Recent results and perspectives on cosmic ray matter and antimatter from Pamela experiment

M. Casolino
INFN & University of Roma Tor Vergata

on behalf of the PAMELA collaboration
PAMELA Collaboration

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

Russia:
- Moscow
- St. Petersburg

Germany:
- Siegen

Sweden:
- KTH, Stockholm

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Past, present and future experiment

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

NINA-1

NINA-2

PAMELA

SIRAD
Sileye-3/Alteino on ISS (Russian)
Altea on ISS (US section)
High precision charged cosmic ray measurement in Low Earth Orbit
Coupling to Soyuz

Pamela during integration in Baikonur

Resurs DK integrated
Gagarinsky Start

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Launch on June 15th 2006  Soyuz-U rocket
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)

RESURS DK1 SATELLITE (6.65T)
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>
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<td>150 x 60</td>
<td>7</td>
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<td>S32</td>
<td>3</td>
<td>180 x 50</td>
<td>7</td>
<td>350</td>
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</table>

Adapted from W. Menn for Vergata
The permanent magnet

- 5 magnetic modules
- Permanent magnet (Nd-Fe-B alloy) assembled in an aluminum mechanics
- Magnetic cavity sizes (132 x 162) mm\(^2\) 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: \(20.5\) cm\(^2\)sr
- Black IR absorbing painting
- Magnetic shields

Adapted from E. Vannuccini ........................................................... ICRC 2005 - 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)
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
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 cm$^2$ sr)
  - Mass: 110 kg
  - Power Consumption: 48 W

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

*Adapted from V. Bonvicini*
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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 $E<1$MeV)
- Triggered counts
- Background counting

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e+ 0.171 GV  Bending view

e- 0.169 GV  Bending view
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
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14.7 GV
Interacting nucleus
(Z = 8)
Pamela as a Space observatory at 1AU

High Inclination Orbit 70.0°

Galactic cosmic ray Matter / Antimatter / Dark Matter

Interplanetary Physics, Solar Wind Termination Shock

SAA, Albedo, secondary particle

Solar Energetic particles

Solar Modulation

Magnetospheric physics
The geomagnetic field is an extremely powerful tool to select particle of different origin and nature and study in situ MHD phenomena.
Pamela
Measurement of the radiation belts

2008 M. Casolino
Selection of galactic component according to geomagnetic cutoff

\[ R_{\text{cutoff}} = 14.9 \text{GV/L}^2 \]

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Particle rigidity vs Vertical Stormer Cutoff

Galactic positive (above cutoff)  
\( e^+ p \)

\( \beta \)

\( \text{rig:14.9/L}^2: \text{abs(beta)} \{ \text{rig!=0. && abs(rig)<20 && beta!=100.} \} \)

\( \text{Rig=_cutoff} \)

\( \text{saa} \)

\( \text{sub_cutoff} \)

\( e^- p^- \)
Particle identification: basic principle

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

\[ \pi^+ e^+ \]

\[ p \]

\[ ^4\text{He} + d \]

Beta = \( \frac{v}{c} \) (from TOF)

Rigidity (from Tracker)

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Proton Absolute flux

- Montecarlo efficiency for cuts
- Trigger efficiency
- Tracking efficiency
- Multiple Scattering
- Back scattering...
- Systematics under close investigation, currently 10% uncertainty on abs flux.
  To be reduced to less than 5%

Selection criteria
- Fitted, single track
- High lever arm
- Rigidity R>0
- Beta>.2
- No anti

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Solar Modulation of Galactic Cosmic Rays

- Balloon: low frequency modulation
- Pamela: low and high frequency modulation
- Long solar minimum
- Variation in Galactic flux
  - Short Term (months)
  - Long term (years)
- Charge dependence
  (e.g. Asaoka Y. et al. 2002, Phys. Rev. Lett. 88, 051101)

\[
J(r, E, t) = \frac{E^2 - E_0^2}{(E^2 + \Phi(t))^2 - E_0^2} J(\infty, E + \Phi(t))
\]

Dati meteor 0.03 GV 0.6 GV, Stozkov 2008
Solar modulation at minimum of solar cycle XXIII years 2006-2008

\[ F_{is} = 1.54 \beta_{is}^{0.7} R_{is}^{-2.76} \]
\[ p/(cm^2 \ s \ sr \ GV) \]

Spectral index \[ 2.76 \pm 0.01 \]

\[ J(r,E,t) = \frac{E^2 - E_0^2}{(E^2 + \Phi(t))^2 - E_0^2} J(\infty,E + \Phi(t)) \]

Solar modulation parameters
\[ \phi(GV) \quad \text{error} \]
JUL06 5.01-01 ± 2e-03
JAN07 4.16-01 ± 2-03
AUG07 4.02-01 ± 3-03
Comparison Pamela – AMS-Bess

--Ams98
--Bess98
--Bess97
Comparison Pamela –AMS-Bess

--Ams98
--Bess98
--Bess97
--PAMJul06
Comparison Pamela –AMS-Bess

--Ams98
--Bess98
--Bess97
--PAMJul06
--PAMAug07
Comparison Pamela –AMS-Bess

--Ams98
--Bess98
--Bess97
--PAMJul06
--PAMAug07
--PAMFeb08
Solar modulation at minimum of solar cycle XXIII years 2006-2008

\[ F_{is} = 1.54 \beta_{is}^{0.7} R_{is}^{-2.76} \text{ p/(cm}^2\text{ s sr GV)} \]

Spectral index \(2.76 \pm 0.01\)

\[ J(r, E, t) = \frac{E^2 - E_0^2}{(E^2 + \Phi(t))^2 - E_0^2} J(\infty, E + \Phi(t)) \]

Solar modulation parameters \(\phi(GV)\) error

- JUL06 5.01-01 ± 2e-03
- JAN07 4.16-01 ± 2-03
- AUG07 4.02-01 ± 3-03
Trapped proton flux in the Van Allen belt (South Atlantic Anomaly)

Integral Pamela flux
(E>35 MeV)
(PSB97 plot by SPENVIS project, model by BIRA-IASB)

\[ \Phi = A E^{-(\gamma_0 + \gamma_1 E)} \]

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Trapped

<table>
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<tr>
<th>Color</th>
<th>Region</th>
<th>Flux (cm(^{-2}) sr GeV/s)</th>
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<td>Yellow 0.22 G &lt; B &lt; 0.23 G</td>
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<tr>
<td>Yellow</td>
<td>0.21 G &lt; B &lt; 0.22 G</td>
<td>Green 0.20 G &lt; B &lt; 0.21 G</td>
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<tr>
<td>Blue</td>
<td>0.20 G &lt; B &lt; 0.21 G</td>
<td>Red   0.19 G &lt; B &lt; 0.20 G</td>
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<tr>
<td>Red</td>
<td>0.19 G &lt; B &lt; 0.20 G</td>
<td>Black B&lt;0.19 G</td>
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<tr>
<td>Black</td>
<td>B&lt;0.19 G</td>
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\[ \chi^2/\text{ndf} \]

<table>
<thead>
<tr>
<th>Color</th>
<th>A</th>
<th>(\gamma_0)</th>
<th>(\gamma_1)</th>
<th>(\chi^2/\text{ndf})</th>
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<td>nero</td>
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<td>6.0±0.4</td>
<td>3.1±0.5</td>
<td>7.1</td>
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<tr>
<td>rosso</td>
<td>(2.3±0.3) 10(^{-2})</td>
<td>5.9±0.5</td>
<td>2.6±0.6</td>
<td>6.8</td>
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<tr>
<td>verde</td>
<td>(5±3) 10(^{-4})</td>
<td>8.1±1.8</td>
<td>4.7±1.8</td>
<td>10.</td>
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Arxiv 0810.4980v1
Comparison with theoretical model of inner rad belt

R. S. Selesnick, M. D. Looper, and R. A. Mewaldt
Comparison with theoretical model of inner rad belt

R. S. Selesnick, M. D. Looper, and R. A. Mewaldt
Primary (galactic) spectra: polar measurements

Galactic protons

RED: JULY 2006
BLUE: AUGUST 2007
Primary and secondary spectra: Intermediate latitudes

P/(cm^2 sr GeV s)

Penumbra

Secondary particles (reentrant albedo)

RED: JULY 2006
BLUE: AUGUST 2007

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Primary and secondary spectra: Magnetic equator

\[ P/(\text{cm}^2 \text{ sr GeV s}) \]

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M. Honda, 2008

RED: JULY 2006
BLUE: AUGUST 2007
Proton flux at various cutoffs

- Atmospheric neutrino contribution
- Astronaut dose on board International Space Station
- Indirect measurement of cross section in the atmosphere
- Agile e Glast background estimation

- Lipari, Astrop. Ph. 14, 171, 2000
- Huang et al, Pys Rev. D 68, 053008 2003
- Sanuki et al, Phys Rev D75 043005 2007
- Honda et al, Phys Rev D75 043006 2007

Arxiv 0810.4980v1
Solar Particle events  13-14/12/06 – GLE 70
Moreton Wave, Dec 6th 2006 (from Ed Cliver)

OSPAN  H-alpha (656.3 nm) - AR 10930
December 13th  2006 event

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Preliminary!
Discrimination between acceleration processes

• Shock accel. \( E^{-a} \exp(E/E_0) \)

• Stochastic Fermi accel.

Impulsive events

Exp in Rigid/Kinene Bessel function,

• Direct Acceleration in magnetic reconnection

Arxiv 0810.4980v1
Boron is a secondary particle. Its abundance is relevant for propagation in the Galaxy.

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**Matter in the Universe**

**Microwave Anisotropy**

**WMAP - NASA - Explorer Mission**

\[ \Omega_{\text{total}} = \frac{\rho_{\text{total}}}{\rho_{\text{crit.}}} = 1 \]

(Universe is flat)

\[ \rho_{\text{crit.}} = \frac{3H^2(t)}{8\pi G} \]

\[ \Omega_{\text{total}} = \Omega_{\text{total, baryon.}} + \Omega_{\text{dyn.}} + \Omega_{\text{required}} \]

- **baryonic matter**
  - 4%
  - stars, galaxies

- **dark matter**
  - 23%
  - candidates:
    - WIMPs
    - Q-balls
    - axions
    - Kaluza-Klein-part.

- **dark energy**
  - 73%
  - quintessence

Adapted from M. Boezio, P. Picozza
Supersymmetry:

Neutralino as Dark Matter candidate

can not decay but can annihilate
**Another possible scenario:**

**KK Dark Matter**

Lightest Kaluza-Klein Particle (LKP): $B^{(1)}$

Bosonic Dark Matter:
- fermionic final states no longer helicity suppressed.
- $e^+e^-$ final states directly produced.

As in the neutralino case there are 1-loop processes that produces monoenergetic $\gamma \gamma$ in the final state.

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*From P. Picozza*
Dark Matter Searches

• Cosmology
  Detection, not identification

• LHC Search
  Supersymmetry, not necessarily DM

• Direct Detection
  Local structure and nature

• Indirect Detection
  Various galactic scales

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Dark matter search in cosmic ray antiparticles

Only secondary production in the galaxy e.g.: \( p_{CR} + p_{ISM} \rightarrow \bar{p} + p + p + p \)

Depends on propagation in the galaxy

Background – free channel to study rare phenomena such as Dark matter decay
Calorimeter Selection Criteria for Antiprotons

From M. Boezio
**Alignment**

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

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From E. Vannuccini, P. Papini
Deflection

$$D = \frac{1}{R}$$

Very sharp and conservative cuts
Maximum lever (top and bottom planes of the spectrometer must be hit)
arm in magnet to keep spillover under control
Then release this criterium

Antiprotons

Protons

-50 GV  +50 GV

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Proton spillover background

Minimal track requirements

Strong track requirements:
• strict constraints on \( \chi^2 \) (~75% efficiency)
• rejected tracks with low-resolution clusters along the trajectory
  - faulty strips (high noise)
  - \( \delta \)-rays (high signal and multiplicity)

From O. Adriani
High-energy antiproton selection

From O. Adriani
High-energy antiproton selection

From O. Adriani
Antiproton-Proton Ratio

Why Ratios?

Reduce systematic error
All (most) efficiencies cancel out

Subsequently absolute fluxes
Antiproton ratio measured with Pamela: Comparison with theoretical models

Released data 1-100 GeV
Currently roughly 10 TB of data
As of March ’08
Out of 8.8 TB
• $10^7$ p
• $800$ p$^-$

Accepted - PRL
Antiproton ratio measured with Pamela: Comparison with experimental data

• Highest energy up to now
• Coherent with secondary production
• Uncertainties of Galactic Propagation
• Would favour Moskalenko 2002 (except highest energy)

Accepted - PRL
Positrons results

• Till August 30th about 20000 positrons from 200 MeV up to 200 GeV have been analyzed

• More than 15000 positrons over 1 GeV

• Other eight months data to be analyzed
• Selection criteria based on calorimeter
• Tuned and tested with
  – Montecarlo
  – Test Beam
  – In flight data
  – Cross-checked with Neutron Detector

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**Preshower Technique to reduce systematics of proton contamination:**

*Optimize electromagnetic/hadronic shower discrimination, reduce systematics*

**Protons:**
- Non Interacting
- Interacting

**Electrons / Positrons**
- Interacting (e.m.)

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*Recipe: M. Boezio, E. Mocchiutti*
**Preshower Technique to reduce systematics of proton contamination:**

1. Take straight track in SmallTop $\rightarrow$ Select Protons
   Take interacting protons in BigBottom
   *known sample of hadronic shower. No leptons*

2. Define cuts (energy/topology) on 40 layers
   Using “BigTop” for e.m. showers (electrons)
   “BigBottom” for hadronic showers (protons)

3. Apply cuts to the positron sample

4. Apply cuts to electron sample to estimate efficiency

---

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Positron selection with calorimeter

Rigidity: 20-30 GV

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

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From P. Picozza, M. Boezio, E. Vannuccini
Positron selection with calorimeter

Rigidity: 20-30 GV

Fraction of charge released along the calorimeter track (left, hit, right) + Energy-momentum match

From P. Picozza, M. Boezio, E. Vannuccini
Positron selection with calorimeter

Rigidity: 20-30 GV

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

- Energy-momentum match
- Starting point of shower
- Longitudinal profile

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From P. Picozza, M. Boezio, E. Vannuccini
Positron selection – independent selection/check with ND

Rigidity: 20-30 GV

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

Neutrons detected by ND

• Energy-momentum match
• Starting point of shower

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Status of Positron - Electron ratio
Status of Positron - Electron ratio

Secondary production
‘Leaky box model’ (Protheroe 1982)

Secondary production
‘Moskalenko + Strong model’ (1998) without reacceleration

Primary production from $\chi\chi$ annihilation ($m(\chi) = 336$ GeV)

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Pamela e+ results

- Till August 30th about 20000 positrons from 200 MeV up to 200 GeV have been analyzed

- More than 15000 positrons over 1 GeV

- Other eight months data to be analyzed


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*Accepted on Nature*
Pamela e+ results


Accepted on Nature

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Comparison with solar cycle – low energy

$qA<0$ measurements (now, 22 years ago)

Solar modulation up to 10 GeV
Comparison with solar cycle

$qA > 0$ measurements

(11 years ago)
Low energy positrons

- Charge dependent solar modulation
- Separate $qA>0$ with $qA<0$ solar cycles
- Evident in the proton flux
- Observed in the antiproton channel by BESS
- Full 3D solution of the Parker equation – drift term depends on sign of the charge
Charge dependent solar modulation

Clem et al.
30th ICRC 2007
High energy nearby Pulsar contribution?

C. Grimani A&A 474, 2, November I 2007, pp.339-343

Potgieter at al.
arXiv:0804.0220v1
ATIC results on all electron flux at 300-500 GeV

- No separation between electrons and positrons
- Requires high boost factor
- Glast?

*Nature*, 456, 362
20 November 2008
doi:10.1038/nature07477

M. Casolino, INFN & University Roma Tor Vergata
• Pamela is operating successfully in space

• Expected three years of operations – completed more than 1000 days

• Data received until now show good potential and fulfillment of scientific goals

http://pamela.roma2.infn.it

http://www.casolino.it