12 years of direct cosmic ray measurements with PAMELA

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PAMELA instrument

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

**Spectrometer**
- microstrip Si track sys
  - Rigidity \( R = \frac{p c}{Z e} \)
  - Charge sign
  - Charge value from dE/dx
  + permanent magnet

**Electromag .calorimeter**
- W/Si samp (16.3 \( X_0 \), 0.6 \( \lambda, \))
  - Discrimination \( e^+ / p, \)
  - anti-\( p / e^- \) (shower topology)
  - Direct E measurement for \( e^- \)

**Neutron detector**
- \(^3\)He tubes + PMT:
  - High-energy e/h discrimination
PAMELA orbit

- Quasi polar and elliptical orbit
- Inclination \( \sim 70^\circ \)
- Altitude \( \sim 300 - 600 \) km
- From 2010 circular orbit
- Data-taking 2006-2016

Resurs-DK1
Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m\(^2\)
Absolute fluxes of primary and secondary GCRs

- Antimatter
- Protons & Heliums
- Electrons
- Light Secondary Nuclei
## Published results

### Antimatter
- p-bar fraction
- e+ fraction
- e+ fraction
- p-bar
- e+
- e+ anisotropies

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<thead>
<tr>
<th>Component</th>
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<tbody>
<tr>
<td>p-bar</td>
<td>PRL 102 (2009)</td>
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### Electrons
- e-
- e- variation jul-2006/dec-2009

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### Nuclear component
- H&He
- H variation jul-2006/dec-2009
- B&C
- H&He isotopes
- Li&Be isotopes

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<td>H&amp;He</td>
<td>Science 332 (2011)</td>
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PAMELA positron fraction

June 2006 – February 2008 – 500 days

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

- High energy: first clear evidence of increasing positron fraction above 10 GeV with respect to pure secondary production;
- Low energy: charge-dependent solar modulation

Secondary production: Moskalenko & Strong 98
Good agreement with AMS02!
PAMELA positrons

June 2006 – December 2009 – 24500 positrons

Results confirmed by AMS02!
Adriani, O et al., PRL 102, 051101 (2009)

Adriani, O et al., 105, 121101 (2010)

Consistent with secondary production models

Secondary production calculations
Comparison with AMS02/BESS

Very good agreement!


Very good agreement!
PAMELA H, He and H/He spectra

- First high-statistics and high-precision measurement over three decades in energy
- Deviations from single power law (SPL):
  - Spectra gradually soften in the range 30 ÷ 230GV
  - Spectral hardening @ R~235GV $\Delta\gamma$~0.2 ÷ 0.3
  - SPL is rejected at 98% CL
- Origin of the hardening?
- (e.g. see P. Blasi, Braz.J.Phys. 44 (2014) 426)
- At the sources: multi-populations, etc.?
- Propagation effects?

O. Adriani et al., Science 332 (2011) 6025
Results confirmed by AMS02: protons

PAMELA data → Jul 2006 ÷ Mar 2008
AMS02 data → May 2011 ÷ Nov 2013


M. Aguilar et al., PRL 114 (2015) 171103
Results confirmed by AMS02: helium

PAMELA data → Jul 2006 ÷ Mar 2008
AMS02 data → May 2011 ÷ Nov 2013


O. Adriani et al., Science 332 (2011) 6025
M. Aguilar et al., PRL 115 (2015) 211101
Solar modulation


O. Adriani et al., PRL 111, 081102 (2013)
Li, Be, B are produced by fragmentation of heavier nuclei, mostly C, N, O, on H and He.


\[
\frac{B}{C} = \frac{\text{Sec/Prim}}{\text{Prim}}
\]

\[
\sim \frac{Q_{\text{sec}}(E)}{Q_{\text{prim}}(E)}
\]

\[
\sim \frac{Q_{\text{prim}}(E)}{D(E)} / Q_{\text{prim}}(E)
\]

\[
\sim 1/D(E)
\]

Diffusion coefficient: \( D(R) = D_0 \beta R^\delta \)
In general, good agreement with Galprop simulations. Better for Be, worse for Li at high energies, but models suffer from unprecise cross-sections (especially for tertiary origin).

CRs in the heliosphere and magnetosphere

LONG-TERM CR-FLUX VARIATION

SOLAR-PARTICLE EVENTS (SEPS)

TRAPPED AND RE-ENTRANDED ALBEDO PARTICLES
Published results

- **Solar modulation**
  - Latitudinal and radial gradients (PAMELA and Ulysses) ASSTRA (2011)
  - Positron/electron charge ratio 2006/2015 PRL 116 (2016)

- **SEP events**

- **Geomagnetic effects**
  - Quasi-trapped electrons and positrons JGR (2009)
  - Trapped antiproton fluxes ApJL (2011)
  - Reentrant albedo proton fluxes JGR (2015)
  - Geomagnetic cutoff variations Space Weather (2016)
PAMELA observations (2006-2016)

Neutron Monitor counts data from http://cosmicrays.oulu.fi/

PAMELA observations covers about one solar cycle
Time Dependence of the $\rho$ flux


Minimum

Maximum

Minimum

Maximum

Normalized Count Rate

Normalized Count Rate

Time [year]
Time Dependence of the $He$ flux

- Preliminary

Helium flux ($m^2 \cdot sr^{-1} \cdot s^{-1} \cdot GeV^{-1}$)

- Minimum
- Maximum

Kinetic energy ($GeV/n$)

Normalized Count Rate

- OULU Neutron monitor (Norm to 2006)
- PAMELA Trigger Rate (Norm to 2006)
Time Dependence of the $e^-$ flux


Evolution of the electron ($e^-$) energy spectrum from July 2006 to December 2009

The ratios between the measured $e^-$ fluxes from January 2007 till December 2009 and the measured fluxes for the period July-November 2006 with the corresponding computed spectra.
The positron to electron ratio measured in this time period clearly shows a sign-charge dependence of the solar modulation introduced by particle drifts.
Time Dependance of the $e^-/e^+$ flux

polarity reversal of the HMF

- PAMELA 0.5 GeV - 1.0 GeV
- PAMELA 1.0 GeV - 2.5 GeV
- PAMELA 2.5 GeV - 5.0 GeV

O. Adriani et al., PRL 116, 241105 (2016)
Time Dependance of the $e^-/e^+$ flux

polarity reversal of the HMF

O. Adriani et al., PRL 116, 241105 (2016)
Solar Energetic Particles (SEP)

Sun can accelerate particles up to relativistic energies
- Magnetic reconnections
- CME-driven shock

SEPs can be observed in the interplanetary space

Often associated to other solar phenomena, eg:
- X and gamma-ray flares
- Coronal-mass ejections (CMEs)
- ...

SEP observation on Earth:
- Propagation of SEPs along IMF lines
  ⇒ Earth must be magnetically connected
- Anisotropic emission
  ⇒ flux observed on Earth depends on geomagnetic location
Consistent with diffusive shock acceleration theories, the measured SEP spectra are well reproduced by a power-law modulated by an exponential cutoff attributed to particles escaping the CME-driven shock during acceleration. Cutoff energies fall above and below the GLE threshold (~1 GV). Three GLEs are among the group, but also some events falling above 1 GV that were not registered as GLEs, but might have.

From the spectrum perspective, we see no qualitative distinction between those events that are GLEs, those that could be, or those that are not.
The proton and the helium amplitude and recovery time are in good agreement while electrons on average shows a faster recovery. This could be interpreted as a charge-sign dependence due to the different global drift pattern between proton and electrons.
PAMELA science output

> 200 REFEREED ARTICLES
  (2001 – 2018)

> 6700 CITATIONS
Review papers:

PAMELA additional talks & posters at this conference

**TALKS**
- **Reconstruction of solar modulation potential from the new PAMELA data and comparison with neutron monitors** (S. Koldobsky)
- **Li and Be in the PAMELA experiment from flight data 2006-2014** (E. Bogomolov)

**POSTERS**
- **The cosmic ray electron and positron anisotropy study with the PAMELA calorimeter** (A. Karelin - ANI146)
- **The galactic cosmic ray electrons and positrons over decade with the PAMELA experiment** (V. Mikhailov – CRD225)
- **Observations of trapped electrons and positrons with $E > 50$ MeV in the inner radiation belt by the PAMELA magnetic spectrometer** (V. Mikhailov – CRD167)
- **Solar modulation of GCR deuterons measured by the PAMELA experiment** (S. Koldobsky - CRD173)
- **2H and 3He isotopes in solar flashes from the PAMELA data 2006-2014** (E. Bogomolov - SH121)
- **Method of determination of the neutron monitor OULU response using the analysis of 27-days variations obtained in PAMELA experiment** (S. Rodenko – SH266)
- **The development of Solar neutron search method with PAMELA neutron detector** (S. Voronov – SH263)
- **The study of 27-days variations of GCR flux based on PAMELA measurements** (S. Rodenko – SH127)
- **Relationship between 27-day variations of galactic cosmic ray intensity measured by PAMELA and heliospheric parameters** (R. Modzelewska – SH270)
- **Proton flux in the Earth magnetosphere based on PAMELA experiment data** (T. Zharaspayev - CR 150)