The BESS experimental astroparticle physics program

Makoto Sasaki, John W. Mitchell
for the BESS Collaboration

Outline:
• Overview of the BESS Program
• BESS-Polar Program
• New Results from BESS-Polar II
Overview of the BESS Program
BESS Collaboration
Balloon-borne Experiment with a Superconducting Spectrometer

High Energy Accelerator Research Organization (KEK)

The University of Tokyo

Kobe University

National Aeronautical and Space Administration Goddard Space Flight Center

University of Maryland

University of Denver

Institute of Space and Astronautical Science/JAXA
BESS Program

- **Balloon-borne Experiment**
  - Steady improvement
    - Continuously upgrade and modify detector components
    - Various new scientific subjects
  - Long period of successive observations
    - Cover more than full cycle (11 years) of solar activity
- **Education/Training**
  - Young people can be responsible for essential parts of the experiment (20 students/engineers awarded with Ph.D)

with a

- **Superconducting Spectrometer**
  - Large acceptance
    - High statistics
  - Uniform magnetic field
    - High resolution MDR 200 – 1400 GV
  - Transparent
    - Thin Solenoid 4.4 g/cm² (2.2 g/cm²)
  - Definitive mass ID
BESS Program

- Balloon-borne Experiment
  - Steady improvement
    - Continuously upgrade and modify detector components
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with a

- Superconducting Spectrometer
  - Large acceptance
    - High Statistics
  - Uniform magnetic field
    - High, uniform resolution (MDR ~ 200 GV)
  - Transparent
    - Thin Solenoid 4.4 g/cm² (2.2 g/cm²)
  - Definitive mass ID

\[ m = ZeR \sqrt{\frac{1}{\beta^2} - 1} \]

- JET, IDC drift chambers: rigidity
- Time-of-flight system (TOF): velocity and charge
- Aerogel Cherenkov detector (ACC, n=1.02/1.03): background rejection
Science Objectives

• Measure cosmic-ray particles and antiparticles as a probe to study the early Universe
  – Antinuclei:
    - Antihelium/antiduteron; none observed in cosmic rays by any instrument
      • Fundamental question: symmetry of matter and antimatter
  – Antiprotons:
    - $\bar{p}/p \sim 10^{-5}$ @ 1 GeV
      • Mainly secondary origin; cosmic ray interactions with ISM
      • Possible small primary component;
        - Evaporation by Hawking radiation of primordial black holes (PBH) initially near $\sim 5 \times 10^{14}$ g?
        - Annihilation of super-symmetric particles?

• Quantify charge-sign dependent Solar modulation

• Measure cosmic ray spectra and composition
  – p, He, Li, Be isotopic and elemental spectra
  – B, C, N, O elemental spectra
  – Atmospheric muons
BESS Flight History

- **Nine** northern latitude BESS flights (1+ days) 1993-2002
- **Two** Antarctic BESS-Polar flights (8.5 & 24.5 days) 2004, 2007

Scientific observation

11 scientific balloon flights during 1993-2008
**BESS Flight History**

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<tr>
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<th>BESS-93,94</th>
<th>BESS-95</th>
<th>BESS-97,98</th>
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<th>BESS-TeV</th>
<th>BESS-Polar</th>
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</tr>
<tr>
<td>(\sigma_{\text{TOF}}) = 300 ps</td>
<td>(\sigma_{\text{TOF}}) = 110 ps</td>
<td>(\sigma_{\text{TOF}}) = 70 ps</td>
<td>Shower Counter</td>
<td>New ODC's</td>
<td>New Mag (ultra thin)</td>
<td></td>
</tr>
<tr>
<td>(97\ n=1.03)</td>
<td>(98\ n=1.02)</td>
<td>Aerogel C</td>
<td>2(\chi_0) Lead e/(\mu) sep.</td>
<td></td>
<td></td>
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</tr>
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<td>6, 2</td>
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- **Nine** northern latitude BESS flights (1+ days) 1993-2002
- **Two** Antarctic BESS-Polar flights (8.5 & 24.5 days) 2004, 2007

<table>
<thead>
<tr>
<th>Flight</th>
<th>Year</th>
<th>Vessel</th>
<th>TOF σ</th>
<th>Additional Details</th>
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<tbody>
<tr>
<td>BESS-93,94</td>
<td>2001-2002</td>
<td>Larger</td>
<td>300 ps</td>
<td>Shower Counter, Aerogel C, 97 n=1.03, p 0.2-3.5 GeV</td>
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<tr>
<td>BESS-95</td>
<td>2001-2002</td>
<td>Larger</td>
<td>110 ps</td>
<td>98 n=1.02, e/μ sep.</td>
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<tr>
<td>BESS-97,98</td>
<td>2001-2002</td>
<td>Larger</td>
<td>70 ps</td>
<td>2X0 Lead</td>
</tr>
<tr>
<td>BESS-99,00</td>
<td>2004, 2007</td>
<td>Larger</td>
<td>70 ps</td>
<td>New ODC’s, New JET/IDC’s</td>
</tr>
<tr>
<td>BESS-TeV</td>
<td>2004, 2007</td>
<td>Larger</td>
<td></td>
<td>p/He up to 1 TeV</td>
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</table>

<table>
<thead>
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<th>Count 2</th>
<th>Count 3</th>
<th>Count 4</th>
<th>Count 5</th>
<th>Count 6</th>
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<tr>
<td>0.2-0.6 GeV</td>
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# Evolution of the BESS Instrument

<table>
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<tr>
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<tbody>
<tr>
<td>$\sigma_{\text{TOF}}$</td>
<td>300 psec</td>
<td>110 psec</td>
<td>70 psec</td>
</tr>
<tr>
<td>$N_{\text{obs}}$</td>
<td>8</td>
<td>43</td>
<td>~500/year</td>
</tr>
<tr>
<td>$E_p$</td>
<td>0.2 ~ 0.6 GeV</td>
<td>0.2 ~ 1.4 GeV</td>
<td>0.2 ~ 4.2 GeV</td>
</tr>
<tr>
<td></td>
<td>First mass-ID</td>
<td>New TOF</td>
<td>Cherenkov Veto</td>
</tr>
</tbody>
</table>
Evolution of the BESS Instrument

First mass-ID

New TOF

Cherenkov Veto

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**Cosmic Ray \(\bar{P} \)**

- **BESS(95+97)**
- **BESS(93)**
- **IMAX**
- **CAPRICE**

![Graph showing the evolution of the BESS Instrument with data points and curves representing different energy ranges.](image)

- **Kinetic Energy (GeV)**:
  - **1993**
  - **1994**
  - **1995**
  - **1997~**

<table>
<thead>
<tr>
<th>Year</th>
<th>TOF, dE/dx and Čerenkov Veto</th>
<th>psec</th>
<th>~500/year</th>
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<tr>
<td>BESS '95</td>
<td>TOF</td>
<td>70</td>
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<td></td>
</tr>
<tr>
<td>BESS '97</td>
<td>TOF, dE/dx</td>
<td>~500</td>
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(S. Orito et al., PRL, Vol. 84, No. 6, 2000)
Most antiprotons are nuclear secondaries - characteristic spectral peak ~2 GeV

Some indication of additional component in low energy Solar minimum data!

(S. Orito et al. PRL, Vol. 84, No. 6, 2000)
BESS Flight History

- **Nine** northern latitude BESS flights (1+ days) 1993-2002
- **Two** multi-day (8.5 & 24.5 days) Antarctic flights in 2004, 2007

### 2001-2002
- **BESS-93,94**: Larger Vessel
  - $\sigma_{TOF} = 300$ ps
  - Aerogel C
  - $p$ 0.2-3.5 GeV
  - $n=1.03$
- **BESS-95**: Larger Vessel
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- **BESS-99,00**: Larger Vessel
  - Shower Counter
  - $2X_0$ Lead e/$\mu$ sep.

### 2004, 2007
- **BESS-TeV**: Larger Vessel
  - New ODC's
  - New JET/IDC's
  - $p/He$ up to 1 TeV
- **BESS-Polar**: No Vessel
  - New Mag (ultra thin)

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BESS-TeV Flight

\[ p + p \rightarrow p + \bar{X} \]

\[ p + A \rightarrow \pi + \pi + \ldots \]
\[ \pi \rightarrow \mu + \nu_\mu \]
\[ \mu \rightarrow e + \nu_e + \nu_\mu \]

Fundamental Data for
- Cosmic-ray physics
- Atmospheric Neutrino Calculation

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Fundamental Data for Cosmic-ray physics

Measurements with BESS
- Proton up to 100 GeV
- Helium up to 50 GeV/n
- > 500 GeV
- > 200 GeV/n

Upgrade of the BESS spectrometer
Improvement of rigidity resolution
(Maximum Detectable Rigidity, MDR)
BESS-TeV Flight

\[ p + p \rightarrow p + \bar{X} \]

\[ p + A \rightarrow \pi + \pi + \cdots \]

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22\textsuperscript{nd} European Cosmic Ray Symposium

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Measurements with BESS
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Upgrade of the BESS spectrometer
Improvement of rigidity resolution
(Maximum Detectable Rigidity, MDR)

Proton
Helium

Flux \times E_k^{2.5} (m^{-2} \text{sr}^{-1} \text{sec}^{-1} \text{GeV}^{1.5})

Kinetic energy \text{E}_k (\text{GeV})

Deflection resolution \Delta R (\text{GV})
**BESS-TeV Flight**

\[ p + p \rightarrow p + X \]

\[ p + A \rightarrow \pi + \pi + \ldots \]

\[ \pi \rightarrow \mu + \nu_\mu \]

\[ \mu \rightarrow e + \nu_e + \nu_\mu \]

Fundamental Data for
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**Measurements with BESS**

- **Proton**
  - up to 100 GeV
  - \(\rightarrow\) \(> 500\) GeV
- **Helium**
  - up to 50 GeV/n
  - \(\rightarrow\) \(> 200\) GeV/n

**Upgrade of the BESS spectrometer**

- Improvement of rigidity resolution
  - (Maximum Detectable Rigidity, MDR)

**Graph**

- Proton and Helium fluxes as a function of kinetic energy \(E_k\) in \(m^2 sr^{-1} GeV^{-1}\).

- BESS-TeV 2002
- BESS 1998
BESS Flight History

- **Nine** northern latitude BESS flights (1+ days) 1993-2002
- **Two** Antarctic BESS-Polar flights (8.5 & 24.5 days) 2004, 2007

### Flight Details:

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### Performance:

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### Equipment:

- BESS-93, 94
- BESS-95
- BESS-97, 98
- BESS-99, 00
- BESS-TeV
- BESS-Polar

### Technology:

- Aerogel C
- 97 n=1.03
- 98 n=1.02
- p/He up to 1 TeV

### Sensor Types:

- New Mag (ultra thin)
Proton Flux Modulation

Proton spectra measured to ~500 GeV

Proton spectra to 100 GeV measured for full solar cycle

Upper solid line shows local interstellar (LIS) proton spectrum from best fit to BESS data (spectral index 2.76)

Lower curves show the variation with time (Solar modulation) of the measured proton spectra extrapolated to the top of the atmosphere
Solar Modulation

Antiproton/Proton Ratio

- Antiprotons and protons differ only in charge-sign
- Simultaneous measurements of proton and antiproton spectra provide a powerful test of models of charge-dependent Solar modulation of cosmic-rays (protons are most sensitive)
- More work is required in the interpretation

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Antimatter Search
( Expected from BESS-Polar )

- Secondary D probability is negligible at low energies due to kinematics
- Any observed D almost certainly has a primary origin!
- D 95% C.L. upper limit (first reported) $1.92 \times 10^{-4}$ (m$^2$ s sr GeV/n)$^{-1}$
- $\overline{\text{He}}$ 95% C.L. upper limit
  - BESS-TeV $1.4 \times 10^{-4}$ (5 – 500 GV)
  - BESS-Polar I $4.4 \times 10^{-7}$ (1 – 20 GV)
  - Combined data $2.7 \times 10^{-7}$ (1 – 14 GV)

BESS-Polar II flight in 2007 with a sensitivity $3 \times 10^{-8}$
BESS-Polar Program
BESS-Polar Program

Very precise measurement
Antiprotons to lower energy

Around south pole, Antarctica
Long duration flight
High latitude

With a new spectrometer
Maintain large acceptance
Minimum material in particle path

Flown Twice
BESS-Polar I (2004)
BESS-Polar II (2007/2008)
Minimize material in spectrometer
New detector (Middle TOF), No pressure vessel
Low power electronics
Solar power system, Longer cryogen life, LHe

Energy range extended down to 0.1 GeV
Long duration flight
BESS-Polar Program

After assembly
BESS-Polar Program

- Digital events directly transfer to Event Builder for DAQ
  >> compact, Fast and Power Saved

Present BESS
- TOF
- ACC
- JET/IDC
- CAMAC VME Crate
  → Event Builder
  → Event Filter
  → Storage controller
  → Storage Device

BESS-Polar
- TOF
- mTOF
- ACC
- JET/IDC
- DSP
- DSP
- DSP
- PLD
- Event Build System
  → Storage Device

HDD: > 1 TB
# BESS-Polar Program

<table>
<thead>
<tr>
<th></th>
<th>BESS</th>
<th>BESS-Polar</th>
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<tbody>
<tr>
<td>Geom. Acceptance:</td>
<td>0.3</td>
<td>0.3 m²•sr</td>
</tr>
<tr>
<td>Material for trigger:</td>
<td>18 g/cm²</td>
<td>4.5 g/cm²</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>1.0 T</td>
<td>0.8 T</td>
</tr>
<tr>
<td>Weight</td>
<td>2.2</td>
<td>2.0 tons</td>
</tr>
<tr>
<td>Power</td>
<td>Battery</td>
<td>Solar-panel</td>
</tr>
<tr>
<td>Comsumption</td>
<td>1.2 kW</td>
<td>450 W</td>
</tr>
<tr>
<td>Cryogen life</td>
<td>5.5</td>
<td>20 days</td>
</tr>
</tbody>
</table>
BESS-Polar I Flight
BESS-Polar I Flight

Status of the BESS-Polar I Flight

Observation Time: 8.5 days
Float Time: 8.5 days (12/13/2004-12/21/2004)
Events recorded: > 9 x 10^8
Data volume: ~ 2.1 terabytes
Data recovery: completed 2004
Payload recovery: completed 2004

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BESS-Polar I Results

Antirotton Flux

• Upper dashed curve is leaky box calculation with spherically symmetric modulation @ 550 MV to fit BESS (95+97) data.
• BESS-Polar I data at higher solar activity (851 MV - lower dashed curve) are consistent with secondary production.
• Solid curve is diffusive reacceleration with break for 30° Solar tilt angle
BESS-Polar II

BESS-Polar II Spectrometer improvement

• **Longer observing time** (10 days → 20 days)
  – New magnet with new cryostat
    • Larger tank, third radiation shield
  – Increase gas bottle for chamber gas
  – Increase storage size (3.6 Tbyte → 16 Tbyte)

• **Detector improvement**
  – Pressurized TOF PMT units
  – ACC rejection power
  – MTOF resolution
  – JET noise reduction
BESS-Polar II

BESS-Polar II Spectrometer improvement
BESS-Polar II Flight
BESS-Polar II Flight
BESS-Polar II Flight

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BESS-Polar II Flight

Status of the BESS-Polar II Flight

Observation Time: **24.5** days

Float Time: **29.5** days (12/23/2007-01/21/2008)

Events recorded: > **$4.7 \times 10^9$**

Data volume: ~ **13.5** terabytes

Data recovery: **completed** Feb 3, 2008

Payload recovery: **completed** Jan 16, 2010
BESS-Polar II Flight

BESS-Polar II Flight Termination

- Location 83° 51.23’ S, 73° 5.47’ W
- Instrument landed upright, with minimal damage
- Data successfully recovered February 3, 2008!
BESS-Polar II Flight

BESS-Polar II Recovery

- Staged from WAIS Divide/Byrd Surface Camp
- Camped on site 13 days for disassembly
- Basler (turboprop DC-3) used due to range and instrument size
BESS-Polar II Flight

BESS-Polar II Spectrometer Status

- Detectors are in good condition
- No additional damage incurred during recovery process and shipping
- Currently the magnet is being refurbished and reassembled in Japan
- Basic functionality test of the TOF and Cherenkov Counter indicate almost all PMTs are still operational.
- Basic functionality test of the JET chamber and IDC conducted. Applied full HV and no wire broken.

Magnet refurbish @ TOSHIBA, Japan
BESS-Polar II Flight

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Future Science Objectives

- Be isotope measurement
- $e^+ / e^-$ measurement
- Continuation of current science objectives
## Flight Summary

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<tr>
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<th>BESS-Polar I</th>
<th>BESS-Polar II</th>
</tr>
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<tbody>
<tr>
<td>Total Floating Time</td>
<td>8.5 days</td>
<td>29.5 days</td>
</tr>
<tr>
<td>Observation Time</td>
<td>8.5 days</td>
<td>24.5 days</td>
</tr>
<tr>
<td>Recorded Event</td>
<td>900 M</td>
<td>4700 M</td>
</tr>
<tr>
<td>Recorded Data Size</td>
<td>2.1 TBytes</td>
<td>13.5 TBytes</td>
</tr>
<tr>
<td>Trigger Rate</td>
<td>1.4 kHz</td>
<td>2.4 kHz</td>
</tr>
<tr>
<td>Live Time Fraction</td>
<td>0.8</td>
<td>0.82</td>
</tr>
<tr>
<td>Altitude</td>
<td>37 ~ 39 km</td>
<td>34 ~ 38 km</td>
</tr>
<tr>
<td>Residual Air Pressure</td>
<td>4 ~ 5 g/cm²</td>
<td>4.5 ~ 8 g/cm²</td>
</tr>
</tbody>
</table>
New Results from BESS-Polar II
BESS-Polar II Spectrometer

Performance

JET position resolution in r-\(\phi\) plane @ each drift length

- 119\(\mu\)m (Polar I)
- 116\(\mu\)m (Polar II)

JET position resolution in z plane

- 38mm (Polar I)
- 25mm (Polar II)

Acceptance

<table>
<thead>
<tr>
<th></th>
<th>BESS-Polar I</th>
<th>BESS-Polar II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Both-side</td>
<td>8/22</td>
<td>20/22</td>
</tr>
<tr>
<td>Single-side</td>
<td>10/22</td>
<td>2/22</td>
</tr>
<tr>
<td>Dead</td>
<td>4/22</td>
<td>0/22</td>
</tr>
<tr>
<td>Acceptance</td>
<td>66%</td>
<td>100%</td>
</tr>
</tbody>
</table>

List of survival TOF PMTs during Flight

TOF timing resolution

- 160\(\text{ps}\) (Polar I)
- 120\(\text{ps}\) (Polar II)
BESS-Polar II Spectrometer Performance

<table>
<thead>
<tr>
<th></th>
<th>BESS-Polar I</th>
<th>BESS-Polar II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficency</td>
<td>92%</td>
<td>97%</td>
</tr>
<tr>
<td>Rejection power</td>
<td>1500</td>
<td>6800</td>
</tr>
</tbody>
</table>

N/A (Polar I)
59mm (Polar II)
Antiproton Measurement

There is no background contamination below 1 GeV!

\[ \beta^{-1} \text{ vs Rigidity plots in BESS-Polar II} \]
The antiproton observation was extended to lower energy by using the Middle TOF. We are now finalizing this analysis.
Antiproton/Proton Ratio

- Agree with the PAMELA data.
- We are now finalizing calibration and including MTOF information for full BESS-Polar II flight data.
- Antiproton flux will be coming soon.
Antihelium Search

Particle Identification using the TOF information

No antihelium candidate was found between -14 and -1 GV after all selection among $4 \times 10^7$ Helium events.

The figure below shows remaining events after all selections applied.

No He candidate

No antihelium candidate was found between -14 and -1 GV after all selection among $4 \times 10^7$ Helium events.
BESS-Polar I antihelium upper limit $4.4 \times 10^{-7}$.
Antihelium Limit

- BESS-Polar I antihelium upper limit $4.4 \times 10^{-7}$.

- We set the upper limit of $9.4 \times 10^{-8}$ by using the BESS-Polar II flight data.
Antihelium Limit

- BESS-Polar I antihelium upper limit $4.4 \times 10^{-7}$.

- We set the upper limit of $9.4 \times 10^{-8}$ by using the BESS-Polar II flight data.

- We set the upper limit of $6.9 \times 10^{-9}$ by using all BESS flight data, which is improved by two orders of magnitude since our first report.
Summary

- BESS-Polar II successfully gathered cosmic-ray data in the solar minimum period with 10 times statistics of the previous solar minimum (’95 + ‘97) at low energy.
- BESS-Polar II Spectrometer was recovered from Antarctica and magnet is now being refurbished. Detector components are still in good shape after two winters on ice in Antarctica.
- Antiproton/proton ratio was reported using ¼ of BESS-Polar II data. Analysis for full flight data is being finalized.
- We searched for antihelium in the BESS-Polar II data. No antihelium candidate was found and we set a stringent upper limit on antihelium/helium.
End of the presentation
Appendix
BESS swam the Canadian Lake