The First Five Years of the Alpha Magnetic Spectrometer on the International Space Station:

Unlocking the Secrets of the Cosmos

December 8, 2016

S. Ting
AMS is an international collaboration based at CERN

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AMS: A TeV precision, multipurpose, magnetic spectrometer

Transition Radiation Detector (TRD)
Identify $e^+$, $e^-$

Silicon Tracker
$Z, P$ or $R=P/Z$

Electromagnetic Calorimeter (ECAL)
$E$ of $e^+$, $e^-$

Time of Flight (TOF)
$Z, E$

Magnet
$\pm Z$

Ring Imaging Cherenkov (RICH)
$Z, E$

Z and $P, E$ or $R$ are measured independently by Tracker, ECAL, TOF and RICH
In five years of operation on the ISS, AMS has collected more than 90 billion charged cosmic rays.

New Physics Results
Support from CERN
AMS in accelerator test beams Feb 4-8 and Aug 8-20, 2010

Particle | Momentum (GeV/c) | Positions |
--- | --- | ---
Protons | 180, 400 | 1,650
Electrons | 100, 120, 180, 290 | 7 each
Positrons | 10, 20, 60, 80, 120, 180 | 7 each
Pions | 20, 60, 80, 100, 120, 180 | 7 each

CERN IT has continuously provided strong support for AMS analysis
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Elementary Particles in Space

There are hundreds of different kinds of charged elementary particles.

Only four of them, electrons, protons, positrons, and antiprotons, have infinite lifetime, so they travel in the cosmos forever.

Electrons and positrons have much smaller mass than protons and antiprotons, so they lose much more energy in the galactic magnetic field due to synchrotron radiation.

© AMS
Electron and Positron spectra before AMS

1. These were the best data.
2. Nonetheless, the data have large errors and are inconsistent.
3. The data has created many theoretical speculations.
Physics Result 1: The Electron and Positron fluxes

The electron flux and the positron flux are different in their magnitude and energy dependence.

AMS (2016)

16,500,000 electrons

1,080,000 positrons

Electron Spectrum

$E^3$ Flux [GeV$^3$/s sr m$^2$ GeV]

Positron Spectrum

e$^\pm$ energy [GeV]
Physics Result 1: The Electron and Positron spectral indices

Traditionally, the spectrum of cosmic rays is characterized by a single power law function

$$\Phi = CE^\gamma$$

where $\gamma$ is the spectral index and $E$ is the energy.

Before AMS, $\gamma$ was assumed to be constant for the electron and positron spectra.

The electron and positron spectral indices are not constant. They are different in their magnitude and energy dependence.
Dark Matter: $\chi$

Collision of Cosmic Rays with the Interstellar Media will produce $e^+, \bar{p}...$

$p, \text{He} + \text{ISM} \rightarrow e^+, \bar{p} + ...$

Dark Matter ($\chi$) annihilations  $\chi + \chi \rightarrow e^+, \bar{p} + ...$

The excess of $e^+, \bar{p}$ from Dark Matter ($\chi$) annihilations can be measured by AMS

Three independent methods to search for Dark Matter

- AMS
  \( \chi + \chi \rightarrow e^+, \bar{p}, \gamma, \ldots \)

- LUX
- DARKSIDE
- XENON 100
- CDMS II
- ...

Scattering

Production

- LHC
  \( \ldots + \chi + \chi \leftarrow p + p \)
Physics of electrons and protons

Annihilation
SPEAR, DORIS, PEP, PETRA, LEP, ... \( \psi, \tau \)

\[ e^+ + e^- \rightarrow p, \bar{p}, e^-, e^+, \gamma \]

Scattering
SLAC ... partons, electroweak

\[ e + p \rightarrow p, \bar{p}, e^-, e^+, \gamma \]

BNL, FNAL, LHC ... \( J, Y, t, Z, W, h^0 \)

Production
Examples of Theoretical Models for positrons and antiprotons

From Dark Matter
1) J. Kopp, Phys. Rev. D 88, 076013 (2013);
4) M. Ibe, S. Iwamoto, T. Moroi and N. Yokozaki, JHEP 1308 (2013) 029
7) L. Bergstrom, T. Bringmann, I. Cholis, D. Hooper and C. Weniger, PRL 111 (2013) 171101
11) Y. Zhao and K.M. Zurek, JHEP 1407 (2014) 017

From Astrophysical Sources
7) E. Amato, Int.J.Mod.Phys.Conf.Ser. 28 (2014) 1460160
10) M. DiMauro, F. Donato, N. Fornengo, R. Lineros and A. Vittino, JCAP 1404 (2014) 006

From Secondary Production
Collision of Cosmic Rays with the Interstellar Media produce $e^+$ … and this is indeed true at low energies.

Unexpectedly, starting from $\sim 8\text{GeV}$, the AMS $e^+$ data show an excess above ordinary Cosmic Ray collisions.
Annihilation of Dark Matter produces additional $e^+$ which are characterized by a sharp drop off at the mass of dark matter.

Physics Result 2: The origin of the AMS positron spectrum

The AMS results are in excellent agreement with a Dark Matter Model

![Graph showing AMS 2016 data with positron spectrum and energy [GeV] on the x-axis and E^3 Flux [GeV^3/(s sr m^2 GeV)] on the y-axis. The graph includes data points for Dark Matter and Collisions of Cosmic Rays with ISM.]
The excess of positrons can also be measured by the positron fraction: $e^+/(e^+ + e^-)$. This is an alternative way to search for the signature of Dark Matter but the positron fraction and positron spectrum have different errors.

Physics Result 3: The origin of the Positron Fraction

Comparison of the positron fraction measurement with a Dark Matter model

- AMS 2016
  17 million events

Model

Model based on

e\pm energy [GeV]

Positron Fraction

Collision of Cosmic Rays with the ISM

M_\chi = 1 \text{ TeV}
Alternative Models to explain the AMS Positron Flux and Positron Fraction Measurements

- Modified Propagation of Cosmic Rays
- Supernova Remnants
- Pulsars

Examples:

R. Cowsik *et al.*, Ap. J. 786 (2014) 124, *(pink band)* explaining that the AMS positron fraction *(gray circles)* above 10 GV is due to propagation effects.

However, this requires a specific energy dependence of the B/C ratio.

The AMS Boron-to-Carbon (B/C) flux ratio

11 million nuclei

Cowsik (2014)
We have been trying (late last night!) to get better fits to the new data but it is not easy ... perhaps our model is too simple and some further refinements are necessary.

This is justified now that we have precision data from AMS!
Alternative Models to explain the AMS Positron Flux and Positron Fraction Measurements

- Modified Propagation of Cosmic Rays
- Supernova Remnants
- Pulsars

Examples:

The AMS Antiproton-to-Proton ratio

The excess of antiprotons observed by AMS cannot come from pulsars.

By 2024, AMS will distinguish Dark Matter from Pulsars
Astrophysical point sources like pulsars will imprint a higher level of anisotropy on the arrival directions of energetic positrons than a smooth dark matter halo.

The fluctuations of the positron ratio $e^+/e^-$ are isotropic $16 < E$ [GeV] $< 350$.

The anisotropy in galactic coordinates

$$\delta = 3 \sqrt{C_1 / 4\pi}$$

$C_1$ is the dipole moment

Data taking to 2024 will allow to explore anisotropies of 1%
Physics Result 5: The \((e^+ + e^-)\) flux

The precision AMS measurement of the \((e^+ + e^-)\) flux contradicts all previous measurements and previous speculations.
AMS will be able to distinguish the (e^+ + e^-) flux behavior above 1 TeV.
Cosmic Protons

1. Protons are the most abundant cosmic rays.
2. Before AMS there have been many measurements of the proton spectrum.
3. In cosmic rays models, the proton spectral function was assumed to be a single power law $\Phi = CE^\gamma$ with $\gamma = -2.7$
AMS Physics Result 6: Precision measurement of the proton flux to an accuracy of 1%
AMS proton flux

New information: The proton flux cannot be described by a single power law \( = CR^\gamma \), 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
Once every 176 years the giant planets are lined up for a Grand Tour, and in 1977 the Voyagers were launched on humankind’s longest journey.
Understanding of the Solar Magnetic Field: The proton flux and the effect of the solar magnetic field

The Spectra of Elementary Particles: $e^-$ and $e^+$ have much smaller mass than $p$ and $\bar{p}$, so they lose much more energy in the galactic magnetic field due to synchrotron radiation.

\[
\Phi \cdot R \propto m^{-1.7} \cdot \text{s}^{-1} \cdot \text{GV}^{-1.7}
\]

Antiprotons

Cosmic ray + ISM $\rightarrow \bar{p} + \ldots$

$\chi + \chi \rightarrow \bar{p} + \ldots$

There is only 1 Antiproton for 10,000 Protons.

A percent precision experiment requires background rejection close to 1 in a million.
Selection of the signal:
The $\bar{p}$ signal is well separated from the backgrounds.
Physics Result 7: The antiproton flux and properties of elementary particle fluxes

Unexpected Result: The Spectra of Elementary Particles $e^+$, $\bar{p}$, $p$ have identical energy dependence from 60-500 GV. $e^-$ does not

The excess of antiprotons observed by AMS cannot come from pulsars.

It can be explained by Dark Matter collisions or by new astrophysics phenomena.

Astrophysics Model examples: P. Mertsch and S. Sarkar, Phys. Rev. D 90, 061301 (2014);
Cosmic Nuclei

AMS has seven instruments which independently identify different elements.
Measuring the interactions of nuclei within AMS

AMS horizontal

First, we use the seven inner tracker layers, L2-L8, to define beams of nuclei: Li, Be, B, ...

Second, we use left-to-right particles to measure the nuclear interactions in the lower part of the detector.

Third, we use right-to-left particles to measure the nuclear interactions in the upper part of detector.
Primary Cosmic Rays (p, He, C, O, ...)

Primary cosmic rays carry information about their original spectra and propagation.

Secondary Cosmic Rays (Li, Be, B, ...)

C, O, ..., Fe + ISM → Li, Be, B + X

Secondary cosmic rays carry information about propagation of primaries, secondaries and the ISM.
Measurements of the Helium Flux

1. Helium is produced in supernovas and is the 2\textsuperscript{nd} most abundant cosmic ray.
2. It has been studied extensively.
3. In cosmic rays models, the helium spectral function was assumed to be a single power law with $\gamma = -2.7$ (as for protons).
AMS Physics Result 8: Precision measurements of the 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 sr^{-1} \cdot sec^{-1} \cdot GV^{-1}]

Rigidity [GV]
New information: The helium spectral index changes with rigidity in a similar way to that of the proton spectral index but the values are different.
Protons and helium are both “primary” cosmic rays. Traditionally, they are assumed to be produced in the same sources and, therefore, their flux ratio should be flat.

Physics Result 9: The AMS proton/helium flux ratio

AMS result: this ratio is not flat.

Theoretical prediction

Each color corresponds to a period of 27 days. The $p/He$ ratio is independent of solar activity outside the solar system and inside the solar system. The $p/He$ ratio is displayed with circles.

The $p/He$ ratio is independent of solar activity.
Physics Result 10: The Lithium flux

New AMS results on Secondary Cosmic Rays (Lithium)

New information: The Lithium spectrum behaves similar to protons and Helium and the Lithium flux cannot be described by a single power law.

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

AMS
1 Million Lithium Events

Flux \times R^{2.7} \text{[GV}^{1.7} \text{m}^2 \text{sr}^{-1} \text{s}^{-1}]
Physics Result 12: The Boron flux

New AMS results on Secondary Cosmic Rays (Boron)

2.3 million boron nuclei

B Flux $E_{K}^{2.7}$ [m$^{-2}$s$^{-1}$sr$^{-1}$ (GeV/n)$^{1.7}$]

Kinetic Energy $E_{K}$ [GeV/n]
Flux Ratios: Beryllium-to-Boron and age of cosmic rays

The $^{10}\text{Be}$ half-life is $1.5 \times 10^6$ years.

The $^{10}\text{Be}$ to $^{10}\text{B}$ ratio rises with energy due to relativistic time dilation. $\text{Be}/\text{B}$ provides information on the age of cosmic rays in the Galaxy.
Beryllium to Boron flux ratio before AMS

- Juliusson et al.
- Orth et al.
- Lezniak & Webber
- Webber & Yushak
- HEAO3-C2
- AMS01

Be/B vs. $E_K$ [GeV/n]
Physics Result 13: The Beryllium-to-Boron flux ratio

AMS: The age of cosmic rays in the galaxy is ~12 million years.

0.9 million beryllium and 2.3 million boron nuclei
The flux ratio between primaries (C) and secondaries (B) provides information on propagation and the ISM.

Cosmic ray propagation is commonly modeled as a fast moving gas diffusing through a magnetized plasma.

At high rigidities, models of the magnetized plasma predict different behavior for $B/C = k R^\delta$.

With the Kolmogorov turbulence model $\delta = -1/3$ while the Kraichnan theory leads to $\delta = -1/2$. 
Physics Result 14: The Boron-to-Carbon (B/C) flux ratio

AMS B/C results

The B/C ratio does not show any significant structures in contrast to many cosmic ray models that require such structures at high rigidities.

Remarkably, above 65 GV, the B/C ratio is well described by a single power law

\[ \frac{B}{C} = k R^\delta \] with \( \delta = -0.333 \pm 0.015 \).

This is in agreement with the Kolmogorov turbulence model of magnetized plasma of \( \delta = -1/3 \) asymptotically.
Physics Result 15: The Carbon flux

AMS 8.3 Million Carbon Nuclei

C Flux $E_k^{2.7}$ [m$^{-2}$s$^{-1}$sr$^{-1}$ (GeV/n)$^{1.7}$]

Kinetic Energy $E_k$ [GeV/n]
Physics Result 16: The Oxygen flux

AMS 7.4 Million Oxygen Nuclei

C2/HEAO3
CRN/Spacelab2
Buckley et al.
ATIC02
TRACER
CREAM-II
TRACER
AMS

O Flux $E_{K}^{2.7} \text{[m}^{-2}\text{s}^{-1}\text{sr}^{-1}(\text{GeV/n})^{1.7}]$

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

AMS 7.4 Million Oxygen Nuclei
Primary cosmic rays carry information about their original spectra and propagation.

Secondary cosmic rays carry information about propagation of primaries, secondaries and the ISM.
Physics Result 17: Primary and secondary Cosmic Rays have very different momentum dependence

- Primary and secondary Cosmic Rays have very different momentum dependence.

![Graph showing flux vs. kinetic energy for different elements](image-url)
Carbon and helium are both “primary” cosmic rays. They are assumed to be produced in the same sources and, therefore, their flux ratio should be flat.

AMS result: the flux ratio is flat.

AMS (2016)
110 million events
Physics Result 19: Primary Cosmic Rays Carbon and Oxygen have identical momentum dependence.
The AMS carbon/oxygen flux ratio

AMS result: the flux ratio is flat.

AMS (2016)

16 million events
Physics Result 20: Iron rate

2 million iron nuclei

Rate (Eev/sec/GV)

Rigidity (GV) = Momentum/26
Physics Result 21: Complex Antimatter in cosmic rays

A Status Report

The Big Bang origin of the Universe requires matter and antimatter to be equally abundant at the very hot beginning.
Search for the explanation of the absence of antimatter in a complex form, that is, the search for Baryogenesis

Baryogenesis requires:

- **Strong Symmetry Breaking**
  - BELLE, BaBar
- **Proton has a finite lifetime**
  - underground experiments
- **Super Kamiokande**
- **FNAL: KTeV, CDF, D0, NOvA**
- **CERN NA-48**
  - T2K,
- **LHC: LHC-b, ATLAS, CMS**

Despite the outstanding experimental efforts over the last half a century, no evidence for strong symmetry breaking nor proton decay have been found
In five years, 3.7 billion helium events have been collected by AMS when both the Upper and Lower TOF measure $|Z| = 2$ with an accuracy of 0.08.

Of these, 100 million passed through the full lever arm (L1 to L9) and are used in the analysis of the helium spectrum.

In our helium publication we used the first 2.5 years of data (50 million events).

In searching for antihelium we use a larger acceptance (L2 to L8) with 700 million helium events to date.
Identification of antihelium

1. Determine direction with TOF.

|Z| = 2

2. To measure |Z|, use the TOF+Tracker+RICH to separate p,e± from He

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

4. To determine mass, use the RICH to measure the velocity.
To date we have observed a few events with $Z = -2$ and with mass around $^3\text{He}$. 
An anti-Helium candidate:

Momentum = 40.3 ± 2.9 GeV/c
Charge = -2
Mass = 2.96 ± 0.33 GeV/c²
Velocity = 0.9973 ± 0.0005 c
Antihelium and AMS

At a signal to background ratio of $1/10^9$, detailed understanding of the instrument is required.

Example A: Discovery of the J particle requires

$$\frac{\text{Background}}{\text{Signal}} = \frac{\pi\pi}{e^+e^-} > 10^{10}$$

Detector Verification: Collecting data at 2 magnetic fields

$$P + Be \rightarrow e^+ + e^- + ...$$
Physicists Produce Antimatter Particles In a Complex Form

By HAROLD M. SCHMECK Jr.

Are there somewhere anti-worlds, populated, perhaps, by antipeople?

The question seems like fantasy, but the answer could conceivably be yes in the light of research just reported from


Precision measurement of Positron Fraction requires e and p separation of $1/10^6$

Positron fraction analysis with TRD+ECAL compared with TRD Only

Example C:

Good agreement between two independent samples
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.
Summary (on elementary particles)

The electron flux and the positron flux are different in their magnitude and energy dependence.

Electron Spectrum

$E^3$ Flux [GeV$^3/(s \cdot sr \cdot m^2 \cdot GeV)$]

16,500,000 electrons

1,080,000 positrons

$e^\pm$ energy [GeV]
Summary (on elementary particles)

The positron flux and the positron fraction data require new physics.

Positron Spectrum

Positron Fraction

$\Phi^{e^{-}} E^3 \left[ m^2 s^{-1} GeV^2 \right]$

$e^{\pm}$ energy \[ GeV \]

$M_\chi = 1 \text{ TeV}$

Collision of Cosmic Rays with the ISM

AMS 2016

$10^{-2}$

$10^{-1}$

$10^2$

$10^3$

$e^{\pm}$ energy \[ GeV \]
By 2024 we will should be able understand the origin of this unexpected data.

**Summary (on elementary particles)**

- **Positron Spectrum**
- **Positron Fraction**

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**Positron Spectrum**

**Positron Fraction**
The excess of antiprotons observed by AMS cannot come from pulsars. It can be explained by Dark Matter collisions or by new astrophysics phenomena.
Summary (on elementary particles)

The $e^+$, $\bar{p}$, $p$ spectra have identical energy dependence from 60-500 GV, $e^-$ does not.

$\Phi \cdot R \ [m^2 \cdot sr^{-1} \cdot s^{-1} \cdot GV^{-1.7}]$

$\Phi / \Phi$ ratio

$|Rigidity| [GV]$
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 nuclei)

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

- **C/He Ratio**
  - Rigidity (GV)
  - AMS-02: 110 million events

- **C/O Ratio**
  - Rigidity (GV)
  - AMS-02: 16 million events

Theoretical prediction

Primary Cosmic Rays (p, He, C, O, ...)

Secondary Cosmic Rays (Li, Be, B, ...)

C, O, ..., Fe + ISM → Li, Be, B + X
Summary (on nuclei)
The B/C ratio does not show any significant structures in contrast to many cosmic ray models that require such structures at high rigidities. Remarkably, above 65 GV, the B/C ratio is well described by a single power law \( \frac{B}{C} = k R^\delta \) with \( \delta = -0.333 \pm 0.015 \).

This is in agreement with the Kolmogorov turbulence model of magnetized plasma of \( \delta = -1/3 \) asymptotically.
Summary (on nuclei)
The beryllium-to-boron (Be/B) flux ratio increases with energy due to time dilation of the decaying Be. The age of cosmic rays in the galaxy is ~12 million years.

0.9 million beryllium and 2.3 million boron nuclei
Summary (on nuclei)
Primary and secondary cosmic rays have characteristically different rigidity dependence.

\[
\text{Flux } E_{K}^{2.7} \text{ [m}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{(GeV/n)}^{1.7}] = K \times E_{K}^{-1} \times \text{sr}^{-1} \times \text{s}^{-2} \\
\text{Kinetic Energy } E_{K} \text{ [GeV/n]}
\]
Summary (on antinuclei)

To date we have observed a few $Z = -2$ events with mass around $^{3}\text{He}$.

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

It will take a few more years of detector verification and to collect more data to ascertain the origin of these events.
The results from AMS to date are unexpected and are unlocking the secrets of the cosmos.

There is no other magnetic spectrometer in space in the foreseeable decades.

We need to work closely with the theoretical community to develop a comprehensive model to explain all of our observations.

By collecting data through 2024, we should be able to determine the origin of many of these unexpected phenomena.