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Latest AMS Results

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The physics of AMS on the Space Station: Long term precision measurement of Charged Cosmic Rays

Charged cosmic rays have mass. They are absorbed by the Earth's atmosphere



AMS: A TeV precision, multipurpose spectrometer in space

Particles and nuclei are defined by their charge (Z) and energy (E ~ p)

TRD (e /p) Rej.Fact = 10⁻² - 10⁻³

Time of Flight (Z, β) σ (t) = 160 ps



Ground Tests and Calibrations

Space Qualification (EMI and TV at ESTEC)

TVT Chamber: P < 10⁻⁹ bar Ambient temperature: -90°C to 40°C





Test Beam at CERN (Calibration)



1,762 positions and angles with p, e⁺, e⁻, pion beams from 10 to 400 GeV/c





AMS installed on the ISS and taking data since 9:35 CDT on May 19, 2011

> In 8 years, over 140 billion charged cosmic rays have been measured by AMS

AMS Results: Positrons and electrons fluxes Nuclei fluxes Solar physics

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AMS Results Cosmic Ray Positrons

New Astrophysical Sources: Pulsars, ...

Supernovae

Protons, Helium, ...

Interstellar Medium

Positrons

Dark Matter

Positrons from Dark Matter

Positrons

from Pulsars

Electrons

Dark Matter

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Positron identification in AMS



0.8 EcalBDT

Positron Analysis: Background identification

Charge Confusion e[±]



Flux of Cosmic Ray Positrons

First 6.5 years of AMS operation



Flux of Cosmic Ray Positrons

Low energy positrons mostly come from cosmic ray collisions



The positron flux is the sum of

low-energy part from cosmic ray collisions plus a new source at high-energy.



Flux of Cosmic Ray Electrons

First 6.5 years of AMS operation



Flux of Cosmic Ray Electrons First 6.5 years of AMS operation

M. Aguilar et al. Phys. Rev. Lett. 122 (2019) 101101



Flux of Cosmic Ray Electrons

The contribution from cosmic ray collisions is negligible



Electron flux characterization

1. Change of the spectral index with more than 7 sigma significance

 $E_0 = 42.1^{+5.4}_{-5.2}$ GeV $\Delta \gamma = 0.094 \pm 0.014$

2. At the 5 sigma level the electron flux does not have an Energy Cutoff below 1.9 TeV



Electron flux characterization

Minimal number of power-law like contributions



The Origin of Cosmic Ray Electrons

New sources of high energy positrons may also produce an equal amount of high energy electrons



The electron flux data are consistent both with the existence of a high energy electron source term identical to that of positrons and also with the absence of such a term

Positrons:

- Low energy from CR Collisions + New source at high energy
- $E_s = 810^{+310}_{-180} \text{ GeV}$

Electrons:

- 2 power law contributions
- $E_s < 1.9$ TeV excluded at 5σ

The Origin of Cosmic Ray Positrons Dark Matter Models

DM self-annihilation would lead to a sharp cutoff in the flux ("kinematic edge")

The Origin of Cosmic Ray Positrons **Astrophysical sources: Pulsar** Pulsars produce and accelerate positrons to high energies.

D. Hooper et al. Phys. Rev. D 96, 103013 (Nov 2017)

- Pulsars may induce an anisotropy in the arrival direction of the particles 1.
- 2. Pulsars do not produce antiprotons.

The positron flux is found to be consistent with isotropy

 $\delta = 3\sqrt{C_1/4\pi}$ C_1 is the dipole moment

Amplitude of the dipole anisotropy on positrons for 16 < E < 350 GeV $\delta < 0.019$ (95% C.I.)

The Origin of Cosmic Ray Positrons

Antiproton data show a similar trend as positrons.

Positrons and electrons by 2024

AMS Results Precision Study of Cosmic Nuclei through the lifetime of ISS

Traditionally, there are two prominent classes of cosmic rays

<u>Primary elements (H, He, C, ..., Fe)</u> are produced during the lifetime of stars. They are accelerated by the explosion of stars (supernovae).

<u>Secondary cosmic nuclei (Li, Be, B, ...)</u> are produced by the collision of primary cosmic rays and interstellar medium

Cosmic ray propagation is commonly modeled as a diffusion process due to the turbulent magnetic field:

Primary ~ source (R^{- α}) x propagation (R^{- δ}) ~ R^{-(α + δ)} Secondary ~ source (R^{-(α + δ)}) x propagation (R^{- δ}) ~ R^{-(α + 2δ)}

Secondary/Primary ~ $R^{-\delta}$

With the Kolmogorov turbulence model $\delta = -1/3$

Precise measurements of primaries and secondaries rigidity dependence provide key information on propagation and source processes

Precision Study of Cosmic Nuclei through the lifetime of ISS

Precision measurements of Cosmic Nuclei fluxes

Main systematic error is due to the uncertainty in the energy scale

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Absolute Rigidity Scale

Comparison of the rigidity R measured by the tracker, with the energy E, measured by the electromagnetic calorimeter, for positron and electron events.

The accuracy of the rigidity scale is found to be 0.033 TV⁻¹, limited mostly by available positron statistics

Measurement of proton spectrum with AMS

Proton flux shows a deviation from a single power law above few hundred GV

Unique properties of AMS:

We measured the nuclei survival probability using data acquired when ISS attitude was rotated so that AMS was pointing in a horizontal direction.

AMS Nucleus + C Inelastic Cross Section Measurements (5-100 GV Rigidity)

Primary and secondary Cosmic Rays Comparison with earlier measurements

M. Aguilar et al. Phys. Rev. Lett. 119 (2017) 251101

M. Aguilar et al. Phys. Rev. Lett. 120 (2018) 021101

Primary and secondary Cosmic Rays with AMS

Both deviate from a tradicional single power law above 200 GeV

 Above 60 GV, the primary cosmic rays have similar rigidity dependence.
Secondary cosmic rays Li, Be, and B also have identical rigidity dependence but they are different from primaries

Secondary/Primary Flux Ratios = KR⁴

Combining the six ratios, the secondary over primary flux ratio (B/C, ...), deviates from single power law above 200 GV by 0.13 ± 0.03 Δ [200-3300GV] - Δ [60-200GV] = 0.13 ± 0.03

Support the interpretation of the hardening in terms of a change in the propagation properties in the Galaxy.

Cosmic ray production and propagation

Understanding the origin, acceleration and propagation of Cosmic rays require the knowledge of the chemical composition over a wide energy range

Effective distance is shown for ~1 GV.

Effective propagation distance

 $\propto R^{-\Delta/2} A^{-1/3}$

 Determine ∆ from secondary-to primary ratios

ii. Different nuclei A (1 - 60) probe different distances.

iii.Different rigidities R (1 – 3000 GV) probe different distances

O, Ne, Mg, Si and S Fluxes

The latest AMS Result on the He/O and C/O Flux Ratios

Above ~60 GV, the He, C and O spectra have identical rigidity dependence

Flux Ratio to Oxygen (Ne/O, Mg/O, Si/O, and S/O)

AMS ³He/⁴He flux ratio Data collected from May 2011 to Nov 2017 (6.5 y)

Helium are the second most abundant nuclei in cosmic rays. They consist of two isotopes, ⁴He and ³He.

The ⁴He is thought to be mainly produced and accelerated in astrophysical sources, while ³He is mostly produced by the collisions of ⁴He with the interstellar medium.

AMS ³He and ⁴He fluxes

Measurements in 21 time periods of 4 Bartels rotations (108 days) each

Below 4 GV the ³He/⁴He flux ratio shows a long-term time dependence in the lowest rigidity bin. Above 4 GV the ³He/⁴He flux ratio was found to be time independent

AMS ³He/⁴He flux ratio

Above 4 GV the ³He/⁴He flux ratio rigidity dependence is well described by single power law (C R^{Δ}) with Δ = -0.294 ± 0.004.

Different from B/O ratio, which shows a maximum around 4 GV, the ³He/⁴He flux ratio was found being always decreasing with rigidity below 4 GV as R^{δ} with < δ >= 0.21 ± 0.02 and a time dependence of ± 0.05.

Solar Physics over an 11-year Solar Cycle: 2011 - 2024

AMS continous measurement of the e⁺ and e⁻ flux in the energy range 1 -50 GeV over 6 years with a time resolution of 27 days.

M. Aguilar et al. Phys. Rev. Lett. 121 (2018) 051102

AMS Results on the Identical monthly time variation of the proton and helium fluxes over 6 years

M. Aguilar et al. Phys. Rev. Lett. 121 (2018) 051101

Solar physics over a complete 11-year solar cycle

Solar physics over a complete 11-year solar cycle

Carbon and Oxygen

Anti-Helium Search with AMS

³He flux models from collisions of cosmic rays

There are large uncertainties in models to ascertain the origin of ³He The rate of anti-helium is ~1 in 100 million helium.

We have also observed two ⁴He candidates. More events are necessary to ensure that there are no backgrounds. Space is the ultimate laboratory. It provides the highest energy particles.

The AMS results contradict current cosmic ray models and require the development of a comprehensive theoretical scheme.

AMS will continue to collect and analyze data for the lifetime of the Space Station.