The Latest Results from AMS on the International Space Station

Y.H. Chang, 17 August 2015

Rencontres du Vietnam, Quy Nhon

5m x 4m x 3m
7.5 tons
Particles and nuclei are defined by their charge ($Z$) and energy ($E \sim P$) are measured independently by the Tracker, RICH, TOF, and ECAL.
AMS is a U.S. DOE sponsored international collaboration
Transition Radiation Detector

20 layers: fleece radiator and proportional tubes

- Proton rejection at 90% efficiency
- Typically, 1 in 1,000 protons may be misidentified as a positron

TRD classifier = -Log$_{10}$(Pe) - 2

TRD likelihood = -Log$_{10}$(Pe)

TRD estimator = -ln(Pe/(Pe+Pp))

Normalized Probabilities

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

\[ P_e = \sqrt[n]{\prod_{i} P_{e}^{(i)}(A)} \]
Time of Flight System

Measures Velocity and Charge of particles

A. Contin, G. Laurenti, F. Palmonari

$Z = 6$
$\sigma = 48\text{ps}$
Inner tracker alignment stability monitored with IR Lasers.

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

Tracker

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

R. Battiston, G. Ambrosi, B. Bertucci
Ring Imaging CHERENKOV (RICH)

Measurement of Nuclear Charge ($Z^2$) and its Velocity to 1/1000

Intensity $\Rightarrow Z^2$

Particle

Aerogel

NaF

$\Theta$

$\Rightarrow V$

Intensity $\Rightarrow Z^2$

$10,880$ photosensors

$\Theta$

Intensity $\Rightarrow Z^2$

$Aerogel$

$Fe$

$p = 633$ GeV/c

$p = 203$ GeV/c

$NaF$

$Fe$

$J. Berdugo, G. Laurenti$
Electromagnetic Calorimeter

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

50,000 fibers, $\phi = 1$ mm distributed uniformly inside 600 Kg of lead provides a precision, $17 \times X_0$, TeV, 3-dimensional measurement of the directions and energies of electrons and positrons

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

Proton rejection at 90% $e^+$ efficiency

ISS data: 83–100 GeV

Momentum (GeV/c)

F. Cervelli, S. Rosier-Lees, H.S. Chen
Extensive tests and calibration at CERN

AMS

27 km

7 km

$p, e^+, e^-, \pi$ 20…400 GeV

2000 positions
In 4 years on ISS,
AMS has collected >68 billion cosmic rays.
To match the statistics,

systematic error studies have become important.
Search for the Dark Matter through its annihilation product: *Positrons and Antiprotons* in the cosmic rays.
The Search for the Origin of Dark Matter

Collisions of Dark Matter (neutralinos, \( \chi \)) will produce a signal of \( e^+, \bar{p}, \ldots \) above the background from the collisions of “ordinary” cosmic rays.

\[
\begin{align*}
\text{Positrons: } & \chi + \chi \rightarrow e^+ + \ldots \\
\text{Antiprotons: } & \chi + \chi \rightarrow \bar{p} + \ldots
\end{align*}
\]

\( m_\chi = 800 \text{ GeV} \)

\( m_\chi = 1 \text{ TeV} \)

I. Cholis et al., JCAP 0912 (2009) 007

Donato et al., PRL 102, 071301 (2009)

Physics of 11 million $e^+$, $e^-$ events

Measuring electrons and positrons

**TRD**
identify $e^\pm$

**TRACKER**
measures $P$

**ECAL**
measures $E$

$e^\pm$: $E=P$
proton: $E<P$

**ECAL**
measures $E$ and shower shape to separate $e^\pm$ from protons

Probability

ISS data: 83-100 GeV

E/P

Normalized entities

ISS data: 83-100 GeV

Fraction of events

ISS data: 83-100 GeV

Boosted Decision Tree, BDT:
$\epsilon_e = 90\%$

From the diagram:
- TRD estimator
- ISS data: 83-100 GeV
- BDT: $\epsilon_e = 90\%$
- Fraction of events
- Probability
- Normalized entities
Verification of Positron Fraction with two independent samples

Positron fraction analysis with TRD and ECAL versus TRD only

Good agreement between two independent samples
1. The energy at which it begins to increase.

2. The rate of increase with energy

3. The existence of sharp structures.

4. The energy beyond which it ceases to increase.

5. Isotropy.

6. The rate at which it falls beyond the turning point.
1. The energy at which it begins to increase.
High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–500 GeV with the Alpha Magnetic Spectrometer on the International Space Station

10.9 million e+ and e- events
2. The rate of increase with energy.
3. The non-existence of sharp structures.

10.9 million $e^+$, $e^-$ events
4. The energy beyond which it ceases to increase.
Galactic coordinates \((b, l)\)

Arrival directions of electrons and positrons are used to build a sky map in galactic coordinates, \((b, l)\), containing the number of observed positrons and electrons. The fluctuations of the observed positron ratio are described using a spherical harmonic expansion

\[
\frac{r_e(b, l)}{<r_e>} - 1 = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\pi/2 - b, l),
\]

where \(r_e(b, l)\) denotes the positron ratio at \((b, l)\); \(<r_e>\) is the average ratio over the sky map; \(Y_{\ell m}\) are spherical harmonic functions and \(a_{\ell m}\) are the corresponding weights. The coefficients of the angular power spectrum of the fluctuations are defined as

\[
C_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2.
\]

The isotropy.

The fluctuations of the positron ratio \(e^+/e^-\) are isotropic.

The anisotropy in galactic coordinates:

\[
\delta \leq 0.030 \text{ at the 95\% confidence level}
\]

\[
\delta = 3\sqrt{C_1/4\pi} \quad C_1 \text{ is the dipole moment}
\]
6. The expected rate at which it falls beyond the turning point.

To be determined in the next 10 years:

- Other astrophysical sources
- Dark Matter $m_\chi \sim 1$ TeV
- Collision of cosmic rays
- Turn over energy
AMS $\bar{p}/p$ results

290,000 $\bar{p}$ events

$\bar{p}/p$ ratio vs. Kinetic Energy (GeV)
AMS $\bar{p}/p$ results

Theoretical prediction based on pre-AMS knowledge of cosmic ray collisions
AMS, Electron Flux and the Positron Flux

Presentation by M. Duranti
The Electron Flux and the Positron Flux

Observations:
1. The electron flux and the positron flux are different in their magnitude and energy dependence.
2. Both spectra cannot be described by single power laws.
3. The spectral indices of electrons and positrons are different.
4. Both change their behavior at ~30 GeV.
5. The rise in the positron fraction from 20 GeV is due to an excess of positrons, not the loss of electrons (the positron flux is harder).
AMS Results: \((e^+ + e^-)\) flux

Independent of charge sign measurement $\rightarrow$ no charge confusion
Small systematics on acceptance: 2% @ TeV

\(E^3 \times \Phi\) (GeV\(^2\) [m\(^2\) sr sec\(^{-1}\)])

- AMS-02
- ATIC
- BETS 97&98
- PPB-BETS 04
- Fermi-LAT
- HEAT
- H.E.S.S.
- H.E.S.S. (LE)

10.6 M events
Spectral Indices of electrons, positrons, and (electrons + positrons)

\[
\gamma = -3.170 \pm 0.008 \text{ (stat + syst.)} \pm 0.008 \text{ (energy scale)} \quad E > 30 \text{ GeV}
\]
To identify the Dark Matter signal we need to measure the $e^+$, $e^-$ and $p$ signal accurately until 2024.

To understand background, we need precise knowledge of:

1. The cosmic ray fluxes ($p, \text{He, C, ...}$)
2. Propagation and Acceleration ($\text{Li, B/C, ...}$)
AMS: Multiple Measurements of Nuclear Charge

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
The isotropic proton flux $\Phi_i$ for the $i^{th}$ rigidity bin $(R_i, R_i + \Delta R_i)$ is:

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

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

**TABLE I: The proton flux $\Phi$ as a function of rigidity**

<table>
<thead>
<tr>
<th>Rigidity [GV]</th>
<th>$\Phi$</th>
<th>$\sigma_{\text{stat.}}$</th>
<th>$\sigma_{\text{trig.}}$</th>
<th>$\sigma_{\text{acc.}}$</th>
<th>$\sigma_{\text{unf.}}$</th>
<th>$\sigma_{\text{scale}}$</th>
<th>$\sigma_{\text{syst.}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 - 108</td>
<td>4.085</td>
<td>0.007</td>
<td>0.006</td>
<td>0.040</td>
<td>0.035</td>
<td>0.022</td>
<td>0.058 $\times 10^{-2}$</td>
</tr>
<tr>
<td>108 - 116</td>
<td>3.294</td>
<td>0.007</td>
<td>0.005</td>
<td>0.033</td>
<td>0.028</td>
<td>0.018</td>
<td>0.047 $\times 10^{-2}$</td>
</tr>
<tr>
<td>116 - 125</td>
<td>2.698</td>
<td>0.006</td>
<td>0.004</td>
<td>0.027</td>
<td>0.023</td>
<td>0.016</td>
<td>0.039 $\times 10^{-2}$</td>
</tr>
<tr>
<td>125 - 135</td>
<td>2.174</td>
<td>0.005</td>
<td>0.004</td>
<td>0.022</td>
<td>0.019</td>
<td>0.013</td>
<td>0.032 $\times 10^{-2}$</td>
</tr>
</tbody>
</table>
AMS proton flux

\[ \langle \hat{R}^2 \rangle \times R \]

Flux \( \times R \)

[\text{m}^{-2} \text{sr}^{-1} \text{sec}^{-1} \text{GV}^{1.7}]$

Rigidity [GV]

AMS-02

300 million events
AMS proton flux

two power laws: $R^\gamma, R^{\gamma+\Delta\gamma}$ with a characteristic transition rigidity $R_0$ and smoothness $s$

 Curve fit of Eq. $\Phi$ to the data above 45 GV: $\chi^2$/d.f. = 25/26
Dashed curve uses the same fit values but with $\Delta\gamma$ set to zero.
Accurate measurement of the flux of nuclei on the ISS.

A new method:

To measure the flux of nuclei (He, Li, Be, B, C, O, ...) accurately, we need to know the interaction cross section of these nuclei with the materials in AMS.

Unfortunately, the interactions of nuclei with the materials in AMS could not be measured on the ground. This limits the accuracy to which we could measure the fluxes.

On ISS we have now a method to measure these interactions in space accurately.
AMS Measurement of $^{4}$He+$^{12}$C Cross Section

AMS Measured Cross Section
- Ableev 1977
- Jaros 1985
- Tanihata 1985

Abdrahmanov 1980 Propane Chamber
Aksinenko 1980 Streamer Chamber
Bokova 1975 Emulsion Technique
AMS Helium Flux

- AMS-02

50 million events
AMS Helium Flux

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

Solid curve fit of Eq. \( \Phi \) to the data above 45 GV: \( \chi^2 / \text{d.f.} = 25 / 27 \)
Dashed curve uses the same fit values but with \( R_0 = \text{infinity} \).
The AMS proton/helium ratio

\[ \frac{\Phi_p}{\Phi_{He}} = C \cdot R^\gamma \]

- Single power law fit (R > 45 GV)

Change of slope at ~45 GV
Spectral index of p/He ratio

\[ \frac{p}{He} \text{ ratio} = CR^\gamma \]

p/He spectral index (\(\gamma\)) = \(\frac{d \log (p/He \text{ ratio})}{d \log (R)}\)

Constant above 45 GV

\[ \gamma_{\frac{p}{He}} = -0.077\pm0.0073 \]
Like B and Be, Li is produced by the spallation of heavier nuclei during their propagation. 

Sensitive to CR propagation parameters (diffusion, convection, reacceleration...).

C, N, O,...Fe + ISM → Li
→ B, Be + ISM → Li
AMS Lithium flux – current status

1.5 M events

AMS
Orth et al (1978)
Lithium flux with two power law fit

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

Slope changes at about the same rigidity as for protons and helium
AMS Carbon Flux – status report

1.4 M events

AMS-02 - status report
PAMELA (2014)
TRACER (2011)
ATIC (2009)
CREAM II (2009)
Buckley et al. (1994)
Derrickson et al. (1992)
CRN-Spacelab2 (1991)
HEAO3-C2 (1990)
Simon et al. (1980)
Orth et al. (1978)
Lezniak & Webber (1978)
Juliussen et al. (1974)
Precise measurement of the rigidity spectra of B/C provides information on Cosmic Ray Interactions and Propagation.

The propagation of cosmic rays and their interactions with the Interstellar Medium (ISM) is measured through the B/C ratio.

Carbon Fragmentation to Boron \( R = 10.6 \) GV

\[
\begin{align*}
Z_{\text{TOF\_LOW}} &= 5.2 \\
Z_{\text{TRK\_IN}} &= 4.8 \\
Z_{\text{RICH}} &= 5.1 \\
Z_{\text{TRD}} &= 6.0 \\
Z_0 &= 9.9 \\
Z_1 &= 5.3 \\
Z_{\text{TRK\_L1}} &= 6.1
\end{align*}
\]
Boron and Carbon: Sample composition

Contamination < 3%
Selection efficiency > 96%

Entries

10^2

10^3

Tracker L1 Charge (c.u.)
AMS B/C Ratio converted in Kinetic Energy

7 M Carbon events
2 M Boron events

comparison with measurements from 0.5 GeV/n to 3 TeV/n

Boron-to-Carbon Ratio

AMS-02
PAMELA (2014)
TRACER (2006)
CREAM-I (2004)
ATIC-02 (2003)
AMS-01 (1998)
Buckley et al. (1991)
CRN-Spacelab2 (1985)
Webber et al. (1981)
HEAO3-C2 (1980)
Simon et al. (1974-1976)
Dwyer & Meyer (1973-1975)
Orth et al. (1972)
The latest AMS measurements of the positron fraction, the antiproton/proton ratio, the behavior of the fluxes of electrons, positrons, protons, helium, and other nuclei is providing new, precise, and unexpected information.

The accuracy and characteristics of the data, simultaneously from many different types of cosmic rays, will soon determine the true nature of the new phenomena we observe.

AMS physics for the lifetime of the Space Station

Accurate measurement (~1%) of Cosmic Rays to higher energies including:

a. Continue the study of Dark Matter
b. Search for the Existence of Antimatter
c. Search for New Phenomena, …