Recent results from PAMELA

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PAMELA
Payload for Antimatter/Matter Exploration and Light-nuclei Astrophysics

→ Direct detection of CRs in space
→ Main focus on antimatter component
Why CR antimatter?

First historical measurements of $p/\bar{p}$ ratio

Background:
CR interaction with ISM
$CR + ISM \rightarrow p/\bar{p} + \ldots$

Evaporation of primordial black holes

Anti-nucleosynthesis

WIMP dark-matter annihilation in the galactic halo

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CR antimatter

Present status

Antiprotons

CR + ISM → p-bar + …
kinematic treshold:
5.6 GeV for the reaction
pp → pppp

Positrons

CR + ISM → π± + x → μ± + x → e± + x
CR + ISM → π0 + x → γγ → e±

Moskalenko & Strong 1998

Charge ratio (e± / (e± + e±))

Charge-dependent solar modulation
Asaoka Y. et al. 2002

1999/2000

Positron excess?

Moskalenko & Strong 1998

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CR antimatter: available data

Why in space?

Antiprotons

- low exposure (~20h)
  ⇒ large statistical errors
- atmospheric secondaries (~5g/cm²)
  ⇒ additional systematic uncertainty @low-energy

• Antiprotons and Positrons

  - Moskalenko & Strong 1998
  - BESS-polar (long-duration)

  "Standard" balloon-borne experiments

AMS-01: space shuttle, 1998
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 λI)
- 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
It provides:
- **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
Characteristics:

- 5 modules of permanent magnet (Nd-B-Fe alloy) in aluminum mechanics
- Cavity dimensions 162x132x445 cm³ → GF 21.5 cm²sr
- Magnetic shields
- 5mm-step field-map
- $B=0.43$ T (average along axis), $B=0.48$ T (@center)
The tracking system

Main tasks:
- Rigidity measurement
- Sign of electric charge
- \( \frac{dE}{dx} \)

Characteristics:
- 6 planes double-side (x&y view) microstrip Si sensors
- 36864 channels
- Dynamic range 10 MIP

Performances:
- Spatial resolution: \( 3 \div 4 \mu m \)
- MDR ~1TV (from test beam data)
The electromagnetic calorimeter

Main tasks:
• e/h discrimination
• e+/− energy measurement

Characteristics:
• 44 Si layers (X/Y) + 22 W planes
• \(16.3 \times_0 / 0.6 \times_0\)
• 4224 channels
• Dynamic range 1400 mip
• Self-trigger mode (> 300 GeV GF ~ 600 cm² sr)

Performances:
• p/e⁺ selection efficiency ~ 90%
• p rejection factor \(10^6\)
• e rejection factor > \(10^4\)
• Energy resolution ~ 5% @ 200 GeV
Main tasks:
- First-level trigger
- Albedo rejection
- dE/dx
- Particle identification (<1GeV/c)

Characteristics:
- 3 double-layer scintillator paddles
- X/Y segmentation
- Total: 48 Channels

Performances:
- $\sigma_{\text{paddle}} \sim 110\text{ps}$
- $\sigma_{\text{TOF}} \sim 330\text{ps}$ (for MIPs)
The anticounter shields

Main tasks:
• Rejection of events with particles interacting with the apparatus (off-line and second-level trigger)

Characteristics:
• scintillator paddles 10mm thick
• 4 up (**CARD**), 1 top (**CAT**), 4 side (**CAS**)

Performances:
• Efficiency > 99.9%
Neutron detector

Main tasks:
- e/h discrimination @ high-energy

Characteristics:
- 36 $^3$He counters: $^3$He(n,p)T $\rightarrow$ Ep = 780 keV
- 1 cm thick polyethylene moderators
- n collected within 200 μs time-window

Shower-tail catcher (S4)

Main tasks:
- ND trigger

Characteristics:
- 1 scintillator paddle 10 mm thick

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Principle of operation

Track reconstruction

**Iterative** $\chi^2$ minimization as a function of track state-vector components $\alpha$

**Magnetic deflection**

$|\eta| = 1/R$

$R = pc/Ze \rightarrow$ **magnetic rigidity**

$\sigma_R/R = \sigma_\eta/\eta$

**Maximum Detectable Rigidity (MDR)**

def: $\@ R=MDR \Rightarrow \sigma_R/R = 1$

$MDR = 1/\sigma_\eta$

- Measured @ground with protons of known momentum
  \( \rightarrow MDR\sim1TV \)

- Cross-check in flight with protons (alignment) and electrons (energy from calorimeter)

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Principle of operation

Z measurement

\[ -\frac{dE}{dx} = KZ^2 \frac{Z}{A} \beta^2 \left[ \frac{1}{2} \ln \frac{2m_e e^2 \beta^2 \gamma^2 T_{\text{max}}}{l^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right] \]

Bethe Bloch ionization energy-loss of heavy (M>>me) charged particles

(track average) \( \leftarrow \text{saturation} \)
Principle of operation

Velocity measurement

- Particle identification @ low energy
- Identify **albedo** (up-ward going particles $\rightarrow \beta < 0$)
  $\rightarrow$ NB! They mimic antimatter!
Principle of operation

Electron/hadron separation

- Interaction topology
e/h separation

- Energy measurement of electrons and positrons
  (~full shower containment)

\[
\frac{\sigma_E}{E} = a \oplus \frac{b}{\sqrt{E}} \rightarrow a < 5\%
\]

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14.4 GV
non-interacting proton
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36 GeV/c interacting proton
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9.7 GV
non-interacting Helium
13 GV
Interacting Helium
1.92 GV
Stopping nucleus
(Z~8)
14.7 GV
Interacting nucleus
(Z~8)
1.2 GV Stopping nucleus (Z~12)
1.97 GV
Interacting nucleus
(Z~12)
calorimeter self-trigger
(m.p. electron)
calorimeter self-trigger (m.p. proton)
calorimeter self-trigger
(m.p. Z=22)
11.6 GV
interacting anti-proton
0.763 GeV/c annihilation antiproton
32.3 GV positron
### PAMELA design performance

<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Energy Range</th>
<th>Particles in 3 Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antiprotons</td>
<td>$80 \text{ MeV} \div 190 \text{ GeV}$</td>
<td>$O(10^4)$</td>
</tr>
<tr>
<td>Positrons</td>
<td>$50 \text{ MeV} \div 270 \text{ GeV}$</td>
<td>$O(10^5)$</td>
</tr>
<tr>
<td>Electrons</td>
<td>up to $400 \text{ GeV}$</td>
<td>$O(10^6)$</td>
</tr>
<tr>
<td>Protons</td>
<td>up to $700 \text{ GeV}$</td>
<td>$O(10^8)$</td>
</tr>
<tr>
<td>Electrons+positrons</td>
<td>up to $2 \text{ TeV}$</td>
<td>(from calorimeter)</td>
</tr>
<tr>
<td>Light Nuclei</td>
<td>up to $200 \text{ GeV/n}$</td>
<td>$\text{He}/\text{Be}/\text{C}: O(10^{7/4/5})$</td>
</tr>
<tr>
<td>Anti-Nuclei search</td>
<td>sensitivity of $3 \times 10^{-8}$ in anti-He/He</td>
<td></td>
</tr>
</tbody>
</table>

→ **Unprecedented statistics and new energy range for cosmic ray physics**
  (e.g. contemporary antiproton and positron maximum energy ~ 40 GeV)

→ **Simultaneous measurements of many species**
The Resurs DK-1 spacecraft

- Multi-spectral remote sensing of earth's surface - near-real-time high-quality images
- Built by the Space factory TsSKB Progress in Samara (Russia)
- Operational orbit parameters:
  - inclination ~70°
  - altitude ~ 360-600 km (elliptical)
- Active life >3 years
- Data transmitted via Very high-speed Radio Link (VRL)

Mass: 6.7 tons
Height: 7.4 m
Solar array area: 36 m²

- PAMELA mounted inside a pressurized container
- moved from parking to data-taking position few times/year

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Satellite orbit

PAMELA orbit
inclination ~70°
altitude ~ 360-600 km

Vertical rigidity cutoff

→ the quasi-polar orbit allows to study low-energy cosmic rays (R>100MV)

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Direct detection of galactic CRs

All-particle CR spectrum

- Solar influence
- Galactic CRs
- Extra-galactic CRs

Direct detection

Indirect detection

1 GeV  1 TeV  1 PeV

CR nuclei

PAMELA

GCR elemental composition (vs solar system)

- H
- He
- C
- N
- O
- Fe
- Li
- B
- Be
- Sc
- V
- Ti
- Cr
- Mn
- Fe
- Ni
- Co
- Cu
- Zn
- Ga
- Ge
- As
- Se
- Br
- Kr
- Rb
- Sr
- Y
- Zr
- Nb
- Mo
- Tc
- Ru
- Rh
- Pd
- Ag
- Cd
- In
- Sn
- Sb
- Te
- I
- Xe
- Cs
- Ba
- La
- Ce
- Pr
- Nd
- Sm
- Eu
- Gd
- Tb
- Dy
- Ho
- Er
- Tm
- Yb
- Lu

Electrons

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CR antimatter

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Direct CR observation @ 1 AU

- Halo & clumps
  - DM annihilation
- SNRs
  - p, He, CNO,..., e-, γ
- Sun
  - p, He, CNO,..., e-, γ
- Magnetosphere
- Heliosphere
- Milky way
- Propagation
- Extragalactic antimatter
  - p-bar, He-bar, γ
- Milky way
- Propagation

- + Li, Be, B,..., p-bar, e±, γ

- Milky way
- Propagation
- Extragalactic antimatter
  - p-bar, He-bar, γ
- Heliosphere
- Sun
- Magnetosphere
- Halo & clumps
  - DM annihilation
- SNRs
  - p, He, CNO,..., e-, γ
PAMELA science

• Search for dark matter
• Search for primordial antimatter

… but also:

• Study of cosmic-ray origin and propagation
• Study of solar physics and solar modulation
• Study of terrestrial magnetosphere
PAMELA milestones

Launch from Baikonur → June 15th 2006, 0800 UTC.

‘First light’ → June 21st 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 11th 2006

Trigger rate* ~25Hz
Fraction of live time* ~ 75%
Event size (compressed mode) ~ 5kB
25 Hz x 5 kB/ev → ~ 10 GB/day
(*outside radiation belts)

Till May 2008:
~500 days of data taking
~10 TByte of raw data downlinked
~12•10^8 triggers recorded and analysed (Data from May till now under analysis)
Analysis of a PAMELA orbit

Low energy particles stops inside the apparatus
⇒ Counting rates: S1 > S2 > S3

Inner radiation belt (SAA)

Outer radiation belt

Ratemeters Independent from trigger

Counts (over 60 ms)

452 434 436 438 440 442 444 446

orbit 3751  orbit 3752  orbit 3753

EQ  NP  SP  95 min

s1 s2 s3
South-Atlantic Anomaly (SAA)
South-Atlantic Anomaly (SAA)

SAA morphology

Latitude
Altitude

Neutron rate (background)

Longitude

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Trigger rate
Magnetic Field (IGRF)
Geomagnetic cutoff

Geomagnetic cutoff (GV/c)
- 0.4 to 0.5
- 1.0 to 1.5
- 1.5 to 2.0
- 2 to 4
- 4 to 7
- 7 to 10
- 10 to 14
- > 14

Magnetic poles (→ galactic protons)

Secondary reentrant-albedo protons

• Upward going albedo excluded
• SAA excluded

Magnetic equator
Trapped-particle spectrum

(statistical errors only)

<table>
<thead>
<tr>
<th>B</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 0.30 G</td>
<td></td>
</tr>
<tr>
<td>0.22 G ≤ B</td>
<td>&lt; 0.23 G</td>
</tr>
<tr>
<td>0.21 G ≤ B</td>
<td>&lt; 0.22 G</td>
</tr>
<tr>
<td>0.20 G ≤ B</td>
<td>&lt; 0.21 G</td>
</tr>
<tr>
<td>0.19 G ≤ B</td>
<td>&lt; 0.20 G</td>
</tr>
<tr>
<td>&lt; 0.19 G</td>
<td></td>
</tr>
</tbody>
</table>

Always: 10 GV < cutoff < 11
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)
Solar modulation

Interstellar spectrum

Decreasing solar activity

Increasing GCR flux

Ground neutron monitor

PAMELA

Solar modulation

(Continent errors on y)

Cosmic rays variations (%).

kinetic energy (GeV)

July 2006
August 2007
February 2008

Decreasing solar activity

Increasing GCR flux

Ground neutron monitor

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sun-spot number

Cycle 22
Cycle 23


2008

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December 2006 CME/SEP events

Coronal Mass Ejection (CME)

X-ray flares

Solar Energetic Particles (SEPs)

GOES Space Environment Monitor

protons: 1÷100 MeV

alphas: 150÷500 MeV
December 13\textsuperscript{th} 2006 SEP event

Solar quiet spectrum

SEPs accelerated during CMEs

SEP spectral shape and time evolution

⇒ study of particle acceleration mechanisms in CME

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Proton flux \* E^{2.75}

- Proton of primary origin
- Diffusive shock-wave acceleration in SNRs
- Local spectrum: 
  injection spectrum \( \otimes \) galactic propagation

Local primary spectral shape:
\[ N_p \propto Q_p \lambda_{\text{esc}} \]
\( \Rightarrow \) study of particle acceleration mechanism

Power-law fit: \( \sim E^{-\gamma} \)
\( \gamma \sim 2.76 \)
Proton flux $\propto E^{2.75}$

- Proton of primary origin
- Diffusive shock-wave acceleration in SNRs
- Local spectrum: injection spectrum $\otimes$ galactic propagation
- Local primary spectral shape: study of particle acceleration mechanism

NBI: still large discrepancies among different primary flux measurements

- Power-law fit: $\gamma \approx 2.76$
- Statistical errors only

\[ N_p \propto Q_p \Lambda_{\text{esc}} \]

LBM
Secondary nuclei

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

**Local secondary abundance:**

⇒ study of galactic CR propagation

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

The main difficulty for the antiproton measurement is the \textit{spillover proton bk} @ high energy:

\rightarrow finite deflection resolution of the spectrometer
\rightarrow p/p-bar $\sim 10^4$ !!
High-energy antiproton selection

MDR depends on:
- number and distribution of fitted points along the trajectory
- spatial resolution of the single position measurements
- magnetic field intensity along the trajectory

\[
M_{\text{DR}} = \frac{1}{\sigma_\eta}
\]

(evaluated event-by-event by the fitting routine)

\[ R < \frac{\text{MDR}}{10} \]

\( p \bar{p} \)

\( 10 \text{ GV} \)

\( 50 \text{ GV} \)

\( \text{p-bar} \)

“spillover” \( p \)

\( p \)
Antiproton-to-proton ratio

(statistical errors only)
Antiproton-to-proton ratio

(statistical errors only)

Preliminary!!

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Antiproton-to-proton ratio

(statistical errors only)

(10^4, 10^5, 10^6, 10^7, 10^8)

kinetic energy (GeV)

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Preliminary!!
Positron identification

The main difficulty for the positron measurement is the interacting-proton background:
- fluctuations in hadronic shower development ⇒ $\pi_0 \rightarrow \gamma \gamma$ might mimic pure em showers
- proton spectrum harder than positron ⇒ $p/e^+$ increase for increasing energy
Proton background suppression

Z=-1

Rigidity: 20-30 GV

\( e^- \)

p-bar (int)

p-bar (non-int)

Z=+1

p (int)

p (non-int)

\( (e^+) \)

Fraction of charge released along the calorimeter track (left, hit, right)
Proton background suppression

Fraction of charge released along the calorimeter track (left, hit, right)

Energy-momentum match

Rigidity: 20-30 GV

Constraints on:

Z=-1

Z=+1
Proton background suppression

Rigidity: 20-30 GV

Fraction of charge released along the calorimeter track (left, hit, right)

Constraints on:
- Energy-momentum match
- Shower starting-point
- Longitudinal profile

\[ Z = -1 \]

\[ Z = +1 \]
Proton background evaluation

Rigidity: 6-8 GV

Fraction of charge released along the calorimeter track (left, hit, right)

Constraints on:
- Energy-momentum match
- Shower starting-point
- Longitudinal profile

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Positron charge ratio

statistical errors only
energy in the spectrometer

PAMELA Results

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Charge dependent solar modulation

Drift Model

Clem J. & Evenson 2007

PAMELA Results

--- Clem 1995
--- Bibier 1999

Positive particles

A > 0
A < 0
High-energy positrons

statistical errors only
ergy in the spectrometer

Pulsars
LSP (Neutralino) annihilation
(Strong-Moskalenko-Ptuskin 2007)

Contribution from pulsars
Contribution from WIMP annihilation in the galactic halo

\[ \text{Charge ratio } \left( \frac{e^+}{e^+ + e^-} \right) \]

\[ \text{Positron fraction } \left[ e^+(e^+ + e^-) \right] \]

\[ 10^6 \quad 10^7 \]

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

\[ \text{Energy (GeV)} \]

\[ \text{Moskalenko & Strong 1998} \]

\[ \text{PAMELA Result} \]

\[ \text{Propagation} \]
\[ \text{Possible pulsars} \]
\[ \text{Dark matter annihilations} \]
\[ \text{CAPRICE94} \]
\[ \text{Golden (1993)} \]
\[ \text{AMS01 (1998)} \]
\[ \text{HEAT combined (1994, 1995, 2000)} \]

\[ \text{HEAT00} \]
\[ \text{AMS} \]
\[ \text{CAPRICE94} \]
\[ \text{HEAT94+95} \]
\[ \text{TS93} \]
\[ \text{MASS89} \]
\[ \text{Muller & Tang 1987} \]

\[ \star \text{ Elena Vannuccini } \star \text{ SSI 2008 } \star \]
Conclusions

• PAMELA is taking data since July 2006
• (lot of fun analyzing the data!)
• Presented preliminary results from ~600 days of data:
  → Antiproton charge ratio (~100 MeV ÷100 GeV)
    → no evident deviations from secondary expectations
    → more high energy data to come (up to ~150 GeV)
  → Positron charge ratio (~400 MeV ÷10 GeV)
    → indicates charge dependent modulation effects
    → more data to come at lower and higher energies (up to ~200 GeV)
  → Galactic primary proton spectra
    → primary spectra up to Z=8 to come
  → Galactic secondary-to-primary ratio (B/C)
    → abundance of other secondary elements (Li,Be) and isotopes (d,³He) to come
  → High energy tail of proton SEP events
    → spectra of other components (electrons, isotopes,...) to come

→ PAMELA is providing significant experimental results, which will help in understanding CR origin and propagation

Many thanks to all my colleagues for providing me the material for the presentation!

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