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PROGRESS IN SEARCH FOR COSMIC-RAY ANTI-PARTICLES BY BESS SPECTROMETER

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Abstract

The balloon-borne experiment using a superconducting magnetic rigidity spectrometer, BESS, has been carried out in northern Canada to search for cosmic-ray antiparticle. The low energy cosmic ray antiprotons were first unambiguously detected and the absolute fluxes of low energy cosmic-ray antiprotons have been measured in the kinetic energy range 0.18 to 1.4 GeV. No antihelium has been detected with corresponding upper limit on the antihelium/helium ratio of 3.1×10^{-6} or less. This report describes the progress in the superconducting magnet spectrometer being upgraded and its scientific progress obtained from the flights in 1993 to 1997.

1. Introduction

The Balloon-borne Experiment using a Superconducting Magnetic Rigidity Spectrometer, BESS, has been performed in north Canada since 1993 with aiming at a very sensitive search for cosmic-ray antiparticle in the Universe, and at a precise measurement of low energy cosmic-ray antiprotons fluxes [1-9].

It is a fundamental question in cosmology whether matter and antimatter are asymmetric or symmetric in the Universe. If there was symmetry breaking in baryon numbers (CP violation) in early history (10E-36 sec) in the Universe, baryon domination in the further history can be explained. Thus, antimatter may not be found in the cosmic rays except that produced in high energy collisions in interstellar space or in atmosphere around the earth. If baryons and anti-baryons are equally abundant in global scale, the anti-baryons are located somewhere in local clusters such as anti-galaxies. Some estimates of the diffusion rate of particles in intergalactic space suggest that cosmic rays samples extra-galactic space out to a few hundred MPc [10,11]. If the volume constrains equal number of mater and antimatter galaxies, one might expect to find antimatter cosmic rays at earth in antimatter/matter ratio of 10^{-5} to 10^{-6}. The BESS experiment aims at to search for antimatter in a sensitivity level of 10^{-6} or below.

The detection of cosmic-ray antiprotons was first reported in 1979 [12]. The subsequent experiments have followed to understand the origin of cosmic ray antiprotons [13-17]. Those results in energy range above 1 GeV suggested that observed antiprotons could be consistent with secondary particle which may be produced in collision of energetic cosmic-ray nuclei with ambient interstellar material. However, in lower energy region below 1 GeV, it is kinematically difficult to produce the secondary particles. Therefore, the low energy region is ideal to search for the cosmic-ray antiproton which might be produced from novel primary sources such as the evaporation of primordial black holes [18, 19] or the annihilation of dark matter in the galactic halo. The BESS experiment has aimed at a highly precise measurement of cosmic-ray low energy antiproton spectrum to understand the origin of cosmic-ray antiproton. The BESS superconducting magnet spectrometer was designed to make such highly sensitive search possible. It has a unique cylindrical configuration with a thin superconducting solenoidal magnet and a geometrical acceptance of 0.3 m^2.sr has been realized in a compact volume.

The project has been started as a Japan/US cooperative program amongst University of Tokyo, KEK, ISAS, NASA/GSFC, and NMSU, and was later re-organized with joining of Kobe University and University of Maryland.

The balloon experiment has been carried out successfully in northern Canada as part of NASA/NSBF balloon campaign program, in every summer since 1993. The BESS particle detector system has been continuously upgraded to intend further sensitive search for cosmic-ray anti-particles.

This report describe the progress of the development of BESS superconducting spectrometer and its scientific results.

2. BESS Spectrometer and Its Upgrade

2.1. Original Configuration in BESS-93

The BESS instrument is a superconducting magnetic rigidity spectrometer that is used to determine the rigidity and velocity of the charged particles passing through the instrument. It was designed to provide statistically significant observation during the limited duration of balloon experiment [1-3]. The thin-wall superconducting solenoid magnet is a key component to provide a uniform solenoidal magnetic field with a large geometrical acceptance of 0.3 $m^2\cdot$sr, with keeping transparency for the incoming particle to pass through the wall with minimum interaction.

Figure 1 shows cross sections of the original spectrometer in BESS-93&94, and updated in '95, and '97. In BESS-93, the spectrometer consists

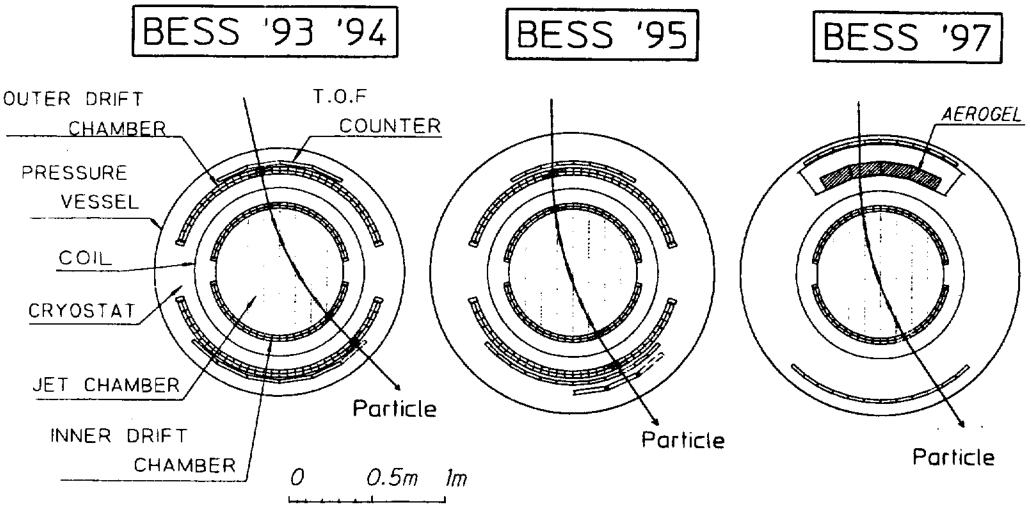

Fig. 1. Cross section of the BESS Spectrometer in BESS-93 & -94, -95 and -97.

of, inside to outside, the main track detector(JET), a pair of inner drift chambers (IDCs), a thin superconducting solenoid magnet (SOL), a pair of outer drift chambers (ODCs), and time-of flight plastic scintillation hodoscopes(TOF).

The superconducting solenoid magnet provides a magnetic field of 1 Tesla in the axial direction with an uniformity of +/- 12 % in the fiducial region of the tracking volume. The magnet wall thickness is $4 g/cm^2$ and transparency is 0.2 in radiation length including the cryostat [20]. The 3D particle trajectory in the magnetic field is measured by the JET chamber with a spatial resolution of 200 micron-meters and with 24 sampling points, resulting in a rigidity resolution of 0.5 % at 1 GV/c. The IDCs and ODCs have 5 cm-wide cells around sensing wires, and those major function is to provide fast rigidity-band selection to provide "on-line track-trigger" for efficient data gathering for negatively charged particles. The track-trigger is to detect negatively charged particles with high efficiency while sampling the higher flux proton and helium nuclei. The TOF plastic scintillator hodoscopes are placed at the top and bottom of the spectrometer. Originally, 4 paddles on the top and 6 paddles at bottom, each 2 cm thick, 20 cm wide, and 110 cm long plastic scintillator (NE102), are placed with a distance of 1.38 m , and with a time resolution of 300 ps. The TOF counter has three major functions of (i) first level trigger, To, (ii) the time-of-flight measurement, and (iii) the energy-deposit, dE/dx, measurement.

The first level trigger is the so-called "T0 trigger" where a simple coincidence between the top and bottom TOF hodoscopes initiate the data gathering process.

Particles are identified by measuring their mass (m). The relationship $m^2 = R^2Z^2(1/\beta^2 - 1)$ can be derived from the relativistic relationships. The BESS spectrometer measures the particle rigidity ,R, by reconstructing the particle track in the magnetic field by means of drift chambers (JET and IDC). The particle velocity , β, is determined by a time-of-flight (TOF) measurement. The information of particle charge, Z, comes from ionization-loss (dE/dx) measurement (Z^2) in the TOF scintillators and in the JET chamber. The particle charge sign is clearly determined from the direction of the trajectory and its deflection.

The all components of the spectrometer as well as front-end electronics and the following data acquisition system are enclosed in an aluminum pressure vessel. The batteries are placed outside the vessel. The total weight of the spectrometer is about 2,100 kg and the power consumption is about 1200 W. The total material for incident particle passing through is about 17 g/cm^2 from the top of the pressure vessel through all detector components. The fraction of the solenoid magnet walls (at top and bottom) is about half of the total material. This configuration provides an spectrometer geometrical acceptance of 0.32 $m^2 \bullet sr$.

2.2. Upgrade in BESS-95

In BESS-95, the following detector improvements were made [21]:

(i) TOF hodoscopes were renewed with new plastic scintillator (BC404) with reducing the paddle width to 10 cm with a shorter counter length of 95 cm and with more optimized light guide. The time resolution was improved to 110 ps.

(ii) A set of acrylic Cherenkov counter hodoscopes were installed at the bottom of the spectrometer in order to identify electrons and to enhance antiproton identification above 1 GV/c.

(iii) The pressure vessel was enlarged in its diameter from 1.5 to 1.7 m with a uniform wall thickness of 2.5 mm to keep further detector upgrade possibility.

2.3 Upgrade in BESS-97

In BESS-97, the spectrometer was upgraded specially in particle identification and in data acquisition system, as follows:

(i) The TOF counters were further improved with renewing light-guides and photomultipliers with a larger diameter of 2.5 inches. As a result, the time resolution was further improved from 110 ps to 75 ps. The distance of the top and bottom hodoscopes were increased from 1.34 to 1.58 m and this extension contributed to the improved resolution of the velocity measurement resulting particle identification.

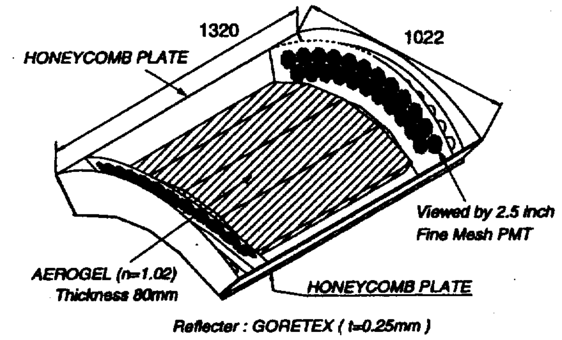

Fig. 2. Schematic view of Aerogel Cherenkov Counter.

(ii) The Aerogel Cherenkov counter was newly developed and installed [22]. The Aerogel Cherenkov counter has a great advantage to extend the energy range in particle identification for proton and antiproton with eliminating background particle such as electron, muons and pions. It is also a great advantage to be very light and transparent in amount of radiating material. The refractive index was chosen to be 1.03 and antiproton identification rigidity range was extended up to 3.5 GV/c. Figure 2 shows the schemative view. A rejection factor of > 5000 was realized against electron, muon, and pions, and it contributed much to identify the antiprotons under very much reduced background, as discussed later.

(iii) The second level trigger (track-trigger) to select the rigidity-band was re-configured by using the TOF counters (instead of ODC) and the IDCs. The ODCs were dismounted to provide the space for the Aerogel Cherenkov counters.

(iv) The data acquisition efficiency was improved with a new trigger system and event builder which may realize parallel on-line data process. As the result, the dead time fraction was reduced from 39 % to 13 %.

(v) On-board data analysis by using Transputer banks in parallel data analysis for further efficient data storage on board. The on-board data storage capacity was also improved to 40 Gbyte (EXB-8900).

3. Balloon Flights

The BESS balloon flights were launched from Lynn Lake (N56-48' and W101-25') directing to Peace River, in Canada, since summer, 1993. Four balloon flights were very successfully carried out with scientific observation at an altitude of 36.5 km with a residual atmosphere of 5 g/cm^2. Figure 3 shows those flight path. The flight in 96 was not successful because of an aerodynamic problem just after balloon launching. The integrated flight time-duration has reached about 60 hours and the integrated net data acquisition time of 40 hours. During those flights, 30 million cosmic ray events were integrated and recorded into data tapes. Those flights conditions are summarized in Table 1 as well as a brief scientific results. Figure 4 shows an event display during ballooning in BESS-97.

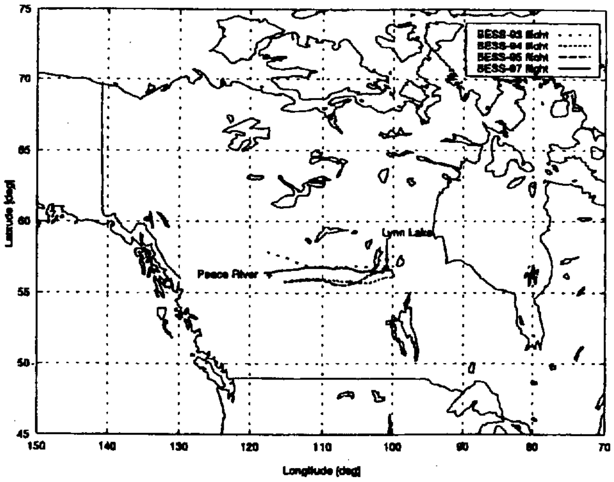

Fig. 3. BESS flight path in BESS-93 to -97.

4. Scientific Results

4.1. Antiproton Flux Measurement [4-7]

The flight data are processed to determine the track curvature (rigidity^{-1}) and "time-of-flight" (velocity, β^{-1}) for each event as follows;

(1) Select single tracks,
(2) Select high quality tracks,

Table 1. BESS Flight Summary

		BESS-93	BESS-94	BESS-95	BESS-97
Flight Conditions:	Launching Date	July 26	July 31	July 25	July 27
	Floating Time	17.5 hrs	17.0 hrs	17.5 hrs	20.5 hrs
	Observation Time	14.0 hrs	15.0 hrs	12.3 hrs	18.3 hrs
	QAQ time effic.	61 %	50 %	61 %	87 %
	Live Time	8.6 hrs	7.3 hrs	7.5 hrs	16.0 hrs
Detector Conditions:	Geom. Acceptance	0.32	0.30	0.30	0.25 m2.st
	Rigidity Resolution	0.5 %$\cdot$GV^{-1}	0.5 %$\cdot$GV^{-1}	0.5 %$\cdot$GV^{-1}	0.5 %$\cdot$GV^{-1}
	TOF hodo. width	0.2 m	0.2 m	0.1 m	0.1 m
	TOF Resolution	300 ps	300 ps	110 ps	75 ps
	Track Trigger by	ODC&IDC	ODC&IDC	ODC&IDC	TOF&IDC
	Particle ID by	TOF	TOF	TOF	TOF & AC
	Aerogel Ch. Index	—	—	—	1.03
	p/p-bar ID Range	0.6-1.2 GeV/c	0.6-1.2 GeV/c	0.6-2.1 GeV/c	0.6-3.5 GeV/c
	He ID Range	1 - 16 GV/c	1 - 16 GV/c	1 - 16 GV/c	1 - 16 GV/c
	On-line event swl.	—	—	—	ON (half period)
Observations:	Recorded Date Size	4.5 Gbytes	6.5 Gbytes	8 Gbytes	31 Gbytes
	Recorded Events	4.0 x 10^6	4.2 x 10^6	4.5 x 10^6	16.2 x 10^6
	p-bar Identified	6	2	43	410
	Up. Limit, He-/He	4.4 x 10^5	8 x 10^6	3.1 x 10^6	

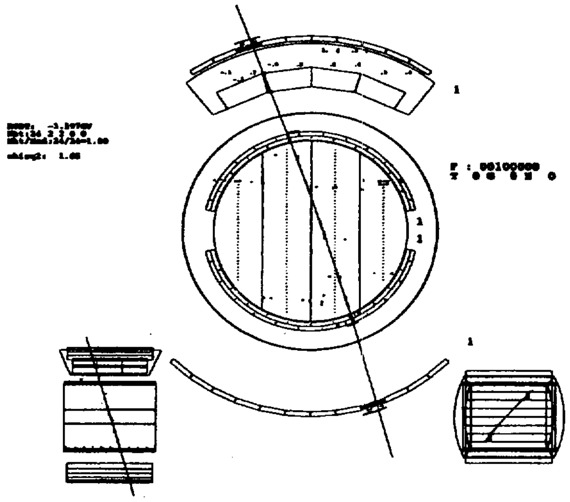

Fig. 4. An event display observed in BESS-97.

(3) Analysis on velocity as a function of rigidity,
(4) Select proper dE/dx both in TOF & JET,
(5) Select rigidity range for positive and negative particle symmetrically (in velocity vs rigidity plot),
(6) Cut electrons/muons/pions by using Aerogel counters (only for the data in BESS-97).

Figure 5 shows plots of velocity v.s. rigidity for the data obtained in (a) BESS-93&94, and in (b) BESS-95. It is well recognized that antiprotons are clearly identified with improved resolution for the velocity measurement in BESS-95. Figure 5 (c) and (d) shows the same plot for the data obtained in BESS-97 (c) without, and (d) with cutting electrons/muons/pions by using Aerogel Cherenkov counter veto signal. According to these process, cosmic ray antiprotons were unambiguously identified with time-of-flight measurement. Totally more than 400 antiprotons were detected in the energy range of 0.16 - 2.5 GeV.

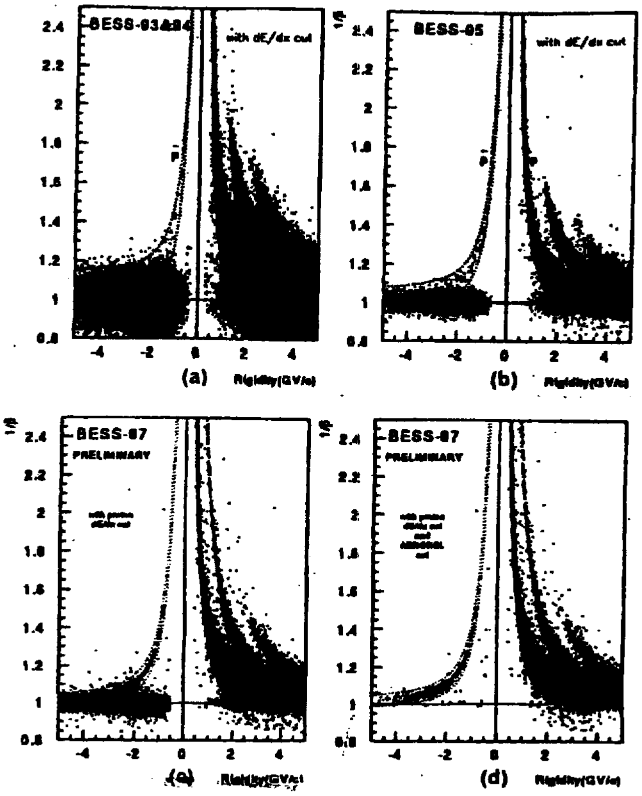

Fig. 5. Particle separation in BESS 93-97. Velocity (1/β v.s. 1/R)

Based on those antiproton events obtained in the flight of BESS-95, the low energy antiproton spectrum at the top of the atmosphere (TOA) was obtained in the following process;

(1) Calibration of the geometrical acceptance,
(2) Calibration for efficiency of pattern (track quality)selection, and rigidity-selection,
(3) Correction for interaction of antiproton with residual air as well as antiproton produced in the air.

Figure 6 shows antiproton flux on TOA obtained based on 43 antiproton events detected in BESS-95 together with previous measurements and various theoretical calculation [7]. Our data are consistent with recent measurements which have larger statistical errors. The energy spectrum obtained appears to be flat below 1 GeV within present statistical accuracy, and does not exhibit the steep decline as expected for the secondary antiprotons in the standard Leaky Box model.

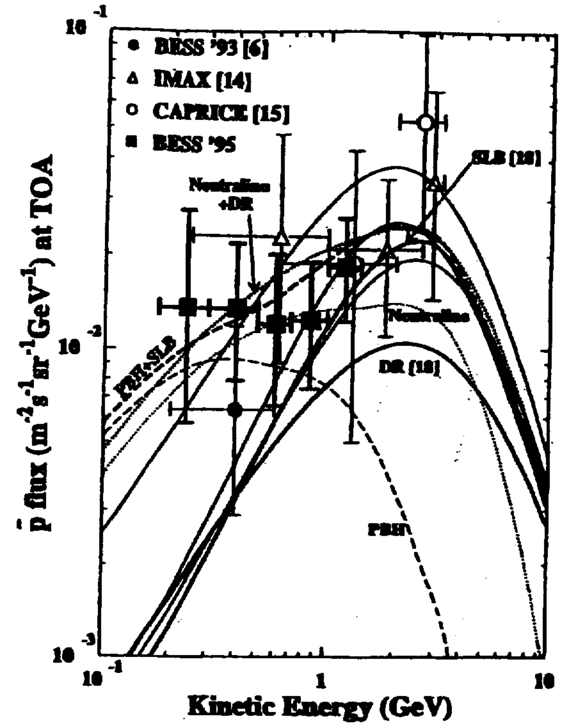

Fig. 6. Low energy antiproton fluxes measure by BESS in comparison with other experiment, and various model calculation.

4.2. Antimatter search[8,9]

Preliminary data reduction process to search for antihelium is the same as those for the antiproton analysis except for the larger dE/dx selection. Major background in the antihelium search comes from the limit of resolution of the rigidity measurement. The rigidity range of the antihelium search is limited within 0.5 - 16 GV/c in the present detector performance. Figure 7 shows 1/rigidity distribution of the events those which survive all selections [9].

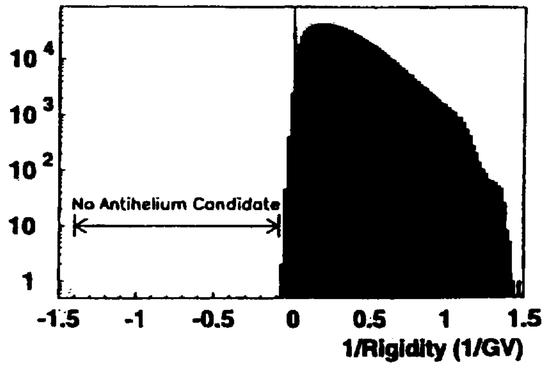

Fig. 7. 1/R distribution of the events corresponding helium/antihelium (Z=2).

Those events in the negative region are apparently the spill-over from the positive region due to the finite 1/R resolution. There exist no events to the left of -0.0625 $(GV/c)^{-1}$, which corresponds to 1 GV/c at the top of the atmosphere (TOA) after correcting for the energy losses in the instrument and the air. Therefore, we conclude that we have observed no antihelium in the rigidity region from 1 to 16 GV/c at TOA.

The corresponding limit on the antihelium /helium flux ratio at TOA is obtained by dividing the upper-limit on the number of antihelium by the total number of helium . The resultant 95 % C.L. upper limit on the antihelium/helium flux ratio at the top of the atmosphere is 3.1×10^{-6} in the rigidity region from 1 to 16 GV/c. The upper limit on the antihelium flux integrated over the rigidity region is $6 \times 10^{-4} m^{-2} sr^{-1} s^{-1}$. It should be noted that these upper limits are very conservative and are valid for any hypothetical antihelium spectrum.

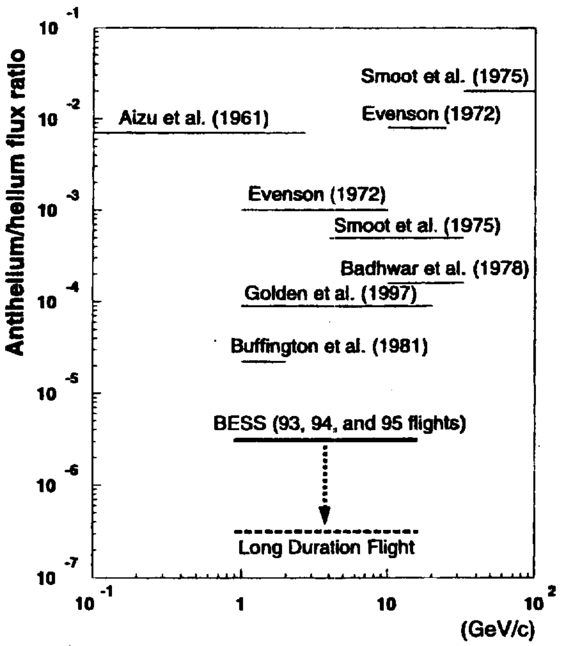

Fig. 8. The resultant upper limit of antihelium /helium flux ratio measured by BESS together with previous experimental limits.

The limit on the flux ratio obtained by this work is shown in Fig. 8 together with the previous searches [9]. Our flux ratio is a factor 7 improvement over the limit of Buffingnton et al. [13] those who looked for the annihilation signal of low rigidity (1-2 GeV) antihelium in a spark chamber calorimeter, and is 30 times more stringent than the limit of Golden et al.[23] those who cover a rigidity region similar to ours. The large acceptance of the BESS spectrometer made it possible to set this limit.

4.3. Summaries and Future Plans

The scientific progress in the BESS experiment in BESS-93 to BESS-97 by now is summarized as follows:

i) The low energy cosmic ray antiprotons below 1 GeV were first detected with unambiguous mass measurement of antiprotons. The absolute fluxes of the cosmic-ray antiprotons at a solar minimum were measured in the energy range of 0.18 qz - 1.4 GeV, based on 43 events detected in the BESS-95 data. The measured energy spectrum appears to be flat below 1 GeV, and it might suggest possibility of primary antiproton from novel sources such as the evaporating primordial black holes, while the possibility of secondary antiproton still can be explained within the statistical uncertainties.

ii) No antihelium candidates have been detected. The corresponding upper limit on the antihelium/helium flux ratio at the top of the atmosphere is 3.1×10^{-6} in the rigidity region from 1 to 16 GV/c.

iii) Analysis for the data obtained in BESS-97 is in progress and further accurate results may be expect.

The BESS experiment intends of further sensitive search for cosmic-ray antiparticles and to study the effect of the solar activity in the following scientific objectives.

- Precise measurement of cosmic-ray antiproton spectrum to establish the secondary antiproton flux around at the peak, 2 - 3 GeV, with the absolute flux accuracy of 10 %.
- Sensitive search for novel primary components of origin of the low energy antiprotons, such as evaporation of primordial black holes, or annihilation of super-symmetric relics, by using possible different effect on the novel primary sources from the one for secondary antiprotons during a solar cycle [18, 19].
- Highly sensitive search for primordial antiparticle, and/or antihelium.
- Precise measurement of cosmic-ray spectra (p, He) over a full solar cycle to examine cosmic-ray propagation model, and precise calculation of atmospheric neutrino flux.

To meet those scientific objectives, BESS experiment intends to realize long duration flights for a level of 10 days, as a future program.

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