Cosmic Ray detection with spaceborne detectors

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MASS-89, 91, TS-93, CAPRICE 94-97-98

PAMELA

NINA-1

NINA-2

SILEYE-1

SILEYE-2

SILEYE-3

ALTEA

LAZIO-SIRAD

SILEYE-3/ALTEINO:

LAZIO-SIRAD

SILEYE-4/ALTEA

JEM-EUSO
Study of the charged cosmic ray spectrum

A) Search for Dark matter and study of cosmic ray particle and antiparticle component with PAMELA detector

B) EUSO Program
Aim: Study of flux, origin and nature of Ultra-High-Energy-Cosmic rays from space (E > 4 \times 10^{19})

C) study of radiation environment and dosimetry on board the ISS with Altea and Sileye-3/Alteino (PI)

D) Technology development and transfer: Development of a radiation detector for testing in the Fukushima area - LANFOS Large Food Non-destructive Area Sampler (PI)
High precision cosmic ray measurements challenge and constrain models of production, acceleration and propagation of cosmic ray in the Galaxy and the heliosphere.

On several different scales

→ Modeling

→ Dose and risk estimation for astronauts on ISS and Moon/Mars

**Pamela results**

**Physics Reports**

544, 4, 323-370

**ApJL** 799 4 2015
2008AdSpR..41..168C
2008AdSpR..41.2037D
2008AdSpR..41.2043C

**Science** 2011
arXiv:1103.4055
Cosmic Ray detection with spaceborne detectors.

This week’s lectures:

• Space instrumentation and detectors

• (extra) Galactic, solar and terrestrial cosmic rays

• Rocket, Satellites and Space Stations
1. Space instrumentation and detectors
Constraints of space experiments

Weight: kg-tonn
Power: W – kW
Radiation hardness
Size, dimension
Telemetry

Pamela: LEO 1.2m  450 kg
Interaction radiation with matter

High energy cosmic rays
Interaction with atomic electrons
Scattering with nuclei

$Z_2$ electrons, $q=-e_0$

W. Riegler, Particle Detectors
Bethe Block formula

Energy loss in matter
Ionization of atomic electrons

Detected energy is a fraction of energy loss

\[
\frac{dE}{dx} = \rho K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_ec^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta}{2} \right]
\]
NINA

- 32 silicon detector planes
- $8 \times 8 \text{ cm}^2$, 16 strips
- GF 10 cm$^2$ sr
- 20 kg detector
- Detectors from TS93 and Caprice flights
Silicon strip detectors

Diode inversely polarized

Ionization releases a charge

High dynamic range

High precision
Resurs-O1 n. 4 satellite
Zenit Launcher: 10/7/1998 from the cosmodrome of Baikonur
dE-dx vs total energy for charged particle identification

CRIS Flux of Z >= 10 Cosmic Rays
E ~ 100 - 400 MeV/nuc

ACE detector
Isotope composition

**Figure 2.** Mass distribution of particles with charge $Z = 1$ (left panel) and $Z = 2$ (right panel) at $L$-shell < 3 and $B > 0.26 \, G$, as measured by NINA-2.

*JGR 108 A5 1211, 2003
Ann. Geoph. 20, 1693, 2002*
Isotope composition of secondary particles

Figure 3. Differential energy spectra of secondary proton, deuterium and tritium at $L$-shell $< 3$ and $B > 0.26$ G, as measured by NINA-2.

Figure 5. Albedo $^3\text{He}/^4\text{He}$ ratio, as measured by NINA and NINA-2, AMS lower limit for $L$-shell $< 2.2$ is also shown.
Relative nuclear abundances

Peak position proportional to $Z^2$ according to Bethe Block
Pamela Collaboration

Italy: Bari, Florence, Frascati, Naples, Rome, Trieste, CNR, Florence

Germany: Siegen

Sweden: KTH, Stockholm

Russia: Moscow, St. Petersburg
Magnetic (0.46T) Spectrometer
Microstrip detector
(6 double sided microstrip planes)

Silicon Tungsten Tracking Calorimeter
(44 planes of 96 strip)
Shower Catcher Scintillator
Neutron Detector

Time of Flight
(three scintillators, 6 planes, 48 phototubes)
PAMELA models

Mass & Thermal Model
Full cycle of vibration/shock/transport tests

Technological Model
Preliminary Acceptance Tests with EGSE: power ON/OFF, telecommands, data transmission through adapter; magnetic tests

Flight Model
Integration, beam tests; pre-flight operations
Coupling to Soyuz

Resurs DK integrated

Pamela during integration in Baikonur
Launch on June 15th 2006  Soyuz-U rocket

70 degrees polar orbit
350*600km i,
now 600km
The PAMELA apparatus

GF $\sim 20.5\text{ cm}^2\text{sr}$
Mass: 470 kg
Size: 120x40x45 cm$^3$
Power Budget: 360 W

Spatial Resolution
- $\approx 2.8\ \mu\text{m}$ bending view
- $\approx 13.1\ \mu\text{m}$ non-bending view

MDR from test beam data $\approx 1\ TV$

Calorimeter Performances:
- $\bar{p}/e^+$ selection eff. $\sim 90\%$
- $p$ rejection factor $\sim 10^5$
- $e^-$ rejection factor $> 10^4$

ND $p/e$ separation capabilities $> 10$ above 10 GeV/$c$, increasing with energy

TOF (S1)
ANTICOINCIDENCE
TOF (S2)
ANTICOINCIDENCE
TOF (S3)
ANTICOINCIDENCE
SPECTROMETER
CALORIMETER
NEUTRON DETECTOR
Principle of detection

Electrons

Positrons

Protons

e- 171 MV
e+ 169 MV
p 36GV
Imaging Calorimeter

- 44 Si detector views (22X and 22Y)
  - 8x8 cm² detectors arranged in a 3x3 matrix
  - 32 strips/detector, 2.4 mm pitch
  - Strips of detectors in the same row (column) are bonded together (ladder) ⇒ 24 cm long strips
  - Each ladder (32 channels) is read out by 2 CR1.4P front-end chips ⇒ 6 front-end chips/view
- In total:
  - 396 silicon detectors
  - 264 CR1.4P chips
  - 4224 channels
Imaging Calorimeter

- **Main tasks:**
  - lepton/hadron discrimination
  - $e^+/-$ energy measurement

- **Characteristics:**
  - 22 W plates (2.6 mm / 0.74 $X_0$)
  - 44 Si layers (X-Y), 380 µm thick
  - Total depth: 16.3 $X_0 / 0.6 \lambda_I$
  - 4224 channels
  - Self-triggering mode option ($> 300$ GeV; GF~600 cm² sr)
  - Mass: 110 kg
  - Power Consumption: 48 W

- **Design performance:**
  - $\bar{p}, e^+$ selection efficiency ~ 90%
  - $p$ rejection factor ~ $10^5$
  - $e$ rejection factor > $10^4$
  - Energy resolution ~ 5% @ 200 GeV

From V. Bonvicini
Charge measurement with Calorimeter

- High dynamic range
- Truncated mean of multiple dE/dx measurements in different silicon plane.
Minimum ionizing peak

- Signal – noise
- Pedestal peak
- Energy loss fluctuations
- Landau Distribution

![Graph showing 1-MIP signal distribution with S/N ~ 9](image.png)
Time of Flight / Scintillator

- 6 x-y layers arranged on 3 planes;
- 48 channels.
- Albedo rejection dE/dx
- Part ident. Up to 1 GeV with 150ps resolution
- Nuclear identification up to Oxygen
- 3 double-layer scintillator paddles
- Timing resolution:
  - $\sigma$(paddle) $\approx$ 110 ps
  - $\sigma$(ToF) $\approx$ 330 ps (MIPs)

**DIMENSIONS**

<table>
<thead>
<tr>
<th></th>
<th>#</th>
<th>Width</th>
<th>Height</th>
<th>Thickness</th>
<th>Volume</th>
</tr>
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<tbody>
<tr>
<td>S11</td>
<td>8</td>
<td>330 x 51 mm$^2$</td>
<td>7 mm</td>
<td>357 mm$^2$</td>
<td></td>
</tr>
<tr>
<td>S12</td>
<td>6</td>
<td>408 x 55 mm$^2$</td>
<td>7 mm</td>
<td>385 mm$^2$</td>
<td></td>
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<tr>
<td>S21</td>
<td>2</td>
<td>180 x 75 mm$^2$</td>
<td>5 mm</td>
<td>375 mm$^2$</td>
<td></td>
</tr>
<tr>
<td>S22</td>
<td>2</td>
<td>150 x 90 mm$^2$</td>
<td>5 mm</td>
<td>450 mm$^2$</td>
<td></td>
</tr>
<tr>
<td>S31</td>
<td>3</td>
<td>150 x 60 mm$^2$</td>
<td>7 mm</td>
<td>420 mm$^2$</td>
<td></td>
</tr>
<tr>
<td>S32</td>
<td>3</td>
<td>180 x 50 mm$^2$</td>
<td>7 mm</td>
<td>350 mm$^2$</td>
<td></td>
</tr>
</tbody>
</table>
Zenith Angle Correction

- Get zenith angle using track information from the spectrometer (or the ToF itself, see method below)

\[
\cos \theta = \frac{ADC}{ADC}
\]

Adapted from Osteria, Menn

TDC Data

Time of Flight scintillator system

Single paddle

Plotting timing information vs. position from tracking, make linear fit

Deviation from linear fit gives intrinsic paddle resolution

Adapted from Osteria, Menn
Full ToF

\[ t_1 = C_1 + \frac{x_1}{v_{eff}} \]

\[ t_2 = C_2 + \frac{x_2}{v_{eff}} \]

\[ t_3 = C_3 + \frac{x_3}{v_{eff}} + \frac{L}{c \beta} \]

\[ t_4 = C_4 + \frac{x_4}{v_{eff}} + \frac{L}{c \beta} \]

"Difference of Sums:"

\[ DS = (t_3 + t_4) - (t_1 + t_2) = C_3 + C_4 - C_1 - C_2 + \left( \frac{x_3 + x_4}{v_{eff}} \right) - \left( \frac{x_1 + x_2}{v_{eff}} \right) + \frac{2L}{c \beta} \]

\[ DS = K_1 + K_2 \frac{1}{\beta} \]

Adapted from Menn
Magnetic tracker
The permanent magnet

- 5 magnetic modules
- **Permanent magnet** (Nd-Fe-B alloy) assembled in an aluminum mechanics
- Magnetic cavity sizes (132 x 162) mm² x 445 mm
- Field inside the cavity 0.48 T at the center
- Average field along the central axis of the magnetic cavity: **0.43 T**
- Geometric Factor: **20.5 cm²sr**
- Black IR absorbing painting
- Magnetic shields

Adapted from E.Vannuccini ............................ ICRC2005 – Pune (India)
The permanent magnet

- 5 magnetic modules
- Permanent magnet (Nd-Fe-B alloy) assembled in an aluminum mechanics
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MAGNETIC FIELD MEASUREMENTS
- Gaussmeter (F.W. Bell) equipped with 3-axis probe mounted on a motorized positioning device (0.1mm precision)
- Measurement of the three components in 67367 points 5mm apart from each other
- Field inside the cavity 0.48 T at the center
- Average field along the central axis of the magnetic cavity: 0.43 T
- Good uniformity
- Measurement of external magnetic field – magnetic momentum < 90 Am²

E.Vannuccini – ICRC2005 – Pune (India)
The tracking system

6 detector planes composed by 3 “ladders”

- **Mechanical assembly**
  - no material above/below the plane (1 plane = 0.3% $X_0$)
  - carbon fibers stiffeners glued laterally to the ladders

- **ladder**:
  - 2 microstrip silicon sensors
  - 1 “hybrid” with front-end electronics

- **silicon sensors (Hamamatsu)**:
  - 300 mm, Double Sided - x & y view
  - Double Metal - No Kapton Fanout
  - AC Coupled - No external chips

- **FE electronics: VA1 chip**
  - Low noise charge preamplifier -
  - Operating point set for optimal compromise:
    - total FE dissipation: 37 W on 36864 channels
    - Dynamic range up to 10 MIP

- **DAQ**: 12 DSPs
  - data compression (>95%)
  - on-line calibration (PED,SIG,BAD)
Energy loss from tracker

Rigidity (from Tracker)

Rigidity from tracker

$dE/dx$ (MIP)

$p$, $He$
Alignment

Critical Issue especially for protons and helium

Flux large $\rightarrow$ Small GF OK
Only tracker.

Performed *only once* after launch
No changes detected in 7 years

Coherent misalignment
Correction with electrons
(or electrons + positrons)
and comparison with simulation
Critical Issue: an antiparticle
Can be faked if alignment of the detector is wrongly considered

Incoherent misalignment
Correction with protons
2 steps: column alignment + inter-column alignment

Coherent misalignment
Correction with electrons (or electrons + positrons) and comparison with simulation

From E. Vannuccini, P. Papini
Spatial resolution

$s_x = (2.77 \pm 0.04) \, \mu m$

$s_y = (13.1 \pm 0.2) \, \mu m$

40-100 GeV pions (CERN-SPS 2000)
beam-test of a small tracking-system prototype
Relation between the curvature and momentum or Rigidity

\[ p = qeQB \ [eV/c] \]
\[ R = cQB \ (R = pc/qs \ [V]) \]
\[ R/GV \approx 0.3 \ (qs/m) \ (B/\text{Tesla}) \]
\[ q < 0 \Rightarrow R < 0 \]

e.g.

\[ p = 1 \ \text{GeV/c}, \ q = 1 \ (R = 1 \ \text{GV}), \]
\[ B = 1 \ \text{Tesla} \Rightarrow q \approx 3.3 \ \text{m} \]
\[
\begin{align*}
    s &= q - \sqrt{q^2 - \left(\frac{L}{2}\right)^2} \\
    &\approx q - q\left(1 - \left(\frac{L}{q}/2\right)^2/2\right) \\
    &= \frac{L^2}{q}/8 = \frac{0.3BL^2}{8R} \\
    \sqrt{1-x} &\approx 1 - x/2 \quad (x \ll 1)
\end{align*}
\]

\[R = \frac{pc}{qe}\]

e.g.

\[R = 1 \text{ GV}, \ B = 1 \text{ Tesla}, \ L = 1 \text{ m} \implies s \approx 38 \text{ mm}\]
Rigidity resolution

\[ s \approx \frac{0.3BL^2}{8R} \]

\[ \Delta(1/R) = \frac{\Delta R}{R^2} \approx \frac{8\Delta s}{0.3BL^2} \]

\( e.g. \)

\( B = 1 \) Tesla, \( L = 1 \) m, \( \Delta s = 0.1 \) mm

\( \Rightarrow \Delta R/R \approx 2.7 \% \) (\( R = 10 \) GV)
Maximum detectable rigidity

\[ \frac{\Delta R}{R} = \frac{8\Delta s}{0.3BL^2} \quad R = 1 \quad \Rightarrow \quad R_{\text{MD}} = \frac{0.3BL^2}{8\Delta s} \]
Multiple scattering

Nuclear ‘Rutherford’ scattering

\[
\frac{d\sigma}{d\Omega} = 4z^2Z^2r_e^2 \left[ \frac{m_e c}{\beta p} \right]^2 \frac{1}{\sin^4 \theta/2}
\]
Multiple scattering

\[ \theta_0 \propto \frac{1}{p} \sqrt{\frac{L}{X_0}} \]

\( X_0 = \text{radiation length (thickness depending on material)} \)

\[ \mu = \frac{\sigma N_0 \rho}{A} \equiv \frac{7}{9X_0} \]
\[ \theta_0 = \frac{13.6 \text{ MeV}}{\beta cp} \cdot z \cdot \sqrt{\frac{x}{X_0}} \left[ 1 + 0.038 \ln \left( \frac{x}{X_0} \right) \right] \]

- \( x/X_0 \): Thickness in radiation length
- \( e.g. \)
  \[ x/X_0 = 1 \% \Rightarrow \theta_0 = 1.1 \times 10^{-3} \text{ rad } / \beta R \]
Simulation with scattering

\( B = 1 \) Tesla, \( \sigma_x = 0.1 \text{ mm} \times 3, \, x/X_0 = 1 \% \)

\( \Delta R \over R = 3.2 \times 10^{-3} \over \beta \)

\( \Delta R \over R = 7.5 \times 10^{-3} \)
Deflection

\[ D = \frac{1}{R} \]

Antiprotons

Protons

-50 GV  +50 GV
Particle identification

\[ \beta = \frac{v}{c} (\text{from TOF}) \]

- Selection criteria
  - Fitted, single track
  - High lever arm, \( N_x \)
  - Rigidity \( R > 0 \)
  - \( \beta > 2 \)
  - No anticoincidence

- Variables
  - Monte Carlo efficiency for cuts
  - Trigger efficiency
  - Tracking efficiency
  - Multiple Scattering
  - Correction for energy loss in det
  - Back scattering...
  - Systematics about 1-2% uncertainty on abs flux.

- Particle identification
  - Rigidity (from Tracker)

\[ \begin{array}{c}
\text{antiparticles} \\
\text{particles} \\
\text{albedo} \\
\text{particles} \\
\text{albedo} \\
\text{antiparticles}
\end{array} \]
The anticoincidence system

Anticoincidences are mounted on the sides, top and interscintillator area. They are used to reject false triggers coming from the satellite.
Main trigger = S1 AND S2 AND S3

Use AC offline or in L2 trigger to reduce false triggers
Neutron Detector
Lebedev Physical Institute Academy of Science, Russia

- 36 $^3$He containers (2 planes)
- 9.5 cm polyethylene moderator enveloped in thin cadmium layer.
- 60x55x15 cm$^3$, 30 kg, 10 W
- (10% eff for E<1MeV n)
- Triggered counts
- Background counting
Electromagnetic showers

Pair production

Bremsstrahlung
(b) Lead ($Z = 82$)

- Experimental $\sigma_{\text{tot}}$

Cross section (barns/atom)

- $\sigma_{\text{p.e.}}$
- $\sigma_{\text{Rayleigh}}$
- $\sigma_{\text{Compton}}$

Photon Energy

$10 \text{ eV}$ to $100 \text{ GeV}$

$1 \text{ Mb}$, $1 \text{ kb}$, $1 \text{ b}$, $10 \text{ mb}$
Figure (3.12)  A 19 GV electron from flight data. Left: the calorimeter response to the developed shower (see text). Right: visualization provided by the PAMELA event viewer.
300 GeV electron in PAMELA calorimeter
Lepton – Hadron separation

Proton: straight track or hadronic shower

Electron positron, gamma : e.m. shower
Flight data: 14.4 GV non-interacting proton

From E. Mocchiutti
Flight data: 36 GV interacting proton
Flight data  84 GeV/c  interacting antiproton
Flight data: 2.8 GV electron
Flight data: 92 GeV/c positron