Cosmic Rays: AMS Experiment

Javier Berdugo (CIEMAT, Madrid)

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Cosmic rays

Cosmic rays are a sample of solar, galactic and extragalactic matter which includes all known nuclei and their isotopes, as well as electrons, positrons and antiprotons.

Sci. Amer. 276 (1997) 44
The collision of cosmic rays with interstellar medium (ISM) produces antiparticles ($e^+$, $\bar{p}$, $\bar{D}$, ...) 

$p, \text{He} + \text{ISM} \rightarrow \text{antiparticles} + ...$

The collision of dark matter particles will produce additional antiparticles 

$\chi + \chi \rightarrow \text{antiparticles} + ...$
Positrons in Cosmic Rays

\[ m_\chi = 800 \text{ GeV} \]

\[ m_\chi = 400 \text{ GeV} \]

\[ e^+ / (e^+ + e^-) \]

\[ 10^{-1} \]

\[ 10 \quad 10^2 \]

e\pm \text{ energy [GeV]}

- I. Cholis et al., arXiv:0810.5344
Flux of antiparticles in cosmic rays

Precision measurements of antiparticles requires long exposure time with detectors with large acceptance and percent level precision.

Experiments operating outside the atmosphere and capable to measure simultaneously the spectra of the different cosmic ray components.
Space based cosmic ray experiments

**PAMELA: Launched on June 15th 2006**


Image credit: NASA/Jerry Cannon, Robert Murray

**FERMI Launched on June 11, 2008**


Image credit: NASA/Jerry Cannon, Robert Murray
Space-born Cosmic Ray Experiments in operation

AMS, started May 2011

CALET, started August 2015

DAMPE, started December 2015

ISS CREAM, started August 2017
5m x 4m x 3m
7.5 tons

TRD
TOF 1, 2
Magnet
and
Veto Counters
TOF 3, 4
RICH
ECAL

Silicon layer 1
Silicon layers 2 - 8
Silicon layer 9

Acceptance: 0.5 m² sr
AMS is an international collaboration based at CERN

It took 650 physicists and engineers 17 years to construct AMS
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
Positron measurement with AMS

Signal identification from 2D template fit in ($\Lambda_{\text{TRD}} - \Lambda_{\text{CC}}$) plane

$237 < |R| < 290$ GV
Positron fraction in cosmic rays with AMS

\[ \frac{\Phi_{e^+}}{\Phi_{e^+} + \Phi_{e^-}} \]
Latest AMS results on **positron** and **electron** fluxes

Energy range from 0.5 GeV to 1 TeV

- **28.1 million electrons**
- **1.9 million positrons**

Energy range from 0.5 GeV to 1 TeV
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

**positrons**

**Isotropic Map**

Amplitude of the dipole anisotropy on positrons

for $16 < E < 350$ GeV

$\delta < 0.019$ (95% C.I.)
Positron flux modeling

Many models proposed to explain the physics origin of the observed behavior

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.
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
Measuring $e^+ + e^-$ is much less sensitive to detect the source term due to the large $e^-$ background.
\((e^+ + e^-)\) AMS data: comparison with other detectors
The Antiproton Flux is $\sim 10^{-4}$ of the Proton Flux. A percentage precision experiment requires background rejection close to 1 in a million.
Antiproton measurement with AMS

Signal identification from 2D template fit in ($\Lambda_{TRD} - \Lambda_{CC}$) plane

$175 < |R| < 211$ GV

$\chi^2$/d.f. = 138/154
Antiproton-to-Proton Flux Ratio

Show no rigidity dependence above 60 GV

\[ \Phi_{\bar{p}} / \Phi_p \]

- AMS-02
- PAMELA


\[ \bar{p} \ 3.49 \cdot 10^5 \text{ events} \]
Collision of cosmic rays with interstellar medium:

- G. Giesen, et al., JCAP 09 (2015) 023
- C. Evoli, et al., JCAP 12 (2015) 039

Graphs showing the distribution of cosmic ray particles with different energy levels and uncertainties.
Primary and secondary cosmic ray

Understanding the origin, acceleration and propagation of CR require the knowledge of the chemical composition over a wide energy range.
Primary and secondary Cosmic Rays
Comparison with earlier measurements


(a) Helium

(b) Carbon

(c) Oxygen

Flux \times E^2 \times 10^7 \text{ [m}^2 \text{s}^{-1} \text{sr}^{-1} \text{(GeV/n)}^2]\)

Kinetic Energy \( E_K \text{ [GeV/n]} \)

Flux \times E^2 \text{ [m}^2 \text{s}^{-1} \text{sr}^{-1} \text{(GeV/n)}^2]\)

Kinetic Energy \( E_K \text{ [GeV/n]} \)
Secondary/Primary Flux Ratios = $KR^\Delta$

Combining the six ratios, the secondary over primary flux ratio $(B/C, \ldots)$, deviates from single power law above 200 GV by $0.13\pm0.03$

\[ \Delta[200-3300\text{GV}] - \Delta[60-200\text{GV}] = 0.13\pm0.03 \]
Primary Component
Secondary Component

$\Phi_N = \Phi_N^P + \Phi_N^S = (0.090 \pm 0.002) \times \Phi_O + (0.62 \pm 0.02) \times \Phi_B$

$^3\text{He}/^4\text{He}$ abundancies

Preliminary data, refer to upcoming AMS PRL publication.
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.

Anti Deuterons have been proposed as an almost background free channel for Dark Matter indirect detection.

The Anti Deuterons Flux is $< 10^{-4}$ of the Antiproton Flux. Additional background rejection.
Anti-deuterons have never been observed in space.

**Search for Cosmic-Ray Antideuterons**

We performed a search for cosmic-ray antideuterons using data collected during four BESS balloon flights from 1997 to 2000. No candidate was found. We derived, for the first time, an upper limit of \( 1.9 \times 10^{-4} \, (\text{m}^2\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1}\text{nucleon}^{-1}) \) for the differential flux of cosmic-ray antideuterons, at the 95% confidence level, between 0.17 and 1.15 GeV/nucleon at the top of the atmosphere.

**BESS results (COSPAR 2018)**

180 antiprotons total

\[ \bar{d} \text{ upper limit} \quad 6.6 \times 10^{-5} \,(95\% \text{C.L.}) \]
Anti-Deuteron Search with AMS

Momentum = 6.23 ± 0.37 GeV/c
Charge = -1
Mass = 1.74 ± 0.24 GeV/c²
M_D = 1.88 GeV/c²

Anti-deuteron candidate

March 2, 2012 11:34
Anti-Deuteron Search prospects

![Graph showing antideuteron flux vs kinetic energy]
First anti-Helium event in the cosmos:

Momentum = 33.1 ± 1.6 GeV/c
Charge = -1.97 ± 0.05
Mass = 2.93 ± 0.36 GeV/c²
Mass ($^3$He) = 2.83 GeV/c²

Date: 2011-269:11:19:32

Anti-Helium Search with AMS
There are large uncertainties in models to ascertain the origin of $^3\text{He}$.

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

We have also observed two $^4\text{He}$ candidates. More events are necessary to ensure that there are no backgrounds.
High precision measurements of cosmic rays open new windows to observe unexpected phenomena.

There are several large scale detectors in space to study high energy charged cosmic rays: AMS, CALET, DAMPE, ISS-CREAM exploring a new and exciting frontier in physics research.