Nuclei Measurements with the Alpha Magnetic Spectrometer on the International Space Station

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On behalf of the AMS collaboration

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**The Alpha Magnetic Spectrometer**

Particles and nuclei are defined by their charge ($Z$) and energy ($E \sim P$)

- **TRD**
  - Identify $e^+$, $e^-$

- **Silicon Tracker**
  - $Z$, $P$

- **ECAL**
  - $E$ of $e^+$, $e^-$

**Z and P ~ E**

are measured independently by Tracker, RICH, TOF and ECAL
Beam Tests at CERN

AMS

27 km

7 km

p, e^+, e^-, π  20...400 GeV

2000 positions
In 5 years on ISS,
AMS has collected >80 billion cosmic rays.
To match the statistics,
systematic error studies are important.
Tracker (L1 – L9) + Magnet
Rigidity (momentum/charge)
Bending Coordinate Resolution $\approx 10 \mu m / 7.5 \mu m$
MDR $\approx 2 \text{TV} / 3.2 \text{TV}$

TOF
Velocity and Direction
$\Delta \beta / \beta^2 \approx 4\% / 2\%$

TRD, Tracker, RICH ,TOF, ECAL
Charge Magnitude Along Particle Trajectory, e.g.
$\Delta Z_{\text{Tracker}} \approx 0.05 / 0.07$
The isotropic proton flux $\Phi_i$ for the $i^{th}$ rigidity bin $(R_i, R_i + \Delta R_i)$ is:

$$\Phi_i = \frac{N_i}{A_i \epsilon_i T_i \Delta R_i}$$

To match the statistics of 300 million events, extensive systematic errors studies have been made.

1) $\sigma_{\text{trig.}}$: trigger efficiency

2) $\sigma_{\text{acc.}}$:
   a. the acceptance and event selection
   b. background contamination
   c. geomagnetic cutoff

3) $\sigma_{\text{unf.}}$:
   a. unfolding
   b. the rigidity resolution function

4) $\sigma_{\text{scale.}}$: the absolute rigidity scale
Trigger efficiency [4/4 TOF (+ VETO)] was measured using 1% prescaled event sample obtained with unbiased 3 out of 4 ToF coincidence trigger:

\[ \varepsilon_T = 90-95\% \text{ for protons, } 95-99\% \text{ for helium, } \sim 100\% \text{ } Z>2 \]

This systematic error is negligible (less than 0.1%) below 100GV and increasing \sim 1.5\% at highest rigidities
The detector is mostly made of C (73% by weight) and Al (17%). The inelastic cross sections of $p + C$ and $p + Al$ are known to few percent between 1 GV and 1.8 TV.

Using MC samples with cross sections scaled by $\pm 10\%$, we found that the errors on the proton flux due to uncertainty in inelastic cross sections are:

- $1\%$ [1 GV]
- $0.6\%$ [10-300 GV]
- $0.8\%$ [1.8 TV]
Nuclei Acceptance

eg. He+C and He+Al are measured only below 10 GV

→ New method to determine interactions from ISS data with AMS pointing in horizontal direction: 2+ days in total

\[ \Phi_i(R_i) = \frac{N_i}{T_i \varepsilon_i A_i \Delta R_i} \]

Method was verified by comparing this \( L8 \rightarrow L9 \) survival probability to one obtained from data collected in nominal AMS orientation:

For Helium \( \sim 1\% < 200 \text{ GV} \) increasing to \( \sim 2\% \) at highest rigidities
Correction of bin-to-bin migration is needed due to the finite tracker resolution.

\[ \Phi_i(R_i) = \frac{N_i}{T_i \varepsilon_i A_i \Delta R_i} \]

Bin-to-bin Migration

Unfolding

Entries

True spectrum

1/R

Resolution function 1/R

\[ \sigma = 1/\text{MDR} \]

Difference between different unfolding algorithms gives a systematic error \(~0.5\%\)
Tracker resolution

**Protons:**
- Resolution function from MC simulation
- Verified with:
  - 400 GeV/c Test Beams data
  - ISS data: tracker residuals, rigidity reconstruction (L1-L8) vs. (L2-L9)

**Nuclei:**
- Resolution function from MC simulation
- Verified with ISS data:
  - Tracker residuals
  - Rigidity reconstruction (L1-L8) vs. (L2-L9)

Uncertainty on the flux < 1% below 300 GV rising to 3% at 2 TV
Two contributions to the uncertainty:

1. **Residual tracker misalignment** \(\frac{1}{\Delta}\): checked with \(E_{ECAL}/R_{Tracker}\) ratio for electrons and positrons, limited by the current high energy positron statistics. The corresponding flux error is 2.5% @1 TV.

2. **Magnetic field**: Mapping measurement (0.25%) and temperature corrections (0.1%). Taken in quadrature and weighted by the measured flux rigidity dependence, this amounts to less than 0.5% systematic error on the flux.
Study the dependence of the integral of the proton flux above 30 GV on the angle $\Theta$ between the incoming proton direction and the AMS zenith axis.

This verifies the systematic error assigned to the acceptance.
Verification (II)

The monthly integral flux above 45GV is within the systematic error of 0.4%.

This verifies that the flux above 45GV shows no observable effect from solar modulation fluctuations and that the detector performance is stable.
The ratios of fluxes obtained using events which pass through different sections of L1 to the average flux is in good agreement and within the assigned systematic errors.

This verifies the errors assigned to the tracker alignment.
The flux obtained with only the inner Tracker (L2-L8) is in good agreement to the one obtained with the full span Tracker (L1-L9).

This verifies the error on the rigidity resolution function and the unfolding.
Proton Flux


Flux \times R^{2.7} [m^{-2}sr^{-1}sec^{-1}GV^{1.7}]

Rigidity [GV]

AMS-02
300 million events
Proton Flux

Flux $\times E_K^{2.7}$ [m$^{-2}$ sr$^{-1}$ sec$^{-1}$ GeV$^{-1.7}$]

Kinetic Energy ($E_K$) [GeV]

AMS-02
ATIC-2
BESS-Polar
CREAM
PAMELA
Double Power Law:

\[ \Phi = C \left( \frac{R}{45 \text{ GV}} \right)^\gamma \left[ 1 + \left( \frac{R}{R_0} \right)^{\Delta \gamma / s} \right]^s \]

\[ \gamma = -2.849^{+0.002}_{-0.002} \text{(fit)}^{+0.004}_{-0.003} \text{(sys)} \]

\[ \Delta \gamma = 0.133^{+0.032}_{-0.021} \text{(fit)}^{+0.046}_{-0.030} \text{(sys)} \]

\[ R_0 = 336^{+68}_{-44} \text{(fit)}^{+66}_{-28} \text{(sys)} \text{ [GV]} \]
Proton Spectral Index

\[ \Phi = C \ R \]

\[ \gamma = \frac{d \log (\Phi)}{d \log (R)} \]
Helium Flux


Flux $\propto R^{2.7}$ [m$^2$ sr$^{-1}$ s$^{-1}$ GV$^{1.7}$]

Rigidity [GV]

50 million events
Helium Flux

Flux $\times E_K^{2.7} [m^2 \cdot Sr^{-1} \cdot s^{-1} (GeV/n)^{1.7}]$

Kinetic Energy ($E_K$) [GeV/n]
Double Power Law: 

\[ \Phi = C \left( \frac{R}{45 \text{ GV}} \right)^\gamma \left[ 1 + \left( \frac{R}{R_0} \right)^{\Delta \gamma/s} \right]^s \]

\[ R \sim 3 \times \text{Flux} \]

\[ \gamma = -2.780 \pm 0.005 \text{(fit)} \pm 0.001 \text{(sys)} \]

\[ \Delta \gamma = 0.119^{+0.013}_{-0.010} \text{(fit)} +^{0.033}_{-0.028} \text{(sys)} \]

\[ R_0 = 245^{+35}_{-31} \text{(fit)} +^{33}_{-30} \text{(sys)} \]

\[ \chi^2 / d.f. = 25/27 \]

Fit to data

\[ \Delta \gamma = 0 \text{ or } R_0 = \infty \]
Helium Spectral Index

\[ \Phi = C R \]

\[ \gamma = \frac{d \log (\Phi)}{d \log (R)} \]

Spectral Index $\gamma$

Rigidity [GV]
Proton/Helium Flux Ratio

Consistent with a single power law above 45 GV

AMS-02
Fit to $\frac{\Phi_p}{\Phi_{He}} = C R^\gamma$

$\chi^2/d.f. = 22/29$
Proton/Helium Ratio Spectral Index

\[ \gamma_{p/He} = -0.077 \pm 0.0073 \]

Constant above 45 GV
Light Nuclei Analysis

Charge Resolution ($Z=6$)

- Tracker Plane 1: 0.30
- TRD: 0.33
- Upper TOF: 0.16
- Inner Tracker 2-8: 0.12
- Lower TOF: 0.16
- RICH: 0.32
- Tracker Plane 9: 0.30

![Diagram of AMS-02 detector system with charge resolution data for various elements.](image)
Acceptance for Light Nuclei Analyses

Protons, Helium: Tracker L1-L9

Z>2: Tracker L1-L8 for Rigidities <1TV

Tracker

ECAL

RICH

TOF

TRD

MAGNET
There is a small background from higher charge nuclei interactions inside AMS, such as
Carbon -> Lithium
Carbon -> Boron or
Oxygen -> Carbon or

Due to their abundance in cosmic rays only nuclei up to Oxygen play a significant role

Background is determined by charge measurement at the top of AMS (Tracker L1) and MC
Lithium Flux – current status

\[ A \left( \frac{R}{50 \text{GV}} \right)^{-\gamma} \left( 1 + \left( \frac{R}{R_0} \right)^{\frac{\Delta \gamma}{s}} \right)^{s} \]

- Flux \( \times R^{2.7} \) [GV\(^{1.7}\) m\(^{-2}\) sr\(^{-1}\) s\(^{-1}\)]
- Rigidity [GV]

\( R_0 = 300 \text{ GV} \)

6/23/16

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Carbon Flux – current status

![Graph showing carbon flux vs kinetic energy](image)

- **AMS-02**
- **ATIC-02 (2003/01)**
- **Balloon (1971/09+1972/10)**
- **Balloon (1972/10)**
- **Balloon (1975/09)**
- **Balloon (1976/10)**
- **Balloon (1991/09)**
- **CREAM-II (2005/12-2006/01)**
- **CRN-Spacelab2 (1985/07-1985/08)**
- **HEAO3-C2 (1979/10-1980/06)**
- **PAMELA (2006/07-2008/03)**
- **TRACER 06 (2006/07)**

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Boron/Carbon ratio—current status

Comparison with measurements from 0.5 GeV/n to 3 TeV/n
In the past hundred years, measurements of charged cosmic rays by balloons and satellites have typically contained ~30% accuracy. AMS is providing cosmic ray information with ~1% accuracy. The improvement in accuracy will provide new insights into the source of cosmic rays and their propagation through the galaxy.

The Space Station is now a unique platform for fundamental physics research.
Back up
Transition Radiation Detector

20 layers: fleece radiator and proportional tubes

Typically, 1 in 1,000 protons may be misidentified as a positron

Normalized Probabilities

\[ P_p = \sqrt[n]{\prod_{i=1}^{n} P_p^{(i)}(A)} \]

\[ P_e = \sqrt[n]{\prod_{i=1}^{n} P_e^{(i)}(A)} \]

TRD estimator = \(-\ln(P_e/(P_e + P_p))\)

TRD likelihood = \(-\log_{10}(P_e)\)

TRD classifier = \(-\log_{10}(P_e) - 2\)

Lead by: K. Luebelsmeyer, S. Schael
Time-of-Flight Detector

Measures Velocity and Charge of particles

Lead by: A. Contin, G. Laurenti, F. Palmonari

\[ Z = 6 \]
\[ \sigma = 48\text{ps} \]
Tracker

9 planes, 200,000 channels
The coordinate resolution is 10 μm.

Inner tracker alignment stability monitored with IR Lasers.

The Outer Tracker is continuously aligned with cosmic rays in a 2 minute window

Lead by: R. Battiston, G. Ambrosi, B. Bertucci
Measurement of Nuclear Charge ($Z^2$) and its Velocity to 1/1000

Lead by: J. Berdugo, G. Laurenti
Electromagnetic Calorimeter

provides a precision, $17 \times X_0$, TeV, 3-dimensional measurement of the directions and energies of electrons and positrons

Lead foil

50,000 fibers, $\phi = 1$ mm
distributed uniformly inside 600 Kg of lead

Fibers

Typically, 1 in 10,000 protons may be misidentified as a positron

**Proton rejection at 90% $e^+$ efficiency**

ISS data: 83–100 GeV

Lead by: F. Cervelli, S. Rosier-Lees, H.S. Chen
Proton / Helium selection

Tracker hits from L1 to L9 with $Z_{L1-L9} \approx 1(2)$, and $Z_{TOF} \approx 1(2)$

Selected primary He $5 \times 10^6$

Selected primary He $5 \times 10^6$
Assuming that the flux is isotropic, the differential flux is defined as:

\[ \Phi_i(R_i, R_i + \Delta R_i) = \frac{N_i}{T_i \varepsilon_i A_i \Delta R_i} \]

- Rigidity: 1-1800 GV, 2-3000 GV
- Exposure Time: 63 \cdot 10^6 \text{ sec} > 30\text{GV}
- Bin to Bin Migration due to Tracker Rigidity Resolution
- Effective Acceptance
- Trigger Efficiency
- Events Corrected for Bin to Bin Migration due to Tracker Rigidity Resolution
Due to the high statistics of AMS, studies of the systematic errors are important:

- **Background contributions** very small in AMS
- **Trigger efficiency uncertainty** typically $\leq 1\%$
- **Acceptance uncertainties** 1-2 \% for all rigidities
  - Interaction cross-sections
  - Data/MC correction
- **Unfolding uncertainties** at high rigidities $\sim 3\%$
  - Unfolding method
  - Rigidity resolution function
- **Rigidity scale uncertainty** at high rigidities 2-3\%
Exposure Time

\[ \Phi_i(R_i) = \frac{N_i}{T_i \varepsilon_i A_i \Delta R_i} \]

Constant at 62.9 million sec. above 30GV