Unexpected results from AMS

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Questions to AMS-02:
Are there galaxies made of anti-matter in the Universe?
What is the nature of Dark Matter?
How do cosmic rays propagate in the Galaxy?
Overview

- Physics with AMS-02
- The AMS-02 detector
- New data from AMS-02:
  - positrons and electrons
  - protons and light nuclei
  - B/C
  - antiprotons
The search for antimatter in the Universe

The Universe was created in the Big Bang.

After the Big Bang, there must have been equal amounts of matter and anti-matter.
The search for antimatter in the Universe

The Universe was created in the Big Bang.

AMS on the ISS

After the Big Bang, there must have been equal amounts of matter and anti-matter.
Atomic nuclei are accelerated in supernovae to very high energies and become cosmic rays.

Are there anti-galaxies in the Universe?

Can we observe an anti-carbon nucleus from a far distant supernova?
Relic Dark Matter

Dark matter makes up a substantial fraction of the energy density of the Universe. But what is its nature?

Freeze-out in the early Universe:

\[ \Omega_X h^2 \approx \frac{3 \cdot 10^{-27} \text{ cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle} \]

relic density $\leftrightarrow$ annihilation cross section
Dark Matter annihilation

Products of Dark Matter annihilations get injected into the cosmic-ray sea:

most promising channels: $e^+$, $p$, $D$, ($\text{He}$), (and photons)
Cosmic ray physics in a nutshell
Excellent results from PAMELA

- Results span 4 decades in energy and 13 in fluxes
Particles and nuclei are defined by their charge ($Z$) and energy ($E \sim P$).

Z, P are measured independently by the Tracker, RICH, TOF and ECAL.

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

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

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

- **Magnet**
  - $\pm Z$

- **TOF**
  - $Z, E$

- **RICH**
  - $Z, E$
1 out of more than 100,000,000,000 events:

$\text{AMS Event Display}$

Run/Event 1315754945 / 173049 GMT Time 2011-254.15:31:15

- **TRD:** identifies electron
- **Tracker and Magnet:** measure charge sign and momentum
- **ECAL:** identifies electron and measures its energy

1.03 TeV electron
Tests at CERN
AMS in accelerator test beams Feb 4-8 and Aug 8-20, 2010

<table>
<thead>
<tr>
<th>Particle</th>
<th>Momentum (GeV/c)</th>
<th>Positions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>180, 400</td>
<td>1,650</td>
</tr>
<tr>
<td>Electrons</td>
<td>100, 120, 180, 290</td>
<td>7 each</td>
</tr>
<tr>
<td>Positrons</td>
<td>10, 20, 60, 80, 120, 180</td>
<td>7 each</td>
</tr>
<tr>
<td>Pions</td>
<td>20, 60, 80, 100, 120, 180</td>
<td>7 each</td>
</tr>
</tbody>
</table>
Inside the cargo bay of Endeavour
Endeavour approaches the International Space Station.
AMS installed on ISS and begins data taking
19th May 2011
Tracker: Rigidity resolution

Comparison between TB and MC p/π 60, 80, 100, 120, 180 and 400 GeV

CERN beamtest data

Rigidity = momentum / charge
TRD: Transition radiation detector

- TR yield proportional to $\gamma = \frac{E}{m}$

1 / 20 TRD layers, AMS flight data:

![Graph showing TR yield distribution for electrons and protons with transition radiation peaks.]

- Protons
- Electrons
- Transition Radiation
- Heavy particle radiator
- Xe/CO2
- Signal wire
- Straw Tube
AMS-02 Transition Radiation Detector

Misidentifies only 1 in 10000 protons as a positron.
TOF: Time-of-Flight system

- Measures velocity and charge:

  - $Z=2$
    - $\sigma_\beta = 2\%$
    - $\sigma_{\text{Time}} = 80$ ps

  - $Z=6$
    - $\sigma_\beta = 1.2\%$
    - $\sigma_{\text{Time}} = 48$ ps

  - Velocity [Rigidity>20GV]
ECAL: Electromagnetic calorimeter

Precision, 3-D measurement of the directions and energies of light rays and electrons up to 1 TeV.

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

Total: $17 \times X_0$
RICH: Ring-imaging Cherenkov counter

Velocity measurement to $1/1000$.

Intensity $\Rightarrow Z^2$

$Z = 13$ (Al)  
$P = 9.148$ TeV/c

$Z = 20$ (Ca)  
$P = 2.382$ TeV/c

$Z = 26$ (Fe)  
$P = 0.795$ TeV/c
Positrons and electrons

In our data sample we identify four components using an ECAL Estimator and a TRD Estimator.
TRD Estimator shows clear separation between positrons and protons with a small charge confusion background.

Energy range 206–260 GeV

\( \chi^2 / \text{d.f.} = 227 / 200 \)
The electron flux and the positron flux are different in their magnitude and energy dependence.
The positron flux and the positron fraction data require new physics.
Cosmic-ray positrons

Positron Spectrum

By 2024 we will should be able understand the origin of this unexpected data.

Positron Fraction

AMS 2024

Pulsars

$M_\chi = 1$ TeV

Collision of Cosmic Rays with the ISM

AMS 2024

Pulsars

$M_\chi = 1$ TeV

Collision of Cosmic Rays with the ISM
Fluxes of protons, positrons, and electrons show a characteristic time dependence below ~20 GeV.
AMS electron flux: June 2011 – May 2016
Cosmic rays interact with the heliosphere, which evolves with time.
Solar modulation

The graph shows the Kiel neutron monitor count rate (monthly smoothed) against the sunspot number. The data is plotted over a period from 1960 to 2010. The graph highlights the modulation effect of solar activity on cosmic rays, with peaks and troughs correlating with solar activity maxima and minima, labeled as $A^-$ and $A^+$.
Positrons and electrons reveal charge-sign dependent solar modulation.
Complex structure of the solar magnetic field causes charge-dependent modulation effects.
Positrons and electrons reveal charge-sign dependent solar modulation.

The full power of the high precision AMS data sets can only be explored after time-dependent effects are extracted and the data can be used to constrain the local interstellar spectra.
Multiple measurements of charge

Charge Resolution for Z=6 (c.u.):
- Tracker Plane 1: 0.30
- TRD: 0.33
- Upper TOF: 0.16
- Tracker Planes 2-8: 0.12
- Lower TOF: 0.16
- RICH: 0.32
- Tracker Plane 9: 0.30
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)

**Helium:**
- Resolution function from MC simulation
- Verified with ISS data:
  - Tracker residuals
  - Rigidity reconstruction (L1-L8) vs. (L2-L9)
Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station

AMS: 300 million events
AMS proton flux

New information: The proton flux cannot be described by a single power law $= CR_0^\gamma$, as has been assumed for decades.

Unexpectedly, we found the spectrum can be described by a double power law with spectral index $\gamma$ below $R_0$ and $\gamma + \Delta\gamma$ above $R_0$. $S$ describes the smoothness of the transition.

$$\Phi = C \left( \frac{R}{45 \text{ GV}} \right)^\gamma \left[ 1 + \left( \frac{R}{R_0} \right)^{\Delta\gamma/S} \right]^S$$
New information: The proton spectral index changes with momentum.

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

\(\gamma\) is not a constant -2.7
Precision Measurement of the Helium Flux in Primary Cosmic Rays of Rigidities 1.9 GV to 3 TV with the Alpha Magnetic Spectrometer on the International Space Station

**50 million helium nuclei**

Using the TRD we will extend this measurement up to ~5 TeV in 2024.
AMS Helium Flux

New information: The Helium flux cannot be described by a single power law.

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

50 million helium nuclei

Helium Spectrum

Flux \times R^{2.7} [m^2 \cdot sec^{-1} \cdot G\text{V}^{-1}]}

Rigidity [GV]
The AMS proton/helium flux ratio

Protons and helium are both “primary” cosmic rays.

Their rigidity ratio has traditionally been assumed to be flat.

Theoretical prediction


AMS: this ratio is not flat.
The p/He ratio is independent of solar activity
Flux ratios: boron/carbon and cosmic-ray propagation

The boron-to-carbon ratio (B/C) is important in the determination of cosmic-ray propagation. Boron is assumed to be produced in the collision of primary cosmic rays, such as carbon, with the interstellar medium (ISM), hence the B/C ratio provides information on cosmic-ray propagation.
B/C ratio measured by AMS

\[
\frac{B}{C} \sim R^\delta, \quad \delta = -0.333 \pm 0.014 \pm 0.005
\]

2.3 million boron and 8.3 million carbon nuclei.

Kolmogorov turbulence model predicts \( \delta = -1/3 \).
Theoretical models to explain the AMS positron fraction.
Among the 100’s of models there are three classes:
  a) dark matter
  b) new forms of propagation
  c) pulsars.

b) An example of new propagation:
B/C ratio measured by AMS

![Graph showing B/C ratio vs. E_K (GeV/n)]

- C2/HEAO3
- Webber et al.
- CRN/Spacelab2
- AMS01
- ATIC02
- CREAM-I
- TRACER
- PAMELA
- AMS02

Cowsik+ (2014)
Summary (on nuclei)

The spectra of protons, helium and lithium do not follow the traditional single power law. They all change their behavior at the same energy.
Summary on fluxes of light nuclei

Flux $E_{K}^{2.7}$ [m$^{-2}$s$^{-1}$sr$^{-1}$ (GeV/n)$^{-1}$]

Kinetic Energy $E_{K}$ [GeV/n]

- Oxygen, primary
- Carbon, primary
- Boron, secondary
- Li, secondary
- Be, secondary
Antiproton analysis

6.5 $\cdot 10^{10}$ cosmic rays
3.49 $\cdot 10^5$ antiprotons
2.42 $\cdot 10^9$ protons

3. RICH measures velocity,

1. TRD (transition radiation) to separate $e^\pm$ from $p^\pm$

2. Tracker measures momentum and separates $+$ from $-$

ISS Data
Monte Carlo
Energy range up to 2 TeV

$\langle \sigma \rangle = 10 \, \mu$m
AMS results on the $\bar{p}/p$ flux ratio

PRL 117, 091103 (2016)
Unexpected Result
Flux Ratio of Elementary Particles $\bar{p}/p$
is energy independent above 60 GeV

$\Phi_{\bar{p}}/\Phi_p$ ratio

AMS-02
$\bar{p} \quad 3.49 \cdot 10^5$
p $\quad 2.42 \cdot 10^9$
PAMELA

PRL 117, 091103 (2016)
AMS $\bar{p}/p$ results and modeling

$\bar{p}/p$ ratio vs. Rigidity [GV]

- AMS-02
- Dark Matter
- Collisions of ordinary cosmic rays

Models from
Donato et al., PRL 102, 071301 (2009); $m_{DM} = 1$ TeV
The positron, proton, and anti-proton fluxes have identical energy dependence from 60-500 GV.
The electrons show a different behaviour.
Identification of antihelium

1. Determine direction with TOF.

\[ |Z| = 2 \]

\[
\begin{array}{c}
\text{Events} \\
10^9 \\
10^8 \\
10^7 \\
10^6 \\
10^5 \\
10^4 \\
10^3 \\
10^2 \\
10 \\
1
\end{array}
\]

\[
\begin{array}{c}
1/\beta \\
2 \\
1.5 \\
1 \\
0.5 \\
0 \\
-0.5 \\
-1 \\
-1.5 \\
-2
\end{array}
\]

UpGoing

DownGoing

2. To measure $|Z|$, use the TOF+Tracker+RICH to separate $p,e^\pm$ from He

\[
\begin{array}{c}
\text{Events} \\
10^8 \\
10^7 \\
10^6 \\
10^5 \\
10^4 \\
10^3 \\
10^2 \\
10 \\
1
\end{array}
\]

\[
\begin{array}{c}
\text{Charge } |Z| \\
1 \\
1.2 \\
1.4 \\
1.6 \\
1.8 \\
2 \\
2.2 \\
2.4
\end{array}
\]

$\alpha_Z = 0.05$

$p,e^-$

He

3. To measure momentum and sign of the charge, use Tracker

MDR ($Z=2$) ~ 3.2 TV

\[
\begin{array}{c}
\text{Events} \\
10^5 \\
10^4 \\
10^3 \\
10^2 \\
10 \\
1
\end{array}
\]

\[
\begin{array}{c}
\Delta y [\mu m] \\
-40 \\
-30 \\
-20 \\
-10 \\
0 \\
10 \\
20 \\
30 \\
40
\end{array}
\]

\[
\text{ISS He Data 55-55 GV} \quad \text{He Simulation}
\]

$\pm 7.5 \mu m$

4. To determine mass, use the RICH to measure the velocity.

\[
\begin{array}{c}
\sigma(\beta)/\beta \\
0.0010 \\
0.0009 \\
0.0008 \\
0.0007 \\
0.0006 \\
0.0005 \\
0.0004 \\
0.0003 \\
0.0002 \\
0.0001 \\
0.0000
\end{array}
\]

\[
\begin{array}{c}
\text{Charge (Z)} \\
0 \\
2 \\
4 \\
6 \\
8 \\
10 \\
12 \\
14
\end{array}
\]
Search for Anti-Helium

In 700 million Helium events we have observed a few events with $Z = -2$ and with mass around 3He.
Antihelium and AMS

At a signal to background ratio of one in one billion, detailed understanding of the instrument is required.

Detector verification is difficult.
1. The magnetic field cannot be changed.
2. The rate is ~1 per year.
3. Simulation studies:

   Helium simulation to date:
   2.2 million CPU-Days =
   35 billion simulated helium events:
Monte Carlo study shows the background is small

How to ensure that the simulation is accurate to one in one billion?

The few candidates have mass 2.8 GeV and charge -2 like $^3\text{He}$.

It will take a few more years of detector verification and to collect more data to ascertain the origin of these events.
Unexpected results from AMS

- Electron and positron flux are different in their magnitude and energy dependence. Positron data require new physics. Dark matter? Pulsars / astrophysics? Propagation effects?

- Positron and electron data reveal charge-sign dependent solar modulation.

- Spectra of protons, helium, and lithium do not follow traditional power law. They all change their behaviour at the same energy.

- The flux ratios of primary cosmic rays are energy-independent except p/He.

- B/C ratio does not show significant structures, is in agreement with Kolmogorov turbulence model.

- Primary and secondary cosmic rays have characteristically different rigidity dependence.

- Positron, proton, and anti-proton spectra have identical energy dependence from 60-500 GV. Electrons do not.

- A few more years of detector verification and more data will be needed to ascertain the origin of a few $^3$He event candidates.