The PAMELA Space Experiment

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INFN Trieste, Italy

On behalf of the PAMELA collaboration
Texas A&M Colloquium
April 9th 2009
The discovery of cosmic rays

- Victor Hess ascended to 5000 m in a balloon in 1912
- ... and noticed that his electroscope discharged more rapidly as altitude increased
- Not expected, as background radiation was thought to be terrestrial
- NPP 1936 (with Carl ‘e⁺’ Anderson)
~500 km
Smaller detectors but long duration.
PAMELA!

Top of atmosphere

Primary cosmic ray

~40 km

Large detectors but short duration.
Atmospheric overburden ~5 g/cm².
Almost all data on cosmic antiparticles from here.

~5 km

Ground

Primary Cosmic Rays

Hess & Kuhler
500 km (1972-74)

Electromagnetic
shower

Mont Blanc
4357 m

Concorde
15000 m

Hypersensitive

~5 km

Ground

Primary cosmic ray

~40 km

Large detectors but short duration.
Atmospheric overburden ~5 g/cm².
Almost all data on cosmic antiparticles from here.
Isotopic composition

Solar Modulation

Antimatter Dark Matter

Elemental Composition

Extreme Energy CR

High Z

[ENTICE, ECCO]

[BESS, PAMELA, AMS]

[CREAM, ATIC, TRACER, NUCLEON, CALET, ACCESS?, INCA?,

Fluxes of Cosmic Rays

(1 particle per m²-second)

Knee

(1 particle per m²-year)

Ankide

(1 particle per km²-year)
PAMELA Collaboration

Russia:
- Moscow
- St. Petersburg

Germany:
- Siegen

Sweden:
- KTH, Stockholm

Italy:
- Bari
- Florence
- Frascati
- Naples
- Rome
- Trieste
- CNR, Florence
Scientific goals

- Search for dark matter annihilation
- Search for antihelium (primordial antimatter)
- Study of cosmic-ray propagation (light nuclei and isotopes)
- Study of electron spectrum (local sources?)
- Study solar physics and solar modulation
- Study terrestrial magnetosphere
PAMELA detectors

Main requirements → high-sensitivity antiparticle identification and precise momentum measure

**Time-Of-Flight**
- plastic scintillators + PMT:
  - Trigger
  - Albedo rejection;
  - Mass identification up to 1 GeV;
  - Charge identification from dE/dX.

**Electromagnetic calorimeter**
- W/Si sampling (16.3 *X₀*, 0.6 *λ*)
  - Discrimination e⁺ / p, anti-p / e⁻ (shower topology)
  - Direct E measurement for e⁻

**Neutron detector**
- plastic scintillators + PMT:
  - High-energy e/h discrimination

**Spectrometer**
- microstrip silicon tracking system + permanent magnet
  - Magnetic rigidity → R = pc/Ze
  - Charge sign
  - Charge value from dE/dx

GF: 21.5 cm² sr
Mass: 470 kg
Size: 130x70x70 cm³
Power Budget: 360W
# Design Performance

<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Energy Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antiprotons</td>
<td>80 MeV - 150 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 700 GeV</td>
</tr>
<tr>
<td>Electrons+positrons</td>
<td>up to 2 TeV (from calorimeter)</td>
</tr>
<tr>
<td>Light Nuclei (He/Be/C)</td>
<td>up to 200 GeV/n</td>
</tr>
<tr>
<td>AntiNuclei search</td>
<td>sensitivity of $3 \times 10^{-8}$ in $\bar{\text{He}}$/He</td>
</tr>
</tbody>
</table>

→ Simultaneous measurement of many cosmic-ray species  
→ New energy range   
→ Unprecedented statistics
The first historical measurements on galactic antiprotons

\[ \text{CR + ISM} \rightarrow \text{p-bar + ...} \]

kinematic threshold: 5.6 GeV for the reaction
The first historical measurements of the $\bar{p}/p$ ratio and various ideas of theoretical interpretations.

Background:
CR interaction with ISM
$CR + ISM \rightarrow p-bar + \ldots$

- Golden 1979
- Bogomolov 1979
- Buffington 1981
ANTIMATTER

Collision of High Energy Cosmic Rays with the Interstellar Gas

Annihilation of Exotic Particles

Evaporation of Primordial Black Holes

Pulsar’s magnetospheres

Cosmic Rays Leaking Out of Antimatter Galaxies

Antimatter Lumps In the Milky Way

He

e+

p

p

e-

e+

e+

p

p

e+

He

Cosmic Rays Leaking Out of Antimatter Galaxies

Antimatter Lumps In the Milky Way

Pulsar’s magnetospheres
There's evidence for dark matter on many scales...

The current content of the Universe

- 63.7% dark energy
- 20.5% cold dark matter
- 0.04% photons
- 4% ordinary matter
- <11.7% hot dark matter (neutrinos)

Searches for WIMP Dark Matter

Accelerators

Direct

Indirect

P. Gondolo, IDM 2008
You are here

Background

\[ \text{Background} \]

\[ p_{\text{CR}} \]

\[ p_{\text{ISM}} \]

\[ p, e^+ \]

\[ \overline{p}, e^+ \]

\[ e^+, e^- ? \]

Pulsar

Signal

\[ \chi \]

\[ \overline{\chi} \]

\[ e^+, e^- ? \]

PAMELA

You are here
CR antimatter

Antiprotons

Positrons

Positron excess?

CR + ISM → p-bar + …
kinematic threshold: 5.6 GeV for the reaction

pp → pppp

CR + ISM → π^± + x → μ^± + x → e^± + x

CR + ISM → π^0 + x → γγ → e^±
CR Antimatter: available data

Why in space?

- Low exposure (~days)  
  ⇒ large statistical errors
- Atmospheric secondaries (~5g/cm²)  
  ⇒ additional systematic uncertainty @low-energy
Resurs-DK1 satellite + orbit

- Resurs-DK1: multi-spectral imaging of earth’s surface
- PAMELA mounted inside a pressurized container
- Lifetime >3 years (assisted, first time last February)

- Data transmitted to NTsOMZ, Moscow via high-speed radio downlink. ~16 GB per day

- Quasi-polar and elliptical orbit (70.0°, 350 km - 600 km)

- Traverses the South Atlantic Anomaly

- Crosses the outer (electron) Van Allen belt at south pole
Subcutoff particles

Protons flux

Arbitrary units vs. Rigidity [GV/c]
Inner radiation belt (SSA)

Outer radiation belt

NP          SP

EQ          EQ

95 min

orbit 3751  orbit 3752  orbit 3753

N. of physics packets/minute

SAA

NP  SP

E

Orbit n. 1095  Orbit n. 1096

On Board Time [ms]

Download @orbit 3754 – 15/02/2007 07:35:00 MWT
PAMELA milestones

Launch from Baikonur → June 15\textsuperscript{th} 2006, 0800 UTC.

ʻFirst lightʼ → June 21\textsuperscript{st} 2006, 0300 UTC.

• Detectors operated as expected after launch
• Different trigger and hardware configurations evaluated

→ PAMELA in continuous data-taking mode since commissioning phase ended on July 11\textsuperscript{th} 2006

<table>
<thead>
<tr>
<th>Trigger rate*</th>
<th>~25Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of live time*</td>
<td>~75%</td>
</tr>
<tr>
<td>Event size (compressed mode)</td>
<td>~5kB</td>
</tr>
<tr>
<td>25 Hz x 5 kB/ev</td>
<td>~10 GB/day</td>
</tr>
</tbody>
</table>

(*outside radiation belts)

Till ~now:
~1000 days of data taking
~13 TByte of raw data downlinked
>10\textsuperscript{9} triggers recorded and analyzed
(Data from April till December 2008 under analysis)
Antiparticles with PAMELA
Flight data: 0.169 GV electron

Flight data: 0.171 GV positron
Flight data: 0.763 GeV/c antiproton annihilation
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⁻/p ~ 10²)

Positron
(NB: p/e⁺ ~ 10³⁻⁴)
Flight data: 51 GeV/c positron
Pre-PAMELA antiproton to proton flux ratio

\[ \frac{\bar{p}}{p} \]

\[ \text{kinetic energy (GeV)} \]

- Bergström & Ullio 1999
- Molnar & Simon 2001 (\(\phi=550\))
- Moskalenko 2002 (\(A=0, \alpha=15^\circ\))

- BESS 1995-97
- BESS 2000
- BESS 1999
- BESS 1993
- HEAT-pbar 2000
- IMAX 1992
- BESS-polar 2004
- MASS 1991
- CAPRICE 1994
- CAPRICE 1998

INFN
Antiproton to proton flux ratio

PRL 102, (2009) 051101, Astro-ph 0810.4994

![Graph showing the antiproton to proton flux ratio versus kinetic energy (GeV).]
Pre-PAMELA positron fraction
Positron to Electron Fraction

End 2007:
$\sim 10,000 \, e^+ > 1.5 \text{ GeV}$

$\sim 2000 > 5 \text{ GeV}$

Solar modulation

A⁺  A⁻  A⁺  A⁻

Smoothed Sunspot Number
Monthly Averages

~11 y

Cycle 19  Cycle 20  Cycle 21  Cycle 22  Cycle 23

Counts/Hour/100

Thule, Greenland, Neutron Monitor
Bertol Research Institute, University of Delaware
27-day Averages - data through August 2008

PAMELA

Annual Variation of P/P Ratio

Y. Asaoka and Y. Shiozawa et al., astro-ph/0109067
accepted by Phys. Rev. Lett.

BESS(97)  BESS(99)  BESS(00)

PAMELA

Low fluxes!

Kinetic Energy (GeV)

Decreasing solar activity

Increasing flux

July 2006
August 2007
February 2008

Position (rad/m²) vs (e²m² - e⁻²)

PAMELA

Energy [GeV]

A⁻ + A⁻
$A > 0$

$A < 0$

$\bar{p}, e^-$

$p, e^+$

$A < 0$
Positron to Electron Fraction

End 2007:
\(~10\,000\ e^+ > 1.5\text{ GeV}\)
\(~2000 > 5\text{ GeV}\)

PAMELA Positron Fraction

But uncertainties on:
- Secondary production (primary fluxes, cross section)

Secondary production
Moskalenko & Strong 98
Galactic H and He spectra
Galactic H and He spectra

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

(statistical errors only)
Secondary production
Moskalenko & Strong 98

But uncertainties on:
• Secondary production (primary fluxes, cross section)
• Propagation models
Diffusion Halo Model

\[
\frac{\partial N_i(E, z, t)}{\partial t} = D(E) \cdot \frac{\partial^2}{\partial z^2} N_i(E, z, t) - N_i(E, z, t) \left( \frac{1}{\tau_{\text{int}}^{\text{int}}(E, z)} + \frac{1}{\gamma(E)\tau_i^{\text{dec}}} \right) \\
+ \sum_{k>l} \frac{N_k(E, z, t)}{\tau_{\text{int}}^{k\rightarrow l}(E, z)} + Q_i(E, z) \\
- \frac{\partial}{\partial E} \left\langle \frac{\partial E}{\partial t} \right\rangle \cdot N_i(E, z, t) + \frac{1}{2} \frac{\partial^2}{\partial E^2} \left\langle \frac{\Delta E^2}{\Delta t} \right\rangle \cdot N_i(E, z, t)
\]

- **diffusion**
- **interaction and decay**
- **secondary production**
- **primary sources**
- **energy changing processes** (ionisation, reacceleration)
Secondary nuclei

- B nuclei of secondary origin:
  \[ \text{CNO + ISM} \rightarrow \text{B} + \ldots \]
- Local secondary/primary ratio sensitive to average amount of traversed matter (\(l_{\text{esc}}\)) from the source to the solar system

Local secondary abundance:
⇒ study of galactic CR propagation

\[ \frac{N_S}{N_P} \propto \lambda_{\text{esc}} \cdot \sigma_{P\rightarrow S} \]

(B/C used for tuning of propagation models)
Nuclei identification

- Important input to secondary production + propagation models
  - Secondary to primary ratios:
    - B / C
    - Be / C
    - Li / C

- Helium and hydrogen isotopes:
  - $^3$He / $^4$He
  - d / He
PAMELA Positron Fraction

But uncertainties on:
- Secondary production (primary fluxes, cross section)
- Propagation models
- Electron spectrum
Theoretical uncertainties on “standard” positron fraction

T. Delahaye et al., arXiv: 0809.5268v3
During first week after PAMELA results posted on arXiv

- 0808.3725 DM
- 0808.3867 DM
- 0809.2409 DM
- 0810.2784 Pulsar
- 0810.4846 DM / pulsar
- 0810.5292 DM
- 0810.5344 DM
- 0810.5167 DM
- 0810.5304 DM
- 0810.5397 DM
- 0810.5557 DM
- 0810.4147 DM
- 0811.0250 DM
- 0811.0477 DM
Where do positrons come from?

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

Typical lifetime

\[ \tau \simeq 5 \cdot 10^5 \text{yr} \left( \frac{1 \text{ TeV}}{E} \right) \]
Astrophysical Explanation: SNR

N.J. Shaviv et al., arXiv:0902.0376v1
Astrophysical Explanation: Pulsars

- Mechanism: the spinning $B$ of the pulsar strips $e^-$ that accelerated at the polar cap or at the outer gap emit $\gamma$ that make production of $e^\pm$ that are trapped in the cloud, further accelerated and later released at $\tau \sim 10^5$ years.

- Young ($T < 10^5$ years) and nearby ($< 1$ kpc)
- If not: too much diffusion, low energy, too low flux.

- Geminga: 157 parsecs from Earth and 370,000 years old
- B0656+14: 290 parsecs from Earth and 110,000 years old.

- Diffuse mature pulsars
Astrophysical explanations?

Are there “standard” astrophysical explanations of the PAMELA data?

Young, nearby pulsars

Example: pulsars

Contributions of $e^-$ & $e^+$ from Geminga assuming different distance, age and energetic of the pulsar

H. Yüksak et al., arXiv:0810.2784v2

Diffuse mature & nearby young pulsars
Hooper, Blasi, and Serpico
arXiv:0810.1527
DM annihilations

DM particles are stable. They can annihilate in pairs.

Primary annihilation channels

Decay

Final states

$\sigma_a = \langle \sigma v \rangle$
DM annihilations

Resulting spectrum for positrons and antiprotons
$M_{\text{WIMP}} = 1 \text{ TeV}$

The flux shape is completely determined by:

1) WIMP mass
2) Annihilations channels
PAMELA \( \bar{p}/p \) implication on DM

Secondary Production Models

Upper limit for enhancement factor for thermal WIMP DM flux as a function of the WIMP mass

Donato et al., arXiv: 0810.5292v1
Data fitting

Which DM spectra can fit the data?

DM with $m_\chi \approx 150$ GeV and $W^+W^-$ dominant annihilation channel (possible candidate: Wino)

M. Cirelli et al., arXiv: 0809.2409v3
Data fitting

Which DM spectra can fit the data?

DM with $m_\chi \simeq 10$ TeV and $W^+W^-$ dominant annihilation channel (no "natural" SUSY candidate)

But $B \approx 10^4$

M. Cirelli et al., arXiv: 0809.2409v3
Data fitting

DM with \( m_\chi \simeq 1 \text{ TeV} \) and \( \mu^+ \mu^- \) dominant annihilation channel

M. Cirelli et al., arXiv: 0809.2409v3
Majorana DM with new internal bremsstrahlung correction. NB, requires annihilation cross-section to be ‘boosted’ by >1000.
• Propose a new light boson \((m_\Phi \leq \text{GeV})\), such that \(\chi\chi \rightarrow \Phi\Phi; \Phi \rightarrow e^+e^-, \mu^+\mu^-, \ldots\)
• Light boson, so decays to antiprotons are kinematically suppressed
Example: $e^+$ & $\bar{p}$ DM

P. Grajek et al., arXiv: 0812.4555v1
Non-thermal wino-like neutralino
Varying propagation model, no boost factor
Data fitting

What if we consider ATIC and PPB-BETS data?

DM with $m_\chi \simeq 1$ TeV and $\mu^+\mu^-$ dominant annihilation channel

M. Cirelli et al., arXiv: 0809.2409v3
Contributions of $e^-$ & $e^+$ from Geminga assuming different distance, age and energetic of the pulsar


H. Yüksak et al., arXiv:0810.2784v2
Future observations of electrons

$\Phi_{e^\pm}$ up to $\sim$1TeV
$\Phi_{e^+}$ up to $\sim$300 GeV
$\Phi_{e^-}$ up to $\sim$500 GeV

Fermi GST: $\Phi_{e^\pm}$ up to $\sim$700 GeV
Summary

- PAMELA has been in orbit and studying cosmic rays for ~30 months. >10⁹ triggers registered and >13 TB of data has been down-linked.

- **Antiproton-to-proton flux ratio** (~100 MeV - ~100 GeV) shows no significant deviations from secondary production expectations. Additional high energy data in preparation (up to ~150 GeV).

- **High energy positron fraction** (>10 GeV) increases significantly (and unexpectedly!) with energy. Primary source? Data at higher energies will help to resolve origin of rise (spillover limit ~300 GeV).

- Analysis ongoing to measure the e⁻ spectrum up to ~500 GeV, e⁺ spectrum up to ~300 GeV and all electrum (e⁻ + e⁺) spectrum up to ~1 TV.

- **Furthemore:**
  - PAMELA is going to provide measurements on elemental spectra and low mass isotopes with an unprecedented statistical precision and is helping to improve the understanding of particle propagation in the interstellar medium
  - PAMELA is able to measure the high energy tail of solar particles.
  - PAMELA is going to set a new lower limit for finding Antihelium

http://pamela.roma2.infn.it
Thanks!

PAMELA Physics Workshop
May 11-12, 2009

ROMA

http://pamela.roma2.infn.it/workshop09