The Latest Results on High Energy Cosmic Rays

AMS

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Energies and rates of the cosmic-ray particles

The Pierre Auger Observatory

Telescope Array

Anisotropy of cosmic rays $E > 57$ EeV

AMS, CALET, DAMPE, ISS-CREAM
Space-born Cosmic Ray Experiments in operation

AMS, started May 2011  CALET, started August 2015

DAMPE, started December 2015  ISS CREAM, started August 2017
Prof. Eun-Suk Seo, Univ. of Maryland, has provided AMS with invaluable information on early, important work on cosmic rays by her and by other groups.
AMS: a TeV precision, accelerator-type spectrometer in space

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

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

Particles and nuclei are measured independently by the Tracker, RICH, TOF and ECAL.
Dark Matter

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

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

The excess of $e^+, \bar{p}, \bar{D}$ from Dark Matter annihilations can be measured by AMS as the background is small.

Ordinary matter is also produced by Dark Matter annihilations, but it is not distinguishable from the large background.

Electron and Positron spectra before AMS

These are very difficult experiments
Latest AMS results on positron and electron fluxes

- 28.1 million electrons
- 1.9 million positrons

Energy [GeV]
Properties of the Positron Flux

Observation 1: At low energies, the data agrees well with the predictions from the collisions of cosmic rays

- 1.9 million positrons
Properties of the Positron Flux

Observation 2: Above 8 GeV, the data flatten out

- 1.9 million positrons

Collision of Cosmic Rays

\[ \Phi_{e^+} E^3 \text{ [m}^2\text{s}^{-1}\text{sr}^{-1}\text{GeV}^2] } \]
Properties of the Positron Flux

Observation 3: Above 30 GeV, the data increase again.
Observation 4: It reaches a maximum at ~300 GeV

- 1.9 million positrons
Properties of the Positron Flux

Observation 5: The data drops sharply above 300 GeV

- 1.9 million positrons
The positron flux appears to be in agreement with predictions from a 1.2 TeV Dark Matter model (J. Kopp, Phys. Rev. D 88, 076013 (2013)).

- 1.9 million positrons

![Graph showing positron flux against energy]
Many models proposed to explain the physics origin of the observed behavior

(>2000 citations of the AMS results)

1) Particle origin: Dark Matter
2) Astrophysics origin: Pulsars, SNRs
3) Propagation of cosmic rays

Models based on very different assumptions describe observed trends of a single measurement.

Simultaneous description of several precision measurements is difficult in the framework of a single model
Current state: a nightmare

Igor Moskalenko/Stanford, 2017 APS meeting

New precise CR data

Theorists now

Aivazovsky: The 9th wave (1850)
Astrophysical sources: Supernova Remnants

Model parameter tuned to fit the positron flux data

Model parameter tuned to fit the B/C data

Positron excess also can be expressed in terms of the positron fraction, which explores the same physics.
New Propagation Models explaining the AMS e+ data

Explaining the AMS positron fraction (gray circles) is due to propagation effects. 

This requires a specific energy dependence of the B/C ratio

AMS: 11 million nuclei

The observed features of the AMS e+ data cannot be explained by standard propagation models
Astrophysical sources: pulsars

The High-Altitude Water Cherenkov Gamma-Ray Observatory
HAWC Collaboration, Science 358, 911-914 (2017)
HAWC rules out that the positron excess is from nearby pulsars

*Science 358, 911-914 (2017)*
AMS ($e^+ + e^-$) data with non-magnetic detectors
Measuring $e^+$ is the most sensitive way to identify $\chi$ via $\chi + \chi \rightarrow e^+, e^-, ...$.
The $\bar{p}/p$ ratio in comparison with pre-AMS models

- AMS Data, 0.56 million antiprotons
- $m_\chi = 1$ TeV

Current band width is based on the pre-AMS data.
Precision AMS data will result in new accurate predictions.

Donato et al., PRL 102, 071301 (2009)
New Models for the $\bar{p}/p$ ratio
The precision AMS data allow for exploration of new phenomena

Collision of cosmic rays with interstellar medium:
G.Giesen, et. al., JCAP 09 (2015) 023
C.Evoli et. al., JCAP 12 (2015) 039
R.Kappl et. al., JCAP 10(2015) 034
...

The antiproton excess around 10 GV:
A. Reinert and M.W. Winkler, JCAP 01 (2018) 055
Elementary Particles in Space

Of the hundreds of charged particles only four of them, e-, e+, p, and \( \bar{p} \), have infinite lifetime, so they travel in the cosmos forever.

AMS Results: The spectra of p and \( \bar{p} \) are identical.

This is difficult to explain if \( \bar{p} \) are secondaries

\[ p + p \rightarrow \bar{p} + X \]
The spectra of electrons and positrons are very different despite the fact that they have identical mass.
Most surprisingly:
The spectra of positrons, antiprotons, and protons are identical, but the proton and antiproton mass is 2000 times the positron mass.
The electron spectrum is different.
Traditionally, there are two prominent classes of cosmic rays:

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

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.
Before AMS: results on Primary Cosmic Rays
(Helium, Carbon, Oxygen)
from balloon and satellite experiments

Flux $\times E_K^{2.7} \left[ \text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}\right] (\text{GeV}/\text{n})^{1.7}$

Kinetic Energy ($E_K$) [GeV/n]
The AMS results show that the primary cosmic rays (He, C, and O) have identical rigidity dependence.

Above 200 GV the data all increase in identical way. This is unexpected.
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.
Rigidity dependence of Primary and Secondary Cosmic Rays

Both deviate from a traditional single power law above 200 GeV. But their rigidity dependences are distinctly different.
Combining the six ratios, the secondary over primary flux ratio (B/C, ...), deviates from single power law above 200 GV by $0.13 \pm 0.03$

$$\text{Secondary/Primary} = KR^\Delta$$

$$\Delta[200-3300\text{GV}] - \Delta[60-200\text{GV}] = 0.13 \pm 0.03$$
The Nitrogen flux together with primary and secondary cosmic rays fluxes.

\[ \text{Flux} \times \tilde{R}^{2.7} \] [m\(^2\)s\(^{-1}\)sr\(^{-1}\)(GV\(^{1.7}\))]

- **Helium**
- **Carbon \times 30**
- **Oxygen \times 28**
- **Nitrogen \times 130**
- **Lithium \times 200**
- **Beryllium \times 400**
- **Boron \times 145**
The nitrogen flux is composed of primary and secondary components.
C-N-O Cycle: the source of energy in stars

AMS measurement in the Galaxy
N/O = 0.09
C/O = 0.90

In Solar System:
N/O = 0.14
C/O = 0.46
New observations of the monthly time variation of the $e^+$, $e^-$, $p$, and He fluxes are providing key information for studying solar physics.
New observation: Identical monthly time variation of the $p$, He fluxes
AMS continuous measurement of the $e^+$ and $e^-$ flux in the energy range 1 - 50 GeV over 6 years with a time resolution of 27 days.

To appear in PRL
Physics of AMS through the lifetime of the Space Station

Examples: Complex anti-matter – $\bar{\text{He}}, \bar{\text{C}}, \bar{\text{O}}$
Positrons and Dark Matter
Anisotropy and Dark Matter
High Z cosmic rays
First antihelium candidate

Momentum = 33.1 $\pm$ 1.6 GeV/c
Charge = -1.97 $\pm$ 0.05
Mass = 2.93 $\pm$ 0.36 GeV/c^2

Mass ($^3$He) = 2.83 GeV/c^2

Date: 2011-269:11:19:32
Physics of AMS on ISS: Study of complex anti-matter $\overline{\text{He}}, \overline{\text{C}}, \overline{\text{O}}$

$^3\text{He}/\text{He}$ flux ratio predictions

**From the collision of cosmic rays:**

- M. Cirelli et al., JHEP 8, 9 (2014): $^3\text{He}/\text{He}[8-40]GV = 3 \times 10^{-11}$
- E. Carlson et al., Phys. Rev. D 89, 076005 (2014) $^3\text{He}/\text{He}[8-40]GV = 1.4 \times 10^{-9}$
- A. Coogan et al., Phys. Rev. D 96, 083020 (2017) $^3\text{He}/\text{He}[8-40]GV \sim 2 \times 10^{-8}$

**AMS Measurement:** $^3\text{He}/\text{He}[8-40]GV = 2 \times 10^{-8}$

There are large uncertainties in models to ascertain the origin of $^3\text{He}$

We have also observed two $^4\text{He}$ candidates.

The rate of anti-helium is $\sim 1$ in 100 million helium.

More events are necessary to ensure that there are no backgrounds.
Study of anti-Carbon, anti-Oxygen
The observed anti-helium events are all below 100 GV

Analysis of $\bar{C}$ and $\bar{O}$ to 100 GV use L2-L8 as for He

By 2024, AMS will have more than 100 million carbon and oxygen to study anti-carbon and anti-oxygen
Extend the measurements to 2 TeV and determine the sharpness of the drop off.

To date, we have a 2-sigma effect.

- 1.9 million positrons

By 2024, we will have a 5-sigma effect.

AMS will collect 4 million positrons

Currently, the approved ISS lifetime is until 2024.
The incremental gain between now and 2024 is from 2-sigma to 5-sigma.
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

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

\( C_1 \) is the dipole moment

Projected amplitude of the dipole anisotropy

The observation of isotropy at the 3-sigma level is an important confirmation of the projected 5-sigma effect in the positron flux.
Study high Z cosmic rays

AMS, CALET, DAMPE, ISS-CREAM
Physics of high Z cosmic ray spectra at high energies:
A. Probe different galactic distances
Systematic study of propagation as function $A$ ($Z$) and $R$.

Effective propagation distance:
$$<X> \sim \sqrt{6D\tau} \sim 2.7 \text{ kpc } R^{\delta/2} \left(\frac{A}{12}\right)^{-1/3}$$

- protons: $\sim 5.6 \text{ kpc } R^{\delta/2}$
- Helium: $\sim 3.6 \text{ kpc } R^{\delta/2}$
- Carbon: $\sim 2.7 \text{ kpc } R^{\delta/2}$
- Iron: $\sim 1.6 \text{ kpc } R^{\delta/2}$

i. Different $Z$ (or $A$) nuclei probe different distances.
ii. Higher energies probe larger distances
B. Precise data on heavy nuclei, Z=9 to Z=28, up to the TV region. Particularly interesting is evidence of the flux break at \( \sim 200 \text{ GV} \). The measurements of the Aluminum, Chlorine, and Manganese spectra will precisely establish the age of cosmic rays as \(^{26}\text{Al},^{36}\text{Cl},^{54}\text{Mn}\) are radioactive clocks.

Events with Z=17 to Z=28 through 2024

AMS

\begin{itemize}
\item Cl \(220K\)
\item Ar \(380K\)
\item Ca \(600K\)
\item Ti \(320K\)
\item K \(300K\)
\item Sc \(150K\)
\item V \(190K\)
\item Mn \(260K\)
\item Fe \(1.7M\)
\item Ni \(70K\)
\end{itemize}
C. The lightest elements created by supernova are **Nickel** and **Zinc**. Compare them with elements produced by stellar nucleosynthesis.
Most of results presented today are unexpected and require much improved accuracy of theoretical predictions.

There are several large scale detectors in space to study high energy charged cosmic rays:

AMS, CALET, DAMPE, ISS-CREAM

AMS is the only magnetic spectrometer in space in the foreseeable decades.

With the new precision data we should be able to uncover the origin of many observed unexpected phenomena.
5m x 4m x 3m
7.5 tons
AMS was installed on the ISS in May 2011.

Over 121 billion charged cosmic rays have been measured.
Calibration of the AMS Detector

Test beam at CERN SPS: $p, e^\pm, \pi^\pm$, 10–400 GeV

12,000 CPU cores at CERN

Computer simulation: Interactions, Materials, Electronics

2000 positions

AMS

7 km

27 km
Positron excess also can be expressed in terms of the positron fraction, which explores the same physics.

$$\frac{\Phi_{e^+}}{\Phi_{e^+} + \Phi_{e^-}}$$

- 1.9 million positrons

A sample of papers on AMS e+ data

1) J. Kopp, Phys. Rev. D 88, 076013 (2013);
4) M. Ibe, S. Iwamoto, T. Moroi and N. Yokozaki, JHEP 1308 (2013) 029
7) M. Ibe, S. Iwamoto, T. Moroi and N. Yokozaki, JHEP 1308 (2013) 029
8) L. Bergstrom, T. Bringmann, I. Cholis, D. Hooper and C. Weniger, PRL 111 (2013) 171101
10) Y. Zhao and K.M. Zurek, JHEP 1407 (2014) 017
12) M. Ibe, S. Iwamoto, T. Moroi and N. Yokozaki, JHEP 1308 (2013) 029
15) M. Ibe, S. Iwamoto, T. Moroi and N. Yokozaki, JHEP 1308 (2013) 029
16) Y. Zhao and K.M. Zurek, JHEP 1407 (2014) 017
20) K. Kohri and N. Sahu, Phys.Rev. D88 (2013) 10, 103001
22) Y. Zhao and K.M. Zurek, JHEP 1407 (2014) 017

and many other excellent papers ...

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) M. Ibe, S. Iwamoto, T. Moroi and N. Yokozaki, JHEP 1308 (2013) 029
8) L. Bergstrom, T. Bringmann, I. Cholis, D. Hooper and C. Weniger, PRL 111 (2013) 171101
10) Y. Zhao and K.M. Zurek, JHEP 1407 (2014) 017
12) M. Ibe, S. Iwamoto, T. Moroi and N. Yokozaki, JHEP 1308 (2013) 029
13) Y. Zhao and K.M. Zurek, JHEP 1407 (2014) 017
19) Y. Zhao and K.M. Zurek, JHEP 1407 (2014) 017

and many other excellent papers ...

Propagation Models


and many other excellent papers ...

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

and many other excellent papers ...
The combined (e+ + e-) energy dependence

The (e+ + e-) flux deviates from a single power law above ~900 GeV

Fit double power law:

\[ \Phi(E) = C \left( \frac{E}{50 \text{ GeV}} \right)^r \left[ 1 + \left( \frac{E}{E_b} \right)^\Delta \right]^s \]

Spectral break

\[ E_{\text{break}} = 900 \pm 200 \text{ GeV} \]
Additional source of cosmic ray Electron

AMS Electron flux disagree with conventional cosmic ray model expectation. Indicates additional primary source of electron starting $\sim$30GeV. However, due to large background and its uncertainties from conventional cosmic ray electron, it is difficult to extract source contribution from electron flux alone.
Summary of AMS results on Cosmic Ray Fluxes

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

Primaries
- He(1)
- C(31)
- O(28)

Particles
- p(0.1)
- e⁺(280)
- p(550)

Primary + Secondary
- N(20)

Secondaries
- Li(20)
- Be(40)
- B(14)

Electrons
- e⁻(1)
Precision Measurements of Cosmic Rays:
AMS has seven instruments which independently measure Cosmic Nuclei
Measurements of proton spectrum before AMS

1. Protons are the most abundant charged cosmic rays.
2. Before AMS, there were many measurements but the data have large errors and are inconsistent.
3. These data limit the understanding of the production, acceleration and propagation of all cosmic rays.
4. The proton flux is assumed to be a single power law = $CR^\gamma$
AMS results on the proton flux

The proton flux cannot be described by a single power law = $CR^\gamma$

AMS
300 million protons

Traditional assumption - single power law (PDG)

Rigidity [GV] = momentum/charge

Flux $\times R^{2.7}$ [m$^{-2}$ sr$^{-1}$ sec$^{-1}$ GV$^{1.7}$]
AMS Measurement of the proton spectrum together with earlier measurements

- AMS-02

**Graph:**
- Y-axis: Flux $\times E^{2.7}$ (m$^{-2}$ sr$^{-1}$ s$^{-1}$ GeV$^{-1.7}$)
- X-axis: Kinetic Energy (GeV)
- Data points from various experiments, including AMS-01, ATIC02, Balloon, BESS93, BESS97, BESS98, BESS99, BESS00, BESS-TeV, BESS-Polar I, BESS-Polar II, CAPRICE94, CAPRICE98, CREAM-I, IMAX92, JACEE, MASS91, PAMELA, RICH-II, RUNJOB, SOKOL.
Proton Flux

Proton

Flux $\times R^{2.7}$ [m$^{-2}$ sr$^{-1}$ sec$^{-1}$ GV$^{1.7}$]

Rigidity [GV]

AMS
PAMELA

unexpected
The AMS results on primary cosmic rays He, C, and O.


- The AMS helium flux is distinctly different from previous measurement.
- He flux shows a smooth change of behavior towards high energy starting from 300 GV.
The AMS Result on the Secondary Nuclei Fluxes

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.

The AMS Result on the Secondary Nuclei Fluxes
Secondary Cosmic Rays: Lithium and Boron
Above 7 GV Li and B have identical rigidity dependence

Flux \times R^{2.7} [m^2 s^{-1} sr^{-1} (GV)^{1.7}]

Rigidity \tilde{R} [GV]

△ Li 1.9 million events
■ B 2.6 million events
Secondary Cosmic Rays: Lithium and Beryllium

Above 30 GV Li and Be have identical rigidity dependence. The fluxes are different by a factor of 2.
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 \( B/C = kR^\delta \).

With the Kolmogorov turbulence model \( \delta = -1/3 \)
The AMS Boron-to-Carbon (B/C) flux ratio

The B/C ratio does not show any significant structures

$B/C = k R^\delta$, $\delta = -0.333 \pm 0.015$

Nitrogen nuclei in cosmic rays

Astrophysical sources, via the CNO cycle

Collisions of heavier nuclei with the interstellar medium

O, Si, ..., Fe + ISM → N + ...

In the Solar System: N/O ≈ 0.14
Energy Production in Stars

Phys. Rev.
Mar. 1, 1939

H.A. Bethe

Abstract
It is shown that the most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons. These reactions form a cycle in which the original nucleus is reproduced ...

Nobel Prize 1967

In the Solar System: N/O = 0.14

Abundances of the Elements in the Solar System, Cameron, A. G. W., Space Science Reviews, 15, 121 (1970)
B. AMS will obtain precise data on heavy nuclei, $Z=9$ to $Z=28$, up to the TV region. Particularly interesting is evidence of the flux break at $\sim 200$ GV. The measurements of the Aluminum, Chlorine, and Manganese spectra will precisely establish the age of cosmic rays as $^{26}\text{Al}$, $^{36}\text{Cl}$, $^{54}\text{Mn}$ are radioactive clocks.

Events with $Z=9$ to $Z=16$ through 2024
Science Example: Strange Quark Matter – “Strangelets”


All the material on Earth is made out of u and d quarks

Diamond (Z/A ~ 0.5)

Is there material in the universe made up of u, d, & s quarks?

Strangelet (Z/A < 0.1)

This can be answered definitively by AMS.
Strangelets

Helium

AMS Z=2
80 Million Events

Events vs. Z/A
Limits from accelerators and lunar soil are much higher than PAMELA.

Strangelets with $Z = 2$ to 8 are ruled out by AMS.