AMS spectrometer on the International Space Station (ISS)
AMS International Collaboration
16 Countries, 60 Institutes and 600 Physicists

Project and design based on NASA’s commitment to deploy AMS on the ISS
Fundamental Science on the International Space Station

Messengers:

1. Neutral component:
   - $\nu, \gamma$
   - Hubble, Chandra, GLAST, JDEM, INTEGRAL
   - Discoveries:
     1. Pulsar,
     2. Microwave,
     3. Binary Pulsars,
     4. X Ray sources, solar neutrinos
     ...

2. Charged component: 
   - He, Be, C, Fe
   - AMS is a particle physics experiment in space

- Anti-matter in Universe
- Precise study of Cosmic Ray
- Dark Matter
- Surprises?
Où est l’anti-matière ?
Questions and problems:
• No signal of presence of antimatter in Universe is presently seen. (No annihilation signals of sufficient intensity)
• If antimatter existed, where is it? Very far?
• Are there relics in the local Universe?
• What is the limit of its non existence

Sakharov Conditions: for a baryogenesis (with no anti-baryons)
• Out of thermal equilibrium (yes)
• Violation of symmetries C (yes) and CP (too small)
• Baryon number (nb of quarks) violation. (no)

The physics applying to the firsts instants of Big-Bang is not yet known.

AMS: Search for anti-nuclei in cosmic ray
Experimental work on Antimatter in the Universe

Direct search

Search for Baryogenesis

New CP
BELLE
BaBar
(sin 2β = 0.672±0.023 consistent with SM)
FNAL KTeV
(Re(ε'/ε) = (19.2±2.1)×10^{-4})
CERN NA-48
CDF, D0

Proton decay
Super K
(T_p > 6.6 × 10^{33} years)

AMS
Increase in sensitivity: x 10^3 – 10^6
Increase in energy to ~TeV

LHC-b
ATLAS
CMS
Les rayons cosmiques: découverte

1910 Théodor Wulf sur la Tour Eiffel:

*L’ionisation de l’air diminue avec l’altitude (ce qui s’explique très bien par la radio-activité naturelle qui vient du sol)*

1912 Victor Hess en ballon:

- *Confirme Théodor Wulf* jusqu’à 700 m.

- *De 1500 à 5000 m, l’ionisation augmente, il y a un rayonnement ionisant qui vient du ciel.*

- *Découverte des rayons cosmiques*
Cosmic Ray in atmosphere

- The thickness of atmosphere (1 kg/cm²) corresponds to a 4 meter thick concrete shielding.

- Practically, only muons can reach earth surface.

- Ballons can fly up to 35 km (5 g/cm²) but with a limited exposure time (~20 days).

- Detectors in space can benefit of large exposure times (3-15 years).
Large number of orders of magnitude in energies and intensities of CR.
Abundances of various particles (→ identification)

Abundance of various nuclei (elements) in CR

Cosmic Ray Fluxes (m\(^{-2}\) sr\(^{-1}\) s\(^{-1}\) GeV\(^{-1}\))

- P
- Fe
- C
- antideuterons
- extragalactic γ
- γ

Rate (acc=0.25 m\(^{2}\)) Hz GeV\(^{-1}\)

- CNO
- Fe

- 1/m\(^{2}\) sr sec
- 1/m\(^{2}\) sr hour
- 1/m\(^{2}\) sr day

Kinetic Energy (GeV/nucleon)

- Individual elements
- Even-Z elements
- Element groups

Nuclear Charge (Z)
Relative abundance of elements in CR and in the solar system

Graph showing relative abundance of elements in CR and in the solar system, with interaction of CR with the interstellar medium by fragmentation and confinement time.

- Interaction des RC avec le milieu interstellaire par fragmentation
- temps de confinement
Tests of CR propagation models using secondaries and ratios

Li, Be, B nuclei come from CNO spallation. Radio-active secondary nuclei like $^{10}\text{Be}$ ($\tau = 2 \times 10^6$ y) are *cosmic clocks*. Chemical composition and isotope ratios depend on cosmic ray confinement time and density of the interstellar medium.
Dark Matter manifests its existence through its gravitational effects:
- Rotational velocities of stars at the edge of the disk galaxies.
- Gravitational lensing

From the many hypotheses on the nature of DM, two are related to particle physics:

- Supersymmetric particles $\chi_0$
- Kaluza-Klein Boson (B)
DM Annihilation in Supersymmetry

Dominant
\[ \chi + \chi \Rightarrow A \Rightarrow b \bar{b} \text{ quark pair} \]

B-Fragmentation known!
Hence Spectra of Positrons, Gammas and Antiprotons known!

\[ m_{\chi} \approx 37 \text{ gammas} \]
Two leading theoretical candidates

Dark Matter is a Kaluza-Klein Boson (B) - assumes extra dimensions - with a typical mass of $M_B = 300\text{GeV}$

Dark Matter is a supersymmetric particle with $M_\chi = 840 \text{ GeV}$. This is not accessible to the next accelerator (LHC).
First flight AMS-01 (STS-91 Docking to MIR)

Elements and Isotopes Ratios measured by AMS-01
Unexpected results from first flight:

1- the existence of two Spectra in proton flux

Proton Flux

Coupure suivant la latitude géomagnétique

Expected Spectra due to Earth’s magnetic field

Second Spectra
Unexpected results from first flight:

2- Under the geomagnetic cut, there are many more positrons ($e^+$) than electrons ($e^-$)

Second Spectra

3- He$^4$ and He$^3$ isotopes are completely separated in space
AMS-02 detector

- **TRD**: Transition Radiation Detector
- **TOF**: Two double layers of scintillators paddles for trigger and time of flight. (+/-)
- **Magnet** (with field perpendicular to cylinder)
- **Silicon microstrip Tracker** (8 XY planes)
- **Anti-counters**
- **RICH**: (proximity focusing with Aerogel and NaF radiators)
- **ECAL**: Electromagnetic Calorimeter with $\sim 17 X_0$ to identify $e^\pm$, $\gamma$ and energy measurement
AMS-01 permanent magnet

Torques are forbidden on spacecrafts

→ The total magnetic moment MUST BE ZERO

B = 0.13 T
L = 1 m

Fig. 6. Magnetic field distribution at a cross-section of the center of the magnet.
Superconducting Magnet

- Cooled with superfluid Helium.
- 2500 liters He for 3 years operation

\[ B = 0.7 \, T \]

\[ L = 1 \, m \]
Silicon microstrip Tracker

- Thickness: 300 µm
- Strip every 25 µm
- Read-out 1 strip/4: 100 µm
- Total 200,000 channels
- Spatial resolution (σ) ~8µm

Mesures position and charge (large dynamic range)
• 8 layers of XY sensors on 5 rigid planes (7 m² total)

• 10 laser beams for survey of movements

• Cooling of the front-end electronics by thermal bars and two phases CO2 circuit at 50 bar pressure.
Test beam 158 GeV/n (fragmentation)

Charge (Z) identification

Spatial resolution (MIPs) versus incident angle

Non bending coordinate

Bending coordinate

Tracker performance
Time of Flight (TOF)

Measures the time of particles to ~ 100 picoseconds
Transition Radiation Detector: TRD
Identify electrons/positron

One of 20 Layers

Fleece–Radiator
LRP 375 BK (ATLAS)
0.06 g/cm\(^3\)

TR–γ

Xe/CO\(_2\)

p

22 mm

6 mm

electrons

Sensitive to relativistic Lorentz factor

12 layers in the bending plane
8 layers in the non-bending plane

AMS TRD BEAMTEST at CERN

Proton Rejection Factor

Design rejection

Number of Events

E in the GeV

0
15
30
45
60
75
90
105
120
135
150
165
180
195
210
225
240
255
270
285
300
315
330
345
360
Transition Radiation Detector: TRD

5248 tubes
2 meter length
centered to 0.1mm
Two radiators:

- Aerogel, 2.5 cm \( (n=1.05) \)
- NaF, 0.5 cm \( (n=1.336) \)

- \( \Delta \beta/\beta \sim 0.1\% \) (for Z=1)
- Photo-multiplier matrix of 680 x 4 x 4 channels
Ring Imaging Cerenkov Counter (RICH)

Particle: Velocity(θ), Charge(Intensity)

Radiator

Reflector

10,880 Photodetectors
Redundancy of charge (Z) measurement (TOF, Tracker, RICH)

**RICH vs Tracker (ohmic side)**

Charge measured by K side vs Charge measured by Rich.

**RICH vs Tracker (junction side)**

Charge measured by S side vs Charge measured by Rich.

**Ion Charge by RICH**

Charge measured in RICH for different ions from light to heavy.

**Nuclear charge (Tracker + RICH)**

Number of events vs Nuclear charge (Tracker + RICH).
**ECAL: electromagnetic calorimeter**

- Pb/scintillating fibers sandwich (640 kg) with 3D sampling by 9 crossed superlayers (18 layers, 5 pairs in X, 4 pairs in Y)
- Segmentation: \( \text{long:} \sim 1 \ X_0, \ \text{lat:} \sim 0.5 \ R_M \)
- Length: \( \sim 17 \ X_0, \approx 1 \ \lambda_R \)
- Angular resolution: \( \sim 1^\circ \)
- \( \Delta E/E = 10\%/\sqrt{E} + 2.6\% \)
- Proton suppression up to \( 10^4 \) at 500 GeV. (\( 10^6 \) with TRD)
Superlayer

1 cell = 35 fibers

324 PMs x 4 cells
Identification grâce à la combinaison de la réponse des sous-détecteurs

La redondance est importante pour identifier des événements rares
AMS goal: Limits on anti-Helium in cosmic rays

- Buffington et al. 1981
- Golden et al. 1997
- Badhwar et al. 1978
- Alcaraz et al. 1998
- Sasaki et al. 2001

AntHe/He Flux Upper Limit 95% CL

Rigidity (GV)

AMS02 SC Magnet 3 Years
AMS02 Perm Magnet 18 Years
BESS
AMS will measure of cosmic ray spectra for nuclei, for energies from 100 MeV to 2 TeV with 1% accuracy over the 11-year solar cycle.

These spectra will provide experimental measurements of the assumptions that go into calculating the background in searching for Dark Matter, i.e., $p + C \rightarrow e^+, p, ...$
DM searches with AMS-02

E. Pontón & L. Randell: arXiv

Integration of AMS: at CERN in a new clean room

- 2007-08: pre-integration with spare vacuum case (waiting for the magnet)
- mid 2008: de-integration

- Dec 2008: arrival of magnet
- Tests, cooling, operation of the magnet and measurement of its field → September 2009
Sub-detector final integration (19-31 octobre 2009)

Tracker integration and cabling
October 19-29, 2009
Nov/Dec 2009:

- end of cabling
- tests with cosmics
- cooling installation (radiators, piping)
- commissioning of magnet cryostat
Tests and alignment with cosmics during magnet commissioning
20 Dicembre 2009: run stabile con carica del magnete @ 400 A

Cosmic muons
AMS in Test Beam (CERN)

Feb 4-8, 2010
Test Beam 2010: momentum resolution of the spectrometer

Feb. 2010, with SC magnet
Test Beam Results with superconducting magnet – Feb 2010

Electron Energy Resolution: 2.5-3%

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

Energy

Measured combined rejection power at 400 GeV: $e^+/p = 10^{-6}$
Journey from CERN to ESTEC
(ESA center at Noordwijk, NL)
Simulation of space conditions (vacuum, temperature and solar radiation)

Feb, March 2010
TRACKER PERFORMANCE at −90°C: a muon track & mip signal in silicon
Change of Strategy after test at ESTEC (April 16, 2010)

- Measured Helium consumption: $\rightarrow$ 20 ±4 months of SC magnet operation
- Refilling is not an option (AMS will stay on ISS)
- ISS life and operation time is extended ($\rightarrow$ 2020, 2028 ?)
- Availability of a 2nd cylindrical support (spare vacuum tank) + AMS-1 magnet
- $\rightarrow$ The exposure time can be multiplied by a large factor.

Magnete superconduttore

B = 0.8 T

Magnete permanente

B = 0.13 T
Tracker geometry is modified in order to increase the lever arms to compensate the lower field, maintaining performance at high energy.

… On démonte, on modifie et on remonte …
Design curves for SC and PM tracker resolution …. Real curves after beam test final analysis and muon data taking
AMS in Test Beam with *permanent magnet*  8-20 Aug 2010

*With e+, e- and protons*
Calibrazione con protons a 400 GeV

<table>
<thead>
<tr>
<th>Particle</th>
<th>Momentum</th>
<th>C1/C2 Pr (Bar)</th>
<th>Min Events Per Pos</th>
<th>Spills Per Pos</th>
<th>Time (hrs) Total</th>
<th>Positions</th>
<th>Rate (p/sp) Expected</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>400 GeV</td>
<td>2/2</td>
<td>$10^6$</td>
<td>75</td>
<td>1</td>
<td>Center, 5°</td>
<td>20k</td>
<td>Initial Setup</td>
</tr>
<tr>
<td>Protons</td>
<td>400 GeV</td>
<td>2/2</td>
<td>$10^4$</td>
<td>3</td>
<td>5</td>
<td>TRACKER60</td>
<td>20k</td>
<td>Inner Tracker Alignment</td>
</tr>
<tr>
<td>Protons</td>
<td>400 GeV</td>
<td>2/2</td>
<td>$10^4$</td>
<td>7</td>
<td>1</td>
<td>TRACKER10</td>
<td>20k</td>
<td>Laser Correlation</td>
</tr>
<tr>
<td>Protons</td>
<td>400 GeV</td>
<td>2/2</td>
<td>$10^4$</td>
<td>3</td>
<td>7</td>
<td>TRACKER416</td>
<td>20k</td>
<td>Layers 1/9 Alignment</td>
</tr>
<tr>
<td>Protons</td>
<td>400 GeV</td>
<td>2/2</td>
<td>$10^4$</td>
<td>6</td>
<td>7</td>
<td>TRACKER80</td>
<td>20k</td>
<td>Layers 2/9 Alignment</td>
</tr>
<tr>
<td>Protons</td>
<td>400 GeV</td>
<td>2/2</td>
<td>$10^4$</td>
<td>3</td>
<td>24</td>
<td>TRACKER280</td>
<td>20k</td>
<td>Layers 1/8 Alignment</td>
</tr>
</tbody>
</table>

67
Risultati preliminari : TRACKER

Les performances des autres détecteurs n’ont pas changé

Beamtest: Aug./2010

Beamtest: Feb./2010
Energy Resolution: 2.5-3%

Febbraio

\[ \sigma = 10\mu \]

Agosto

\[ \sigma \approx 10\mu m \]

Protons 400GeV/c

\[ \sigma = \frac{1}{1000} \]

Proton Rejection

TRD

Electron Efficiency (%)
Preliminary energy resolution

e± data collected:

Positrons: 10, 20, 80, 100, 120, 180 GeV

Electrons: 100, 120, 180, 300 GeV

preliminary results: equalization from old AMS configuration (SC magnet, no tracker plane above, ...)

ECAL
Preliminary AMS rejection

- 400GeV protons:
- ECAL+TRACKER+TRD rejection:
  - $R_p < 1.2 \times 10^{-6}$ (0 out of 1.96e6)
23-24 août 2010: departure from CERN to GVA airport and loading in a C5-Galaxy airplane
• August 24: landing at KSC on the space shuttles runway

• Mechanical and electrical interfacing activities.

• Communication and control procedures are presently defined and tested between CERN, JSC and KSC
AMS astronauts

Mark E. Kelly  
(Captain, USN)

Gregory H. Johnson  
(Colonel, USAF, Ret.)

E. M. “Mike” Fincke  
(Colonel, USAF)

Roberto Vittori  
(Italian Air Force Colonel)

Andrew J. Feustel  
(Ph.D.)

Gregory Errol Chamitoff  
(Ph.D.)
We will be ready for the journey to the ISS foreseen Feb. 27, 2011 with the *Endeavour* space shuttle.

Mission duration: → 2020 (2028 ?)

Les résultats de Pamela seront-ils confirmés ?
L’aïmant d’AMS
Addition des champs et des moments magnétiques
AMS-02 (10 to 18 Yrs)
Silicon Tracker Alignment with Cosmic protons

10,000 cosmic protons / min measured by 7 tracker layers in the magnet
Extrapolated track from 7 measurements inside the magnet

The thermal model predicts the movement of 1N and 9 in x and y are both less than 150 μm.
Extrapolated track from 7 measurements inside the magnet

Layers 1 to 7 are aligned with existing laser system

10,000 cosmic protons / min measured by 7 tracker layers in the magnet
External Plane Alignment with Cosmic Rays  Minute by Minute

1 Minute Thermal Movement measurements

Simulated Top Plane Thermal Movement

Simulated Bottom Plane Thermal Movement

1 mm
Strangelet candidate from AMS-01

Observed 5 June 1998 11:13:16 UTC

Lat/Long = -44.38°/ +23.70°, Local Cutoff 1.95 ± 0.1 GV, Angle = 77.5° from local zenith

Front view

Side view

Rigidity \( = 4.31 \pm 0.38 \text{ GV} \)

Charge \( Z = 2 \)

\( \beta_1 = \beta_2 = 0.462 \pm 0.005 \)

Mass \( = 16.45 \pm 0.15 \text{ GeV/c}^2 \)

\( Z/A = 0.114 \pm 0.01 \)

Flux (1.5 < \( E_K \) < 10 GeV) = 5 \times 10^{-5} (\text{m}^2 \text{ sr sec})^{-1}

Background probability < 10^{-3}
Strangelets

All the known material on Earth is made out of u and d quarks. Is there material in the universe made up of u, d, & s quarks? Z/A ~ 0.1

\[ \Phi_{\text{strangelets}} = 5 \times 10^{-10} (\text{cm}^2 \text{s sr})^{-1} \]

This can be answered definitively by AMS.

**Jack Sandweiss, Yale**
AMS goals: $\text{He}/\text{He} = 1/10^{10}$, $e^+/p = 1/10^6$ & Spectra to 1%

- $e^+/p = 10^{-2}$
- $e^+/p = 10^{-4}$

a) Minimal material in the tracker, so that it does not become a source of background nor of large angle scattering.

b) Repetitive measurements of momentum, to ensure that particles which had large angle scattering are not confused with the signal.

c) $\pm$ detectors are separated by magnetic field, so that particles from TRD do not enter into ECAL.

Measured rejection at 0.4 TeV $e^+/p = 10^{-6}$