Latest results from the AMS Experiment

EPS-HEP Conference 2019
Ghent, Belgium

July 11, 2019
A. Kounine / MIT
The physics of AMS on the Space Station: Study of Charged Cosmic Rays

Charged cosmic rays have mass. They are absorbed by 100 km of Earth’s atmosphere (10m of water).

To measure their charge and momentum requires a magnetic spectrometer in space.

AMS on ISS provides long term (20 years) precision measurements of charged cosmic rays.
AMS is an International Collaboration
It took 650 physicists and engineers 17 years to build AMS

The detectors were constructed in Europe and Asia and assembled at CERN, Geneva.
AMS is a space version of a precision detector used in accelerators.

Transition Radiation Detector (TRD)

Silicon Tracker

Electromagnetic Calorimeter (ECAL)

Time of Flight Detector (TOF)

Magnet

Ring Imaging Cherenkov (RICH)

300,000 electronic channels, 650 fast microprocessors

5m x 4m x 3m

7.5 tons
Transition Radiation Detector (TRD) built by RWTH: identifies Positrons and Electrons, rejects protons to <1 in 1000

- **CO₂ loss [mg/day]**
- **Lifetime**
  - CO₂ at launch = 5 kg
  - Lifetime = 5000g / 0.47g/d ➔ 2035
Silicon Tracker

Coordinate resolution 5-10 microns
Measure momentum P and nuclear charge Z

200,000 channels
Tracker stable to 2 microns over eight years

Inner tracker alignment (< 1 micron) monitored with IR lasers

Outer tracker stable to 2 micron over 8 years

Maximal Detectable Rigidity – 2TV for Z=1 particles
Ring Imaging CHerenkov (RICH)
Measurement of Nuclear Charge and its Velocity to 1/1000

Aerogel NaF

Intensity $\Theta \Rightarrow Z^2$

$10,880$ photosensors

$10,880$ photosensors
Electromagnetic Calorimeter (ECAL) to measure the highest energy electrons in space with ~2% accuracy

A precision, 17 $X_0$, TeV, 3-dimensional measurement of the directions and energies of light rays and electrons
AMS is a unique magnetic spectrometer in space

Cosmic rays are defined by:

- Energy ($E$ in units of GeV)
- Rigidity ($R=p/Z$ in units of GV)
- Charge ($Z$ - location on the periodic table: H $Z=1$, He $Z=2$, …)
Calibration at CERN
with different particles at different energies

AMS

27 km

7 km

Measurement - Prediction

-0.02 -0.01 0 0.01 0.02

Events

10^6

10^5

10^4

10^3

10^2

10

-0.02 -0.01 0 0.01 0.02

Measurement - Prediction

-0.02 -0.01 0 0.01 0.02

Events

10^6

10^5

10^4

10^3

10^2

10

400 GeV/c TestBeam Data

400 GeV/c Simulation

400 GeV/c Simulation
The accuracy of the rigidity scale is found to be 0.033 TV$^{-1}$, limited mostly by available positron statistics.
In 8 years, over 140 billion charged cosmic rays have been measured by AMS.
AMS Physics Results: on the Origins of Cosmic Positrons

New Astrophysical Sources: Pulsars, ...

- Supernovae
- Protons, Helium, ...
- Interstellar Medium
- Positrons, antiprotons from Collisions
- Positrons from Pulsars
- Positrons, antiprotons from Dark Matter
- Electrons from Dark Matter
Towards understanding the origin of cosmic ray positrons

$E^3 \Phi_{e^+} \ [\text{GeV}^2 \text{m}^{-2} \text{sr}^{-1} \text{s}^{-1}]$

AMS-02

1.9 million positrons

Energy [GeV]

Flattening

Rise

Fall
Comparison with other recent measurements

\[ \tilde{E} \Phi_{e^+} [\text{GeV}^2 \text{m}^{-2} \text{sr}^{-1} \text{s}^{-1}] \]

Energy [GeV]

AMS-02
PAMELA
Fermi-LAT
MASS
CAPRICE
AMS-01
HEAT
The Origin of Positrons

Low energy positrons mostly come from cosmic ray collisions

AMS 1.9 million positrons

Model based on positrons from cosmic ray collisions.
The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from a new source or dark matter both with a cutoff energy $E_s$.

\[
\Phi_{e^+}(E) = \frac{E^2}{\bar{E}^2} \left[ C_d (\bar{E}/E_1)^\gamma_d + C_s (\bar{E}/E_2)^\gamma_s \exp(-\bar{E}/E_s) \right]
\]
A finite energy cutoff of the source term $E_s = 810^{+310}_{-180}$ GeV, is established with a significance more than $4\sigma$.

$$\Phi_{e^+}(E) = \frac{E^2}{E^2} \left[ C_d (E/E_1)^{\gamma_d} + C_s (E/E_2)^{\gamma_s} \exp(-\frac{E}{E_s}) \right]$$

Collisions

Source

$1/E_s = 0 \text{ or } E_s = \infty$ excluded at $4.07\sigma$
At high energies positrons come from dark matter or new astrophysical sources with a cutoff energy $E_s$.

$$\Phi_{e^+}(E) = \frac{E^2}{\bar{E}^2} \left[ C (\bar{E}/E_2)^{\gamma_s} \exp(-\bar{E}/E_s) \right]$$

- AMS positrons (data-collision term)

The cutoff energy $E_s = 810^{+310}_{-180}$ GeV is established with a confidence of more than 99.99%.
Positrons from Pulsars

1. Pulsars produce and accelerate positrons to high energies without a sharp cutoff.

2. Pulsars do not produce antiprotons.
AMS Physics Results:
Antiproton data show a similar trend as positrons.
Antiprotons cannot come from pulsars.
Collision of Dark Matter produces positrons and antiprotons. Dark Matter particle have mass $M$ and they move slowly. Before collision the total energy $\approx 2M$.

The conservation of energy and momentum requires that the positron or antiproton energy must be smaller than $M$. So, there is a sharp cutoff in the spectra at $M$. 


Positrons and Dark Matter 2018

- Data 2018

- Dark matter Model
  (Mass = 1.2 TeV)

+ cosmic ray collisions
Positrons and Dark Matter by 2024
AMS will provide the definitive answer on the nature of dark matter

Projection to 2024
based on dark matter model

$E^3 \Phi_{e^+}$ [m$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV$^2$]

Energy [GeV]

Dark matter Model
+ cosmic ray collisions
AMS Physics Results:

The Origins of Cosmic Electrons

The contribution from cosmic ray collisions is negligible

AMS 28.1 million electrons
Comparison with other recent measurements

\[ E^3 \Phi_{e^-} [\text{GeV}^2 \text{ m}^{-2} \text{ sr}^{-1} \text{ s}^{-1}] \]

- AMS-02
- PAMELA
- Fermi-LAT
- MASS
- CAPRICE
- AMS-01
- HEAT

Energy [GeV]

Diagram comparing the measured electron flux with different experiments.
The electron flux can be described by two power law functions:

\[
\Phi_{e^-}(E) = S(E) \left[ C_a \left( \frac{E}{E_a} \right)^{\gamma_a} + C_b \left( \frac{E}{E_b} \right)^{\gamma_b} \right]
\]

What is the origin of power law a and power law b?

- AMS electrons
No source term in the electron spectrum

\[ \Phi_{e^-}(E) = C_s (E/41.61 \text{ GeV})^{\gamma_s} \exp(-E/E_s) \]

\( E_s < 1.9 \text{ TeV} \) excluded at 5\( \sigma \)
Electrons originate from different sources than positrons; the electron spectrum comes from two power law contributions.

The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from a new source or dark matter both with a cutoff energy $E_s$. 

AMS Physics Results:

Electrons

- Power law a
- Power law b

Positrons
Physics of cosmic electrons to 2024

What is the origin of power law $a$ and power law $b$?

Is there a cutoff for electrons at higher energies?

AMS data 2018

Projection to 2024

based on data trend
Astrophysical point sources like pulsars will imprint a higher anisotropy on the arrival directions of energetic positrons than a smooth dark matter halo.

The anisotropy in galactic coordinates

\[ \delta = 3 \sqrt{C_1 / 4\pi} \]

\( C_1 \) is the dipole moment

Currently at 95% C.L.:

- positrons: \( \delta < 0.019 \)
- electrons: \( \delta < 0.005 \)
Precision Study of Cosmic Nuclei through the lifetime of ISS

Exploring an uncharted region

Events

In progress to 2024 and beyond

Analyzed

ToF Charge

Tracker Charge

H He Li Be B C N O F Ne Na Mg Al Si P S Cl Ar K Ca Sc Ti V Cr Mn Co Ni Zn
Primary Cosmic Rays

Primary elements (H, He, C, ..., Fe) are produced during the lifetime of stars.

They are accelerated by the explosion of stars (supernovae).
Latest results – 1 billion protons
AMS Measurement of the proton spectrum
AMS Physics Results:

Surprisingly, above 60 GV, the primary cosmic rays have identical rigidity (P/Z) dependence.
Secondary cosmic nuclei (Li, Be, B, ...) are produced by the collision of primary cosmic rays and interstellar medium.
Physics Results on Lithium and Beryllium
The rigidity dependences are identical above 30 GV
Fluxes are different by a factor of $2.0 \pm 0.1$
AMS Physics Results:
Secondary cosmic rays Li, Be, and B also have identical rigidity dependence but they are different from primaries.
The ratio of secondary flux to primary flux directly measures the amount and properties of interstellar medium.

Before AMS, the B/C ratio was assumed to be $\propto R^\Delta$ with $\Delta$ a constant for $R > 60$ GV.
AMS Physics Results:

The Secondary/Primary Ratios $\neq kR^\Delta$

$\Delta$ is not a constant

$\Delta_{[200-3300]GV} - \Delta_{[60-200]GV} = 0.13 \pm 0.03$
All AMS Publications in *Physical Review Letters*


3) M. Aguilar *et. al.*, Phys. Rev. Lett. 113 (2014) 121102. Editor’s Suggestion


8) M. Aguilar *et. al.*, Phys. Rev. Lett. 117 (2016) 231102. Editor’s Suggestion


17) M. Aguilar *et. al.*, *To be submitted to Phys. Rev. Lett.*, “Rigidity Dependence of Ne, Mg, and Si Cosmic Rays”

18) ...
$^3\text{He}/^4\text{He}$ flux ratio

![Graph showing $\phi_3^3\text{He}/\phi_4^4\text{He}$ vs. $E_K$ (GeV/n)]

- AMS-02
- PAMELA-CALO
- PAMELA-TOF
- IMAX-92
- BESS-98
- BESS-93
- GALPROP

Where $\phi_i$ represents the flux of nuclei with charge $i$. The graph shows the variation of the ratio with energy $E_K$. The data points from various experiments are plotted, along with a model curve for comparison.
The fit above 4 GV with $C(R/4GV)^4$ yields
\[ \Delta = 0.294 \pm 0.004 \]
Primary elements (He, C, ..., Fe) are produced during the lifetime of stars and then accelerated by the explosion of stars (supernovae).

Are heavier elements Ni and Zn different from He, C, ..., Fe?
How many classes of cosmic rays exist in the universe?

- Helium
- Carbon×30
- Oxygen×28
- Neon×175
- Magnesium×150
- Silicon×160
- Sulfur×840

Flux $\times R^{\gamma}$ [$\text{m}^2\text{s}^{-1}\text{sr}^{-1}(\text{GV})^{1.7}$]

Rigidity $\tilde{R}$ [GV]
Flux Ratios Ne/O, Mg/O, Si/O, and S/O

Preliminary data, please refer to the forthcoming publication in PRL

$\Delta_2 \approx \Delta_1 \approx -0.035$
The measured spectra of Cosmic Rays break at ~200 GV. 
Is there a break for all the elements? Why?
How old are cosmic rays?

$^{10}\text{Be}$ ($Z=4$) decays with a half-life $1.4 \times 10^6$ years $^{10}\text{Be} \rightarrow ^{10}\text{B} + e^- + \nu_e$. Precision measurement of the rigidity dependence of Be/B ratio provides information on the age of cosmic rays.

The measurements of radioactive Aluminum ($Z=13$), Chlorine ($Z=17$), and Manganese ($Z=25$) spectra will precisely establish the age of cosmic rays as they (like Be) are radioactive clocks.
The Big Bang origin of the Universe requires matter and antimatter to be equally abundant at the very hot beginning.
No explanation found for the absence of antimatter. No reason why antimatter should not exist.
Observation of anti-He events

Charge $= -2$
Mass $= 2.96 \pm 0.33 \text{ GeV}/c^2$

Charge (He) $= +2$
Mass ($^3\text{He}$) $= 2.83 \text{ GeV}/c^2$

anti-He track in Y-Z bending plane

anti-He track in non-bending plane

Cherenkov cone in RICH (X-Y plane)
Complex Antimatter

The rate in AMS of antihelium candidates is less than 1 in 100 million helium. At this extremely low rate, more data (through the lifetime of the ISS) is required to further check the origin of these events.
AMS Results on Structures in the positron and electron fluxes in 6 years

Solar magnetic field polarity reversal

A<0

A>0

1.01 – 1.22 GeV

2.00 – 2.31 GeV

5.00 – 5.49 GeV

positron flux [m sr s GeV]^{-1}

electron flux [m sr s GeV]^{-1}

2012 2014 2016

Solar magnetic field polarity reversal

A<0

A>0

1.01 – 1.22 GeV

2.00 – 2.31 GeV

5.00 – 5.49 GeV

positron flux [m sr s GeV]^{-1}

electron flux [m sr s GeV]^{-1}

2012 2014 2016
Solar physics

Identical daily time variation of the $p$, He fluxes
Solar physics over a complete 11-year solar cycle

So far, the maximum and minimum fluxes differ by a factor of ~3. What is the largest difference over a solar cycle?
Solar physics over a complete 11-year solar cycle

Carbon and Oxygen

The maximum and minimum fluxes differ by a factor of ~3.

What is the largest difference over a solar cycle?
The accuracy and characteristics of the AMS data on many different types of cosmic rays require the development of a comprehensive model of cosmic rays.

AMS will continue to collect and analyze data for the lifetime of the Space Station because whenever a precision instrument such as AMS is used to explore the unknown, new and exciting discoveries can be expected.
AMS contributions to EPS-HEP 2019:

Nikolas Zimmermann “Towards Understanding the Origin of Cosmic-Ray Positrons”

Jorge Casaus “Anisotropy of Cosmic Ray Fluxes Measured with the Alpha Magnetic Spectrometer on the ISS”

Laurent Derome “Properties of Primary and Secondary Cosmic Ray Nuclei Measured with the Alpha Magnetic Spectrometer on the ISS”

Cheng Zhang “Towards Understanding the Origin of Cosmic-Ray Electrons”