles. Particles with the same mass but opposite charge-sign, such as protons and $\bar{p}$, are affected differently, depending on the solar magnetic field polarity and solar activity. BESS results on the $\bar{p}/p$ ratio cover most of a solar cycle, including a solar polarity reversal. Fig. 4 shows the $\bar{p}/p$ ratio using the $\bar{p}$ [3] and p spectra [4] obtained with BESS-Polar II together with the results from BESS-Polar I and PAMELA. $\bar{p}/p$ ratios as a function of tilt angle were converted into ratios as a function of time by taking the tilt angle as the mean position of the monthly variation of the maximum latitudinal extent of the current sheet. The time variation of $\bar{p}/p$ ratios by the spherically symmetric approach were estimated by using a linear relation between the BESS proton spectra measured in 6 flights and the monthly averaged count rates at the Climax neutron monitor.

Figure 5 shows the variation in $\bar{p}/p$ over more than a solar cycle. The drift model and the symmetric model reproduce equally well the $\bar{p}/p$ ratio during the positive phase. The sudden increase of the ratio observed by BESS measurements after the positive-to-negative solar field reversal is better reproduced by the drift models at energies below 1 GeV. During the negative phase, the $\bar{p}/p$ ratio depends on the tilt angles more than it does during the positive phase, mainly due to the modulation of protons, which in the negative phase are expected to arrive from a 'horizontal' direction in heliosphere, i.e. along the current sheet. Figure 5 shows that the spherical model is slightly better in reproducing $\bar{p}/p$ during the negative phase.

5 Antihelium Search

A fundamental question in cosmology is whether matter and antimatter are asymmetric or symmetric in the Universe. The Sakharov conditions (direct violation of baryon number conservation, CP symmetry breaking, and a period out of equilibrium in the very early Universe) indicate a way to explain the apparent baryon domination observed. However, direct violation of baryon number conservation has never

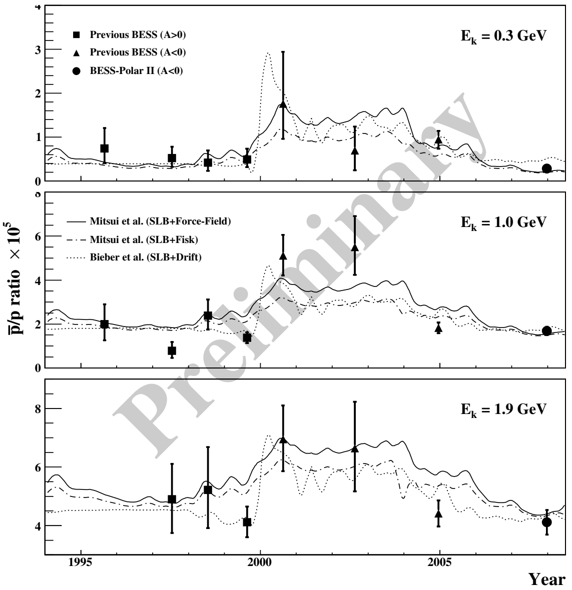

Figure 5: $\bar{\mathrm{p}}/\mathrm{p}$ measured by BESS over more than a full Solar cycle.

been demonstrated, and the strengths of CP violations currently measured at accelerators are insufficient to explain strong matter/antimatter asymmetry. Detection of $\overline{\mathrm{He}}$ would provide direct evidence of antimatter domains in the current Universe. Although $\overline{\mathrm{He}}$ might, in principle, be produced in cosmic-ray interactions, the cross-sections are small and the resulting $\overline{\mathrm{He}}/\mathrm{He}$ ratio should be much less than 10^{-12}. No $\overline{\mathrm{He}}$ was found in combined BESS data through BESS-Polar II [5], giving a 95% confidence upper limit on $\overline{\mathrm{He}}/\mathrm{He}$ of 2.7×10^{-7} in the 0.6–20 GV rigidity range. Fig. 6 shows the BESS upper limits compared with other experiments. BESS-Polar II data was also carefully searched for evidence of $\overline{\mathrm{He}}$. Between 1 and 14 GV 4×10^{-7}helium nuclei were identified, but no $\overline{\mathrm{He}}$. The resulting upper limit on $\overline{\mathrm{He}}/\mathrm{He}$ is 9.4×10^{-8} (at 95% confidence). Combining this with data from all other BESS flights, including BESS-Polar I, gives an upper limit of 6.9×10^{-8}, the most stringent limit to date, stronger by more than three orders of magnitude compared to the first limits reported.

6 Conclusion

The BESS program has provided accurate measurements of light elemental and isotopic spectra, made definitive measurements of cosmic-ray $\bar{\mathrm{p}}$ spectra, carried out sensitive searches for rare species such as $\overline{\mathrm{He}}$ and $\bar{\mathrm{d}}$, and provided important insights into solar modulation. The recent Antarctic flights of BESS-Polar I (2004) and BESS-Polar II (2007–2008) have yielded measurements of cosmic-ray $\bar{\mathrm{p}}$ with unprecedented statistical accuracy and greatly increased the sensitivity of the $\overline{\mathrm{He}}$ search. The measurements made by BESS-Polar II took place near solar minimum when sensitivity to a potential primary antiproton component at low energies is greatest. With statistics increased a factor of 10–20 compared to BESS measurements at the previous Solar minimum, BESS-Polar II data have clearly determined that there is no significant contribution the low-energy $\bar{\mathrm{p}}$ spectrum from PBH evaporation.

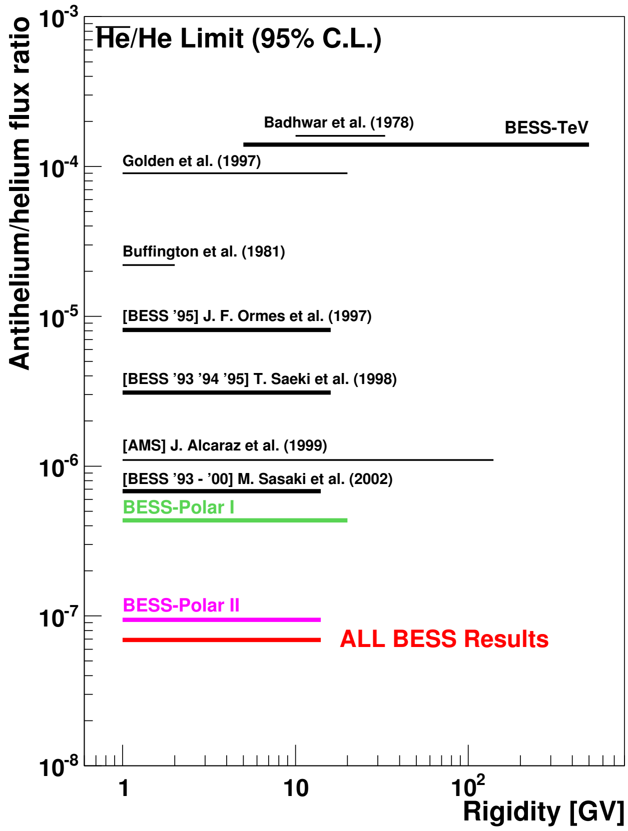

Figure 6: Limits on the possible existence of $\overline{\mathrm{He}}$ in the cosmic radiation.

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