PAMELA: Measurements of Matter and Antimatter in Space

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on behalf of the PAMELA Collaboration

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PAMELA

Payload for Antimatter Matter Exploration and Light Nuclei Astrophysics
WiZard  RIM Program
(Russian Italian Missions)

MASS-89, 91, TS-93, CAPRICE 94-97-98
NINA-1
NINA-2
PAMELA

The Physics of PAMELA

- Search for dark matter annihilation
- Search for antihelium (primordial antimatter)
- Search for new matter in the Universe (strangelets?)
- Study of cosmic-ray propagation
- Study of solar physics and solar modulation
- Study of terrestrial magnetosphere
PAMELA Instrument

GF ~21.5 cm$^2$sr

Mass: 470 kg

Size: 130x70x70 cm$^3$
1200 GV (6 planes)

- S1, S2, S3; double layers, x-y
- plastic scintillator (8mm)
- ToF resolution ~300 ps (S1-3 ToF >3 ns)
- lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

- Permanent magnet, 0.43 T
- 21.5 cm² sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view → MDR
- ~1200 GV (6 planes)

- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm² sr

- 36 ³He counters
- ³He(n,p)T; \( E_p = 780 \text{ keV} \)
- 1 cm thick poly + Cd moderator
- 200 μs collection

~1.3 m
# Design Performance

<table>
<thead>
<tr>
<th>Species</th>
<th>Energy range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antiprotons</td>
<td>80 MeV - 190 GeV</td>
</tr>
<tr>
<td>Positrons</td>
<td>50 MeV – 300 GeV</td>
</tr>
<tr>
<td>Electrons</td>
<td>up to 500 GeV</td>
</tr>
<tr>
<td>Protons</td>
<td>up to 1 TeV</td>
</tr>
<tr>
<td>Helium</td>
<td>up to 400 GeV/n</td>
</tr>
<tr>
<td>Electrons+positrons</td>
<td>up to 2 TeV (from calorimeter)</td>
</tr>
<tr>
<td>Light Nuclei (Li/Be/B/C)</td>
<td>up to 200 GeV/n</td>
</tr>
<tr>
<td>AntiNuclei search</td>
<td>sensitivity of $3 \times 10^{-8}$ in $\text{He}/\text{He}$</td>
</tr>
</tbody>
</table>
PAMELA

Launch
15/06/06

16 Gigabytes transmitted daily to Ground
NTsOMZ Moscow
PAMELA Status

- Till now: 1550 days in flight
- ~20 TBytes of raw data downlinked
- $>2 \times 10^9$ triggers recorded and under analysis
Orbit Characteristics

- Low-earth elliptical orbit
- 350 – 610 km
- Quasi-polar (70° inclination)
- SAA crossed
Outer radiation belt

Inner radiation belt (SSA)

95 min

NP SP

EQ

S1 S2 S3

orbit 3751 orbit 3752 orbit 3753

Counts (over 60 ms)

NP SP

EQ

S1 S2 S3

orbit 3751 orbit 3752 orbit 3753

On Board Time [ms]
Particle ID with PAMELA
Flight data:
0.171 GV positron

Flight data:
0.169 GV electron
Flight data: 58.1 GeV/c positron
Flight data: 28.8 GeV/c interacting anti-proton
Flight data: 0.632 GeV/c antiproton annihilation
Flight data: 92 GeV/c positron
Antiproton / Positron Identification

Time of-flight: trigger, albedo rejection, mass determination (up to 1 GeV)

Bending in spectrometer: **sign** of charge

Ionisation energy loss (dE/dx): magnitude of charge

Interaction pattern in calorimeter: electron-like or proton-like, electron energy

**Antiproton**
(NB: e⁻/\(\bar{p}\) ~ 10²)

**Positron**
(NB: p/e⁺ ~10³-4)
Antiparticles with PAMELA
THE UNIVERSE ENERGY BUDGET

- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.1–1.5%
- Rest of ordinary matter
  (electrons, protons & neutrons) are 4.4%
- Dark Matter 23%
- Dark Energy 73%
- Anti-Matter 0%
- Higgs Bose-Einstein condensate
  ~10^{62}??
DM annihilations

DM particles are stable. They can annihilate in pairs.

Primary annihilation channels:

\[ W^-, Z^0, b, \tau^-, t, h^0, \ldots \]

Decay:

\[ e^\pm, p^(-), D^(-), \ldots \]

Final states:

\[ e^\pm, p^(-), D^(-), \ldots \]

\[ \sigma_a = <\sigma v> \]
Antiparticle detection

Where do positrons come from?

Mostly locally within 1 Kpc, due to the energy losses by Synchrotron Radiation and Inverse Compton scattering.

Typical lifetime

\[ \tau \simeq 5 \times 10^5 \text{yr} \left( \frac{1 \text{ TeV}}{E} \right) \]

Antiprotons within 10 Kpc
Searching for Antimatter
We have to identify the particles...

For Z=1 particles:

\[ \frac{\bar{p}}{p} \leq 10^{-4} \]
\[ p/e^+ \geq 10^3 \]
\[ \frac{\bar{p}}{e^-} \leq 10^{-3} \]

Particle identification results from the combination of measurements from the full instrument.
Deflection spectrum of the remaining Protons and Antiprotons

Deflection = 1/Rigidity

Strong track requirements:
MDR > 850 GV

Tracker Identification
- Antiprotons
- Protons (& spillover)
Antiproton Flux
(0.06 GeV - 180 GeV)


Systematics errors included


Adriani et al., astro-ph 1007.0821 PRL in press
Antiproton to proton ratio
(0.06 GeV - 180 GeV)


Donato et al. (PRL 102 (2009) 071301)

Systematics errors included

Adriani et al., astro-ph 1007.0821
Wino Dark Matter in a non-thermal Universe

G. Kane, R. Lu, and S. Watson

Trapped Antiprotons in the South Atlantic Anomaly

- PAMELA trapped pbar/p
- PAMELA galactic pbar/p
- CRAND model

Graph showing the antiproton-to-proton ratio with data points and a model curve.
Proton / positron discrimination

Time-of-flight:
- trigger, albedo rejection, mass determination (up to 1 GeV)

Bending in spectromete:
- sign of charge

Ionisation energy loss (dE/dx):
- magnitude of charge

Interaction pattern in calorimeter:
- electron-like or proton-like, electron energy

Proton

Positron
Fraction of charge released along the calorimeter track: ~ 0.6 \( R_m \)

**Positron Selection**

- Positron
- Proton

**Energy-Momentum Match**

Cut on starting point, lateral & longitudinal profile
PAMELA Positron Fraction

End 2007: ~20 000 e⁺

Solar Modulation
Secondary production
Moskalenko & Strong 98
PAMELA Positron Fraction (2010)

- Neuronal network software: TMVA package from CERN
- Use more data 2006-2008

Statistics increase ~2.5 (factor 3 in the highest energy bin)

Secondary production
Moskalenko & Strong 98
Positron to Electron Fraction

Adriani et al, Astropart. Phys. 34 (2010) 1
A Challenging Puzzle for CR Physics

Positrons (and electrons) produced as secondaries in the sources (e.g. SNR) where CRs are accelerated. But also other secondaries are produced: significant increase expected in the pbar/p and B/C ratios.

Contribution from DM annihilation.

Contribution from DM annihilation.

Y. Fujita arXiv. 0904.5298
Y. Fu, arXiv.0904.5298

Contribution from diffuse mature & nearby pulsars.
Dark Matter (and other) Interpretations have to bring these two observations into a common theoretical framework.

Antiprotons

No Excess

Positrons

Excess
A Challenging Puzzle for Dark Matter
Example: Dark Matter

Majorana DM with new internal bremsstrahlung correction. NB: requires annihilation cross-section to be ‘boosted’ by >1000.

Kaluza-Klein dark matter
PAMELA Cosmic Ray Spectra
Cosmic Rays Propagation in the Galaxy

\[
\frac{\partial N_i(E, z, t)}{\partial t} = D(E) \cdot \frac{\partial^2}{\partial z^2} N_i(E, z, t) - N_i(E, z, t) \left\{ \frac{1}{\tau_{i}^{int}(E, z)} + \frac{1}{\gamma(E)\tau_{i}^{dec}} \right\}
\]

**diffusion**

\[+ \sum_{k\neq l} \frac{N_k(E, z, t)}{\tau_{k \rightarrow l}^{int}(E, z)}\]

**interaction and decay**

\[+ Q_i(E, z)\]

**secondary production**

\[- \frac{\partial}{\partial E} \left\{ \left( \frac{\partial E}{\partial t} \right) \cdot N_i(E, z, t) \right\} + \frac{1}{2} \frac{\partial^2}{\partial E^2} \left\{ \frac{\Delta E^2}{\Delta t} \right\} \cdot N_i(E, z, t)\]

**primary sources**

**energy changing processes**

(ionisation, reacceleration)
Standard Positron Fraction

Theoretical Uncertainties

\[ \gamma = 3.54 \]

\[ \gamma = 3.34 \]

T. Delahaye et al., arXiv: 0809.5268v3
Electron (e-) Spectrum

See the talk Thursday 9
PAMELA: **Spectrometer & Calorimeter: e⁻**

- Spectrometer to select events with negative curvature
- Calorimeter to select electrons
- Spectrometer Rigidity $\rightarrow$ Energy

See the talk Thursday 9

**Preliminary**
See the talk Thursday 9
PAMELA: Only Calorimeter : $e^+ + e^-$

Use different topology of EM and hadronic showers in the calorimeter to select electrons (totally 21 parameters were used).
Electron spectrum - tracker-based

• Spectrometer to select events with negative curvature, loose cuts
• Calorimeter to select electrons, strong cuts
• Energy with calorimeter

See the talk Thursday 9

Preliminary

Tracker-based
Calorimeter-based
All electrons
PAMELA very preliminary

Graph
Proton and Helium spectra

Very high statistics over a wide energy range
→ Precise measurement of spectral shape
→ Possibility to study time variations and transient phenomena

Flux $\times E^{2.7}$ ($m^2 s sr GeV/n$)$^{-1}$ vs $E$ (GeV/n)
Proton and Helium Spectrum

Both spectra exhibit a change in the spectral index around 200 GV.
• Different injection mechanisms or sources for protons and helium?
• No other source or mechanism which effects the ratio down to ~ 4 GV?
Proton Helium ratio

\[ \Delta \gamma = -0.101 \]
Proton flux

\[ \frac{dN}{dE \cdot E^{2.7}, \text{GeV}^{-1} \text{sr}^{-1} \text{m}^{-2}} \]

\[ \log_{10}(E, \text{GeV/n}) \]

Graph showing proton flux data with various data sets and error bars.
Nuclei identification

- Important input to secondary production + propagation models
  - Secondary to primary ratios:
    - B / C
    - Be / C
    - Li / C
  - Helium and hydrogen isotopes:
    - $^3\text{He} / ^4\text{He}$
    - d / He

5.7 GV non-interacting carbon nucleus

Truncated mean of multiple dE/dx measurements in different silicon planes
PAMELA Boron and Carbon Spectra

Boron

Carbon

Light Nuclei Spectra and Ratios: Work in Progress…

Preliminary

Preliminary

Light Nuclei Spectra and Ratios: Work in Progress…
Boron Spectrum

![Graph showing the differential flux versus kinetic energy for Boron spectrum. The graph includes data from PAMELA and HEAO-3-C2.]
Carbon Spectrum

![Graph showing the differential flux of carbon spectrum vs kinetic energy. The graph has a logarithmic scale for both axes. The data is labeled as PAMELA and HEAO-3-C2. Preliminary notes are visible on the right side of the image.](image-url)
C/O ratio

Preliminary

C/O ratio vs. Kinetic energy, GeV/n
Solar Modulation of galactic cosmic rays

- Study of charge sign dependent effects
  J. Clem et al. 30th ICRC 2007
Time Dependence of PAMELA Proton Flux
Time Dependence of PAMELA Proton Flux

Preliminary
Time Dependence of PAMELA Electron ($e^-$) Flux

\begin{center}
\begin{tikzpicture}
\begin{loglogaxis}[
    width=\textwidth,
    height=0.8\textwidth,
    xlabel=Kinetic energy (GeV),
    ylabel=electrons / (cm$^2$ sr s GeV),
    xmin=1, xmax=10,
    ymin=1e-5, ymax=1e-2,
    legend style={at={(0.95,0.05)},anchor=north east,draw=red}
]
\addplot [black, thick] coordinates { (1, 0.5) (10, 0.05) };
\addplot [green, thick] coordinates { (1, 0.5) (10, 0.1) };
\addplot [blue, thick] coordinates { (1, 0.5) (10, 0.2) };
\addplot [red, thick] coordinates { (1, 0.5) (10, 0.3) };
\end{loglogaxis}
\end{tikzpicture}
\end{center}
Time Dependence of PAMELA Electron (e⁻) Flux

2007 / 2006
2008 / 2006
2009 / 2006

Kinetic energy (GeV)
Time Dependence

Flux variation as a function of time for rigidities between 0.72 and 1.04 GV

A < 0
Time Dependence

Increase of the flux measured by PAMELA from July 2006 to December 2008
Charge dependent solar modulation

\[ A < 0 \]

Negative particles

Positive particles
Gradients in the Heliosphere, PAMELA & ULYSSES

\[
\ln \left( \frac{I(t, R, \theta)}{I_{PAMELA}(t)} \right) = G_R R + G_\theta \theta
\]
Comparison of the proton flux measured between 1.5 and 1.57 GV by PAMELA and ULYSSES as a function of time
Comparison of the proton flux measured between 1.5 and 1.57 GV by PAMELA and ULYSSES as a function of time.
1. Period: Radial distance decreases and absolute value of heliographic latitude increases, while intensity ratio decreases
2. Period: Radial distance and latitude first decrease and then increase, while intensity ratio is constant
3. Period: Radial distance increases and heliographic latitude decrease, while intensity ratio increases
December 2006 Solar particle events

Dec 13th largest CME since 2003, anomalous at sol min

X3.4 solar flare
The Sun on December 13, 2006

White light

30 nm emission

Active region AR10930

Ground level effect of a solar flare X3.4/2B S06 W24 02.26 UT

Enhancement profiles at neutron monitors:

Oulu (Rc=0.77 GV), Apatity (Rc=0.60 GV), Moscow (Rc=2.4 GV), Barentsburg (Rc=0... GV), Fort Smith (Rc=0... GV),
December 13

Proton flux

Helium flux

Protons / cm² sr s (GeV)

Helium / cm² sr s (GeV/n)

quiet flux (nov 2006)
December 13

Proton flux

Helium flux

quiet flux (nov 2006)

13/00:00 - 13/02:57
December 13

Proton flux

Helium flux

- quiet flux (nov 2006)
- 13/00:00 - 13/02:57
- 13/03:18 - 13/03:29
December 13

Proton flux

Helium flux

- quiet flux (nov 2006)
- 13/00:00 - 13/02:57
- 13/03:18 - 13/03:29
- 13/04:06 - 13/04:20

protons / (cm² s s GeV)

helium / (cm² s s GeV/n)

kinetic energy (GeV)

kinetic energy (GeV/n)
December 13

Proton flux

Helium flux
December 13

Proton flux  Helium flux

[Graphs showing proton and helium flux over kinetic energy ranges]
December 14

Proton flux

Helium flux

quiet flux (nov 2006)

14/23:05 - 15/02:35

quiet flux (nov 2006)

14/23:05 - 14/23:21
December 13th 2006 event

Protons

Arbitrary units

\[10^2\]

\[10\]

\[1\]

\[10^{-1}\]

\[10^{-2}\]

\[10^{-1}\] 1

GeV

Preliminary!
December 13th 2006 He differential spectrum
December 14th 2006 event

Protons

<table>
<thead>
<tr>
<th>Time Range</th>
<th>Proton Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/1/07 00:00 - 05:50</td>
<td></td>
</tr>
<tr>
<td>14/12 16:00 - 18:00</td>
<td></td>
</tr>
<tr>
<td>14/12 19:15 - 21:30</td>
<td></td>
</tr>
<tr>
<td>14/12 22:55 - 15/12 01:00</td>
<td></td>
</tr>
<tr>
<td>15/12 12:00 - 24:00</td>
<td></td>
</tr>
</tbody>
</table>

End of event of Dec 14th

Preliminary!
Radiation Belts

South Atlantic Anomaly

Secondary production from CR interaction with atmosphere
Study terrestrial magnetosphere

Pamela World Maps: 350 – 650 km alt

(S11*S12) [hit/time]

36 MeV p, 3.5 MeV e-
Subcutoff particles

Protons flux

Arbitrary units vs. Rigidity [GV/c]

- L > 3.86
- 3.86 > L > 2.73
- 2.73 > L > 2.23
- 2.23 > L > 1.93
- 1.93 > L > 1.73
- 1.73 > L > 1.58
- 1.58 > L > 1.46
- 1.46 > L > 1.36
- 1.36 > L > 1.29
- 1.29 > L > 1.22
- 1.22 > L > 1.16
- 1.16 > L > 1.11
- 1.11 > L > 1.07
- 1.07 > L > 1.03
- 1.03 > L > 1
In spectrum in SAA, polar and equatorial regions.
Thanks!

http://pamela.roma2.infn.it
Other Objectives
Search for New Matter in the Universe:

An example is the search for “strangelets”.

There are six types of Quarks found in accelerators. All matter on Earth is made out of only two types of quarks. “Strangelets” are new types of matter composed of three types of quarks which should exist in the cosmos.

i. A stable, single “super nucleon” with three types of quarks

ii. “Neutron” stars may be one big strangelet

AMS courtesy