Precise Measurements of Hydrogen and Helium Isotopes with BESS-Polar II

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Objectives of the BESS Program

**Precise Antiproton Measurements:**
- If deviation observed from expected secondaries
  - Primordial Black Hole or Dark Matter

**Search for Antinuclei:**
- Antideuteron
- Antihelium
- Novel Origins
- Antimatter Asymmetry

**Precise Measurements of H & He Spectra:**
- Solar Modulation
- Secondary Production in ISM and Atmosphere

**Precise Measurements of H & He Isotope Spectra:**
- $^1$H, $^4$He are primaries,
- $^2$H, $^3$He are secondaries
- Secondary-to-Primary ratios ($^2$H/$^1$H, $^2$H/$^4$He, $^3$He/$^4$He)
  - Probe Galactic cosmic-ray propagation
  - Test if propagation history is the same for light and heavy elements

K. Abe et al., PRL 108, 051102, 2012
K. Abe et al., PRL 108, 131301, 2012

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BESS Flights

9 Northern latitude balloon flights (~1 day) / 2 Antarctic flights

<table>
<thead>
<tr>
<th>BESS-Polar I</th>
<th>BESS-Polar II</th>
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<tbody>
<tr>
<td><strong>Launch date</strong></td>
<td>Dec. 13th, 2004</td>
</tr>
<tr>
<td><strong>Observation time</strong></td>
<td>8.5 days</td>
</tr>
<tr>
<td><strong>Cosmic-ray observed</strong></td>
<td>9 x 10^8 events</td>
</tr>
<tr>
<td><strong>Flight altitude</strong></td>
<td>37-39 km (5-4 g/cm^2)</td>
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5 times more events recorded with BESS-Polar II.

✿ **Significantly reduces statistical uncertainties** for H and He isotope flux measurements.
Determination of particle’s characteristics:

**Velocity** $\beta$: Use of top-bottom (or top-middle) TOFs  
Resolution of $\sim$ 2%.

**Charge** $Z$: From $dE/dx$ in TOFs  
Resolution of 0.4% at 1 GV. MDR of 240 GV.

**Rigidity** $R$: From gyroradius $\rho$ in mag. field $B = 0.8$ T  
$R = \frac{\rho}{B}$

**Mass** $M$: With $M = ZR\sqrt{1/\beta^2} - 1$

**Kinetic energy per nucleon** $E_k$:  
$E_k = \sqrt{R^2Z^2 + M^2} - M$

The BESS-Polar instrument allows to measure hydrogen and helium isotopes from $\sim 0.2$ GeV/n to $\sim 1.5$ GeV/n.
Data Selection

- **Geometric Acceptance:**
  Events crossing top & bottom TOFs => 0.29 m$^2$sr (GEANT4 MC simulations)
  2 malfunctioning PMTs were excluded out of 44.

- **Charge selection:** Selection of $Z=1$ or $Z=2$ particles with top TOF $dE/dx$.
  
  - **“Single-track” selection criteria:** Remove hadronic interacting events and ensure that particles are passing through the fiducial region of the JET.
    - 1 or 2 hits in top/bottom TOFs.
    - 1 reconstructed track.
    - 40 expected hits in JET.
    - Selection of $Z=1$ or $Z=2$ particles with LTOF $dE/dx$.
    - 1 hit in JET center.

  Cut efficiency of 53% for $Z=1$ and 44% for $Z=2$ particles.

- **“Quality” selection criteria:**
  Remove particles with poorly reconstructed tracks due to noise or detector limitations.
  - Good XY and YZ $\chi^2$.
  - $\Delta R^{-1} < 0.015$.
  - Hits < 100 in JET.
  - $L_{XY} > 500$ mm.
  - $3/4$ Vernier pads in each IDC layer.
  - TOF hit position – track position < 75 mm.

  Cut efficiency of 95%.

* Efficiencies were estimated using $Z=1$ and $Z=2$ flight data sub-samples preselected with top TOF and JET. MC simulations were used for cross checking.

H & He Isotopes with BESS-Polar II
Isotope Separation

$Z=1$ particles with BESS-Polar II (flight data)

- High mass separation power.
- $e^+$, $\mu^+$, $\pi^+$, $\kappa^+$ and $^3$H are mostly secondary particles produced in the atmosphere.
- Good mass resolution up to $\sim 4$ GV to separate isotopes.
- Reliable measurements, good agreement with theoretical lines, except at the lowest energies.

$Z=2$ particles with BESS-Polar II (flight data)

- Double Crystal ball functions are used for separation at the highest energies.

$^2$H identification

$0.45 < E_k < 0.50$ GeV/n

$1.05 < E_k < 1.19$ GeV/n

$^3$He identification

$0.45 < E_k < 0.50$ GeV/n

$1.05 < E_k < 1.19$ GeV/n
Flux Calculation:

Atmospheric Secondary Calculation:

Method from Papini et al., 1996.
Calculates secondaries considering 3 different physical processes: Ionization, attenuation and production.

The flux measured at TOI is used as starting point, and the Runge-Kutta method is employed to solve the equations numerically.

Atmospheric secondaries are negligible for $^3$He and $^4$He, above $\sim$0.4 GeV for $^1$H and above $\sim$0.8 GeV/n for $^2$H.
H and He Isotope CR Propagation with GALPROP

**GALPROP**: Realistic model that calculates CR propagation in the Galaxy. Incorporates as many processes and astrophysical data as possible to reproduce observations.

Use of modified version of GALPROP (Picot-Clemente et al., 2015):

The proton fusion process was implemented: \( p + p \rightarrow d + \pi^+ \)

This version uses also more accurate fragmentation cross sections at low energies (from Coste et al., 2012):

**Interstellar secondary-to-primary ratios using the modified version compared to default version of GALPROP with the Reacceleration model**

Fusion cross section Vs. proton kinetic energy (Lock and Measday, 1970)

Max at \(~600\) MeV
Hydrogen and Helium Isotope Fluxes

BESS-Polar II in good agreement in magnitude with PAMELA for $^1$H, $^2$H and $^4$He, as expected for same solar modulations.

BESS-Polar II fluxes higher than previous experiments, in agreement with NM data.

However: PAMELA $^2$H falling earlier than BESS-Polar II. PAMELA $^3$He at most 30% lower than BESS-Polar II.

GALPROP in general good agreement with same solar modulation parameter 450 MV with BESS-Polar isotope measurements.

GALPROP Model used:
- Diffusion $D_{xx} = \beta D_{0x}(\rho/\rho_0)^{\delta}$
- Reacceleration Model $D_{0xx} = 6.05 \times 10^{28}$ cm$^2$ s$^{-1}$; $\delta=0.34$, Valfvén=34 km s$^{-1}$.
2H/3H BESS-Polar II consistent with BESS-93 and PAMELA.

3He/4He not much affected by Solar modulations.
=> BESS-Polar II consistent within uncertainties with AMS-01 and BESS-93.

PAMELA 3He/4He significantly lower than other measurements, except IMAX-92 data that were taken at Solar maximum.

The version of GALPROP that includes deuteron fusion production and more accurate production cross sections agrees well with BESS-Polar II hydrogen and helium isotope fluxes and ratios, with a same Solar modulation parameter of 450 MV.
Conclusion

BESS-Polar II gives the most precise measurements of hydrogen and helium isotope fluxes and ratios in the range $0.2 \text{ – } 1.5 \text{ GeV/n}$.

Measurements are consistent with previous data (except PAMELA $^3\text{He}$) and with expectations for data taken during Solar minimum.

GALPROP was modified to be more suitable for hydrogen and helium cosmic-ray isotopes between 0.2 and 1.5 GeV/n:
- Implementation of proton fusion to deuteron (Acknowledgement to A. Strong).
- Adding more accurate low energy hydrogen and helium isotope cosmic-ray production cross-sections.

Although calculations still need improvement, predictions from GALPROP with reacceleration model fit well BESS-Polar II isotope measurements using one same Solar modulation parameter.

Hydrogen and helium isotope fluxes and ratios bring important information to better constrain cosmic-ray propagation models and parameters.