Cosmic rays as seen from Space with AMS

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Società Italiana di Fisica
XCVIII Congresso Nazionale
Naples, 17 September 2012
V. Hess: 7th balloon flight (August 7th, 1912)

Also Theodor Wulf, Domenico Pacini
The Positive Electron

CARL D. ANDERSON, California Institute of Technology, Pasadena, California
(Received February 28, 1933)

Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the curvatures and ionizations produced require the mass to be less than twenty times the electron mass. These particles will be called positrons. Because they occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from atomic nuclei.

Editor

Fig. 1. A 6.3 million electron-volt positron passing through a 6 mm lead plate and emerging with an energy of 25 million electron-volts. The length of this latter path is at least ten times greater than the possible length of a proton track of this curvature. (Magnetic field 15,000 gauss.) In all the photographs the magnetic field is directed into the paper.
Discovery of Muons

Note on the Nature of Cosmic-Ray Particles
Seth H. Neddermeyer and Carl D. Anderson
California Institute of Technology, Pasadena, California
(Received March 30, 1937)

Discovery of Pions

PROCESSES INVOLVING CHARGED MESONS
By Dr. C. M. G. LATTES, H. MUIRHEAD,
Dr. G. P. S. OCCHIALINI and
Dr. C. F. POWELL
H. H. Wills Physical Laboratory, University of Bristol

Discovery of Kaons and Lambdas

EVIDENCE FOR THE EXISTENCE OF NEW UNSTABLE ELEMENTARY PARTICLES
By Dr. G. D. ROCHESTER
AND
Dr. C. C. BUTLER
Physical Laboratories, University, Manchester
The highest energy particles are produced in the cosmos. The Largest Accelerator on Earth (LHC) will produce particles of 7 TeV. Cosmic Rays with energies about 100 Million TeV have been detected.
Fundamental Science on the International Space Station (ISS)

There are two kinds of cosmic rays traveling through space

1- Neutral cosmic rays (light rays and neutrinos):
Light rays have been measured (e.g., Hubble) for over 50 years. Fundamental discoveries have been made.

2- Charged cosmic rays: Following the pioneering experiments with balloons and small satellites, using a magnetic spectrometer (AMS) on ISS is a unique way to provide precision long term (10-20 years) measurements of high energy charged cosmic rays.
The scientific goals of AMS on the ISS

Search for primordial antimatter
Search for Dark Matter
Chemical composition and energy spectra of cosmic rays
ACC $\sim 0.45$ m$^2$ sr
Exposure time: ISS live time

300,000 electronic channels
650 computers

5m x 4m x 3m
7.5 tons
AMS-02 Collaboration

16 countries, 60 institutes, 600 physicists, 17 years
Italy in AMS

- Milano
- Bologna
- Pisa
- Perugia
- Terni
- Roma

60 Scientists and Engineers
- 6 Universities
- 51 INFN Sections
- 2 INFN National Laboratories

16 years of collaboration among INFN and ASI
Italian Industries in AMS

- FBK-irst
- CARSO
- CGS
- Ri-Ba Composites
- CAEN
- G&A Engineering
- Galli e Morelli
- Euromecc

Space Companies
Particles and nuclei are defined by their charge ($Z$) and energy ($E \sim P$).

$Z, P$ are measured independently by the Tracker, RICH, TOF, and ECAL.
The Magnet

The detailed 3D field map (120k locations) was measured in May 2010.

In 12 years the field has remained the same to <1%.
Time of Flight System

Measures Velocity and Charge of particles
Provide trigger for charged particles

Resolution = 160ps

nuclear charge Z

He  C  O  Al  Ca

TOF 1 and 2
TOF 3 and 4

PMTs
Scintillator
Light Guides
PMTs
Light Guides

1, 2
3, 4

Resolution = 160ps
Anti-Coincidence Counters

Efficiency >99.99%
To use the bending power of the magnet, we have built a state of the art Tracking Detector based on 9 thin layers of Silicon Detectors.
Silicon Tracker: 9 planes, 200,000 channels

Construction:
- Mechanical:
  50 engineers 3 yrs
- Electronics:
  10 yrs at CSIST
Tracker: coordinate resolution 10\,\mu m

dE/dX: identify nuclei

TRD

ECAL

RICH

MAGNET

TOF

TOF

Test Beam
Tracker Alignment System

accuracy: 3 µm with 20 UV lasers

5 x Laser Beam Port Boxes (LBBXs)

1080 nm

Laser Fiber Couplers
Transition Radiation Detector (TRD)

20 Layers each consisting of:
- 22 mm fibre fleece
- Ø 6 mm straw tubes
  filled with Xe/CO$_2$ 80%/20%
Transition Radiation Detector: identifies Positrons and Electrons

9,000 Straw Tubes Manufactured
5,248 tubes selected from 9,000, 2 m length centered to 100µm, verified by CAT scanner

Life time: ~20 years in Space

p/e+ rejection: Test Beam (400GeV): >10^2
In Space: > 10^3 – 10^4

dE/dX: identifies nuclei (He ....)
Ring Imaging Cherenkov (RICH)

Cherenkov radiation

- Particle
- Charge Velocity
- Cherenkov Radiator
- Conical Reflector
- Photo-detectors 10880

Velocity

Electric Charge
10,880 photosensors to identify nuclei and their energy
On the ISS, AMS will measure the composition of high energy Cosmic Rays with extraordinary accuracy.

Test results from accelerator
Calorimeter (ECAL)

A precision, 17 $X_0$, 3-dimensional measurement of the directions and energies of light rays and electrons

- 50,000 fibers, $\phi = 1$ mm distributed uniformly inside 600 kg of lead
- Test Beam Results:
  \[ \frac{\sigma(E)}{E} = \frac{10.6 \pm 0.1}{\sqrt{E}} \oplus (1.25 \pm 0.03)\% \]
AMS electronics
650 computers, 300,000 channels, up to 400% redundancy

Fast: 10 x the commercial space electronics
Accurate: measure coordinate to 10 microns
Linear: 1 in $10^5$, 10 MeV to 1 TeV

Electronics fabricated in Taiwan, under NASA supervision
AMS-02: Subdetector Qualification Test

**CSIST, NSPO (Taiwan):** Electronics modules
**AACHEN (Germany):** TRD and electronics crates
**INTA (Spain):** RICH and electronics crates
**SERMS (Italy):** TOF, TRK, ECAL and electronics crates
Dedicated Space Qualification Facilities have been developed for AMS in Italy.
Vibration tests of Flight Model Time of Flight
2009: AFTER 9000 hrs of TVT...
THE END OF SUB-SYSTEMs TESTS
AMS in the ESA Electromagnetic Interference (EMI) Chamber, March 2010, ESTEC, Noordwijk, Netherlands
AMS in the ESA TVT Chamber, April 2010, ESTEC

Duration 330 hours
P < 10^{-6} mbar

Ambient temperature from -90°C to +40°C
Test at CERN
AMS in accelerator test beam Feb 4-8 and Aug 8-20, 2010
Test Beam Results – 8-20 Aug 2010, CERN

Velocity measured to an accuracy of 1/1000 for 400 GeV protons

Reconstructed Velocity/c

Energy

TRD: 400 GeV protons
Arrival of the AMS C5 at Geneva – 25 Aug 2010
AMS mated with the Payload Attach System simulator during Space Station interface verification test

KSC, October 22, 2010
Transport of Space Shuttle to the Vehicle Assembly Building

Installation of Space Shuttle onto External Tank and Solid Rocket Boosters
Transfer of STS-134 to the launch pad
AMS in the Payload Bay of Endeavour – ready for launch
Closing Endeavour’s Payload Bay Doors at the Launch Pad
After 123 seconds, 1,000 tons of fuel is spent.
Endeavour approaching the Space Station, May 18, 2011
AMS is grappled by the Shuttle Arm
May 19, 2011
May 19: AMS installation completed at 5:15 AM.
Data taking started at 9:35 AM
Thermal Control is the most challenging task in the operation of AMS.

**Solar Beta Angle (β)**

The angle between the ISS Orbital Plane and the Solar Vector.

β changes constantly, ~4.5°/day, from −75° to +75°.
Thermal variables:

- ISS Radiator positions
- ISS attitude changes (primarily for visiting vehicles)

Visiting Vehicles (Soyuz or Progress)

- STBD Main Radiator moved from -8° to +25°
- STBD Main Radiator parked at -8°

TRD Pump temperature

3 Sep

4 Sep, 2011
Thermal variables:

- Solar Array positions
AMS Flight Electronics for Thermal Control

Over 1,100 temperature sensors and 298 heaters are monitored in the AMS POCC to assure components stay within thermal limits and avoid permanent damage.
AMS Tracker on ISS

Stability of the temperature of Tracker planes 5 and 6 over 4 months

Temperature/°C

AMS Tracker on ISS

The alignment stability (3 microns) of the uppermost Tracker plane L1

Over 150 days.

Alignment (μm)

Day (2011)

Alignment stability (3 (μ)

Entries 352
χ²/ndf 21.16/20
Constant 41.07 ± 2.99
Mean -0.682 ± 0.185
Sigma 3.217 ± 0.155

Alignment (μm)
Due to temperature variations the TRD is moving on top of the inner tracker by up to 1 mm.

We use protons for alignment to an accuracy of 0.04 mm for each straw module.
AMS TRD on ISS

Due to temperature, pressure, gas composition and HV changes the TRD detector response is changing.

We use cosmic ray protons to calibrate the detector response to 3% accuracy.

before Calibration

after Calibration
Orbital DAQ parameters

Acquisition rate [Hz]

Time at location [s]

Particle rates vary from 200 to 2000 Hz per orbit

On average:
- DAQ efficiency 85%
- DAQ rate ~700Hz
AMS SOC: Data Processing

Reconstructed data are available in average less than 3 hrs after flight data arrived at POCC

AMS computing requirements:
1,000 cores for data production and analysis
2,500 cores for Monte Carlo production
The INFN Computing center

- Master Copy of the AMS Raw Data
- Data reprocessing
- Montecarlo Production
AMS collected over 20 billion events

First year of AMS operations
The leading candidate for Dark Matter is a neutralino ($\chi^0$).

Collisions of $\chi^0$ will produce excess in the spectra of $e^+$ different from collisions of cosmic rays.

The physics of AMS include:

The Origin of Dark Matter

AMS data on ISS

Collisions of Cosmic Rays

$e^+/\left(e^+ + e^-ight)$

$e^+$ Energy [GeV]

1 TeV

AMS-01
HEAT
PAMELA
Detection of High Mass Dark Matter from ISS

AMS-02

$m_\chi = 800\text{ GeV}$

$m_\chi = 200\text{ GeV}$

$m_\chi = 400\text{ GeV}$

Collision of Cosmic Rays

AMS data on ISS

$e^+/e^+ + e^-$
AMS data on high energy $e^\pm$:

1.03 TeV electron

AMS Event Display  Run/Event 1315754945 / 173049  GMT Time 2011-254.15:31:15

- **Tracker and Magnet**: measure momentum
- **ECAL**: identifies electron and measures its energy
- **RICH**: charge of electron
- **TRD**: identifies electron

(front view)
Proton Rejection vs. Electron Efficiency

Proton Rejection $= 9601 @ 90(\%)$
$R = 3 - 100$ GV
AMS ECAL on ISS
ECAL rejection (E/P>0.5)
AMS data: High energy $e^\pm$

205 GeV Positron

388 GeV Positron

369 GeV Positron

424 GeV Positron
Experimental work on Antimatter in the Universe

Direct search

AMS
Increase in sensitivity: $x 10^3 - 10^6$
Increase in energy to $\sim$TeV

Search for Baryogenesis

New CP
BELLE
BaBar
$(\sin 2\beta = 0.672 \pm 0.023$ consistent with SM)
FNAL KTeV
$(\text{Re}(\epsilon'/\epsilon) = (19.2 \pm 2.1) \times 10^{-4})$
CERN NA-48
CDF, D0

Proton decay
Super K
$(\tau_p > 6.6 \times 10^{33} \text{ years})$

Increase in sensitivity: $x 10^3 - 10^6$
Increase in energy to $\sim$TeV

LHC-b
ATLAS
CMS
AMS data on ISS: He rate

![Graph showing events per second per GV versus rigidity (GV) with different theta regions labeled: 1.0 < \( \Theta_M \), 0.6 < \( \Theta_M \) < 0.8, 0.4 < \( \Theta_M \) < 0.6, \( \Theta_M \) < 0.2. The graph includes data points and a legend.](image-url)
AMS data: He rate and Solar Flare

Polar region

Equatorial region

Solar Flare, 24/1/2012

Quiet period
Physics of AMS: Nuclear Abundances Measurements

For energies from 100 MeV to 1 TeV with 1% accuracy over the 11-year solar cycle.

These spectra will provide experimental data that go into calculating the background in the Search for Dark Matter, i.e., $p + C \rightarrow e^+$, ...
AMS RICH on ISS: Nuclei in the TeV range

Z = 7 (N)  
P = 2.088 TeV/c

Z = 10 (Ne)  
P = 0.576 TeV/c

Z = 13 (Al)  
P = 9.148 TeV/c

Z = 14 (Si)  
P = 0.951 TeV/c

Z = 15 (P)  
P = 1.497 TeV/c

Z = 16 (S)  
P = 1.645 TeV/c

Z = 19 (K)  
P = 1.686 TeV/c

Z = 20 (Ca)  
P = 2.382 TeV/c

Z = 21 (Sc)  
P = 0.390 TeV/c

Z = 22 (Ti)  
P = 1.288 TeV/c

Z = 23 (V)  
P = 0.812 TeV/c

Z = 26 (Fe)  
P = 0.795 TeV/c
AMS dE/dx data from Tracker, TOF, TRD and ECAL together with photon counting from RICH will provide more accurate separation
First Year Data from AMS and detector performance

The detectors function exactly as designed, we have collected over 20 billion events.

Every year, we will collect $16 \times 10^9$ events and in 10-20 years we will collect $160-320 \times 10^9$ events.

This will provide unprecedented sensitivity to search for new physics.
During 100 years of Cosmic rays studies
The Cosmos is the Ultimate Laboratory.
Cosmic rays can be observed at energies higher than any accelerator.

The most exciting objective of AMS is to probe the unknown; to search for phenomena which exist in nature that we have not yet imagined nor had the tools to discover.