The Latest Results from the Alpha Magnetic Spectrometer (AMS) on the International Space Station (ISS)

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Particles and nuclei are defined by their charge ($Z$) and energy ($E$) or momentum ($P$). Rigidity $R = P/Z$.

**Particles and Nuclei**

- **AMS**: a unique TeV precision, accelerator-type spectrometer in space

**Detector Components**

- **TRD**: Identify $e^+$, $e^-$, $Z$
- **Silicon Tracker**: $Z$, $P$
- **ECAL**: $E$ of $e^+$, $e^-$
- **Magnet**: $\pm Z$
- **RICH**: $Z$, $E$
- **TOF**: $Z$, $E$

**Detection Parameters**

- **Z and P**: are measured independently by the Tracker, RICH, TOF, and ECAL.
AMS was installed on the ISS in May 2011 and it will continue through the lifetime of ISS. Over 117 billion charged particles have been measured.
AMS goals

Look for dark matter in space
New forms of matter
Studies galactic cosmic rays
Three complimentary methods are being used to search for dark matter

**Annihilation**

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

**AMS**

**Scattering**

LUX
DARKSIDE
XENON 100
CDMS II
...

**LHC**

**Production**
Collision of Cosmic Rays with Interstellar Matter produces $e^+, \bar{p}, \bar{D}$

Dark Matter annihilation also produces light antimatter: $e^+, \bar{p}, \bar{D}$

The excess of $e^+, \bar{p}, \bar{D}$ from Dark Matter annihilations can be measured by AMS
Latest results on electron flux and positron fluxes

- 23.2 million electrons
- 1.6 million positrons
Nature of the positrons excess is still unknown

Dark matter contribution? Pulsars? Super Novae physics?
Anisotropic Local effects of propagation of cosmic rays?

- 1.6 million positrons
Antiproton-to-proton flux ratio

Is there an excess?

An excess of antiproton may be explained by Dark Matter collisions or by new astrophysics phenomena

Large uncertainties on the background prediction:
- Primary fluxes
- Secondary fluxes
- Solar modulation
- Nuclear Cross-sections

Latest AMS data will resolve the large uncertainties

G. Giesen, et. al.  
JCAP, 2015(09), 023
Most surprisingly:
The spectra of positrons, antiprotons, and protons are identical but the proton and antiproton mass is 2000 times the positron mass. Positron and Antiproton have identical rigidity dependence

![Graph showing the comparison of positron, proton, and antiproton spectra.]

Protons, anti-protons and positron have very different origin and propagation history. Traditional models predict:
Secondary positrons: softer than proton due to diffusion and energy loss.
Secondary antiprotons are generated by spallation of P with the ISM: softer than P.
Anti-Deuterons from Dark Matter Annihilations

In six years we have collected
100 million deuterons

Dark Matter annihilation will produce
anti-Deuterons

Anti-Deuterons have never been observed in space
Anti-Deuteron Analysis

Charge sign x Mass [GeV]

Number of events

$\pi^\pm$, $K^\pm$

$\pm \Delta D$

$\bar{p}$

$p$, $\bar{p}$, $\pi^-$, $\pi^+$, $K^+$, $K^-$, $D$
Deuteron to Proton ratio

Flux Ratio

- AMS-02 (ToF)
- AMS-02 (NaF)
- AMS-02 (AgI)
- CAPRICE94(1994/08)
- IMAX92(1992/07)
- PAMELA-CALO
- PAMELA-TOF

Kinetic Energy [GeV/n]
Status of Anti-Deuteron Analysis

MC simulations are on going.

AMS: 100 million deuterons

D from annihilation of Dark Matter: up to 15 events expected

D from collisions of ordinary cosmic rays: up to 34 events expected

Number of events

10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
-3
-2
-1
0
1
2
3
Charge sign x Mass [GeV]

Flux [(m^2 sr s GV)^{-1}]

10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
10^{-30}
10^{-32}
10^{-34}

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Dark Matter model:

Collisions of CR model
Precision Measurements of Cosmic Rays:
AMS has seven instruments which independently measure Cosmic Nuclei
Traditionally, there are two prominent classes of cosmic rays:

**Primary Cosmic Rays** \( (p, \text{He}, \text{C}, \text{O}, \ldots) \)

are produced at their source and travel through space and are directly detected by AMS. They carry information on their sources and the history of travel.
Traditionally, there are two prominent classes of cosmic rays:

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

**Secondary Cosmic Rays** (Li, Be, B, ...) are produced in the collisions of primary cosmic rays. They carry information on the history of the travel and on the properties of the interstellar matter.
AMS primary cosmic rays fluxes: He, C, and O

Helium

- AMS
- PAMELA

He flux measurement:
90 million events

Carbon

AMS
PAMELA

C flux measurement:
8.4 million events

Oxygen

AMS

O flux measurement:
7 million events
The AMS results show that the primary cosmic rays (He, C, and O) have an identical rigidity dependence. Break at about 200 GV, above the data all increase in identical way.
Secondary Cosmic Rays: Lithium and Boron

Above 7 GV Li and B have identical rigidity dependence

![Graph showing the flux of Lithium and Boron versus rigidity. The graph indicates that above 7 GV, the fluxes of Li and B are identical.]
Secondary Cosmic Rays: Beryllium
Both deviate from a traditional single power law above 200 GeV. But their momentum dependences are distinctly different. Secondary have identical rigidity dependence above 7GV.
Primary and Secondary Cosmic Rays Spectral Indices

All deviate from single power law above 200 GV. Secondary hardening is stronger. Is it due to propagation?
Summary of AMS results on Cosmic Ray Fluxes

High energy cosmic ray fluxes have 4 classes of rigidity dependence.

- **Primaries**
  - He
  - C (31)
  - O (28)

- **Particles**
  - p (0.12)
  - $e^+ (632)$
  - $\bar{p} (322)$

- **Secondaries**
  - Li (50)
  - B (35)
  - Be (100)

- **Electrons**
  - $e^- (5)$
Nitrogen Flux has peculiar Rigidity Dependence

Please refer to the AMS PRL publication.
The flux ratio between primaries (C) and secondaries (B) and isotopes (4He and 3He) provides information on propagation and on the Interstellar Medium (ISM).

As most of the B in CR is produced by C spallation, most of 3He is produced by 4He spallation. He isotopes span a larger distance compared to B/C due to their smaller cross section.
The B/C ratio does not show any significant structures.

B/C = kR^δ, \( \delta = -0.333 \pm 0.015 \)

Isotopes with AMS: He Isotopes flux

AMS measurement of He isotopic He3 and He4 fluxes from 1 GeV/a to 10 GeV/A.
He Isotopes flux in context

AMS analysis can be extend to lower energy using TOF.
A FEW GENERAL CONSIDERATIONS

- The spectra of nuclei behave as protons, $E^{-\gamma-\delta}$, at high energies, where spallation is weak.

- At low energies, where spallation dominates, nuclei have the same spectrum as injection.

- At even lower energies the spectrum further hardens because of ionization losses.

- The injection spectra of secondary nuclei, positrons and antiprotons reflect this trend.
SURPRIZES...

- Breaks in the spectra of nuclei
- Proton spectrum different from that of nuclei
- Positron excess
- Secondary nuclei
- Antiprotons, positrons, protons — same spectrum?

AMS data force to revisit the models of CR acceleration and propagation.

Whether such modifications are a symptom that a major revisitation of the paradigm is needed remains to be understood but there are tools to get there...
Plans for the Future
AMS Periodic Table
Solar activity measured by AMS

Cosmic rays entering the heliosphere are subject to diffusion, convection, adiabatic energy losses, and magnetic drift.
Cosmic ray flux variation over time correlate with solar activity.
Long term solar modulation
Monthly Proton and Helium time variation

(a) AMS Proton
(b) AMS Helium
High Energy Solar Energetic Particles

Preliminary Data. Please refer to the AMS forthcoming publication.
Science at low energy and space radiation with AMS

• Long term solar modulation of GCR and the transport of GCR in the heliosphere -> C. Consolandi’s talk
• Short term modulation of GCR (Forbush decrease and their time evolution) -> M. Palermo’s talk
• Solar energetic particles and their time evolution -> A. Popkow’s talk
• Anisotropies study and differential flux of SEPs
• Direct measurement of geomagnetic cut-off
• Trapped particles (under cut-off), SAA
Conclusions

• The International Space Station is a unique platform for precision physics research for the next decade.

• A new era in galactic cosmic rays understanding has started, at high energy where unexpected results are imposing changes in the GCR acceleration and propagation paradigm, and also at low energy in the region affected by the solar modulation thanks to the precise and continuous observations from space.

• The AMS results are playing a major role in heliophysics for the understanding of solar modulation, SEP and Forbush decrease and in space radiation for future manned mission to the Moon and Mars.

• These measurements will serve as a high-precision baseline for continued studies of GCR solar modulation, SEPs, space radiation hazards, magnetospheric effects, trapped particles and in many other fields.
Backups
In particular, $^{10}\text{Be}/^{9}\text{Be}$ allows to put constraints on the confinement time of CR in the galaxy, since $^{10}\text{Be}$ is decay with half-life $=1.39 \times 10^6$ years. It is possible to explore isotopic composition up to $\approx 10 \, \text{GeV}/n$, where previous measurement substantially stop at $\approx 1 \, \text{GeV}/n$. 

![Graph showing the $^{7}\text{Be}/\text{Be}$ ratio vs. kinetic energy/n (GeV/n).]