Results from PAMELA

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~500 km
Smaller detectors but long duration.
PAMELA!

~5 km

Top of atmosphere

Primary cosmic ray

~40 km
Large detectors but short duration. Atmospheric overburden ~5 g/cm².
All previous data on cosmic antiparticles from here.

Discovery!
Victor Hess, 5 km, 1912
PAMELA Collaboration

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

Germany
- Siegen

Sweden
- KTH, Stockholm

Russia
- Moscow
- St. Petersburg
Resurs-DK1 satellite + orbit

- **Resurs-DK1**: multi-spectral imaging of earth’s surface
- **PAMELA mounted inside a pressurized container**

- **Quasi-polar and elliptical orbit**
  \(70.0^\circ, 350 \text{ km} - 600 \text{ km}\)

- Data transmitted to NTsOMZ, Moscow via high-speed radio downlink.
  ~15 GB per day

- **As of ~now:**
  - ~1130 days of data taking (~73% live-time)
  - ~15 TByte of raw data downlinked
  - >10^9 triggers recorded and under analysis

**Resurs-DK1**
- Mass: 6.7 tonnes
- Height: 7.4 m
- Solar array area: 36 m^2

**PAMELA**

Launched: June 15th 2006

[Image of the launch and satellite]
Electron energy, dE/dx, lepton-hadron separation
- 44 ‘Si-x / W / Si-y’ planes (380 μm)
- 16.3 X₀ / 0.6 λₗ
- dE/E ~5.5% (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm²sr

Lepton-hadron separation
- 36³He counters
- ³He(n,p)T; Eₚ = 780 keV
- 1 cm thick poly + Cd moderator
- 200 μs collection time

Sign of charge, rigidity, dE/dx
- Permanent magnet, 0.43 T - 21.5 cm²sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view ⇒ MDR
  ~ 1000 GV (6 plane) ~600 GV (5 plane)

Trigger, ToF, dE/dx
- Plastic scintillator (8 mm) + PMT
- ToF resolution ~300 ps (S1-3 ToF > 3 ns)
- lepton-hadron separation < 1 GeV/c

Scientific goals

• Search for dark matter particle annihilations

• Search for antihelium (primordial antimatter)
• Search for exotic matter (e.g. strangelets...)

• Study of cosmic-ray propagation (light nuclei and isotopes)
• Study of electron spectrum (local sources)

• Study solar physics and solar modulation
• Study terrestrial magnetosphere
Indirect detection of dark matter

Signal

μ, e⁻

PAMELA

You are here

μ, e⁻

Dark Matter

Background

p, e⁺

Majorana

e.g. supersymmetric neutralino, $\chi$

Dirac

e.g. lightest Kaluza-Klein particle from Universal Extra Dimension models

‘Milky Way’
High energy antiproton analysis

- Data-set: July 2006 – February 2008 (~500 days)
- Collected triggers ~$10^8$
- Identified ~$10 \times 10^6$ protons and ~$1 \times 10^3$ antiprotons between 1.5 and 100 GeV (100 antiprotons above 20 GeV)

**Antiproton/proton identification:**
- Rigidity (R) from *spectrometer*
- Select $|Z|=1$ ($dE/dx$ vs- R), *spectrometer + ToF*
- $\beta$-vs- R consistent with proton mass, *ToF*
- antiproton/p separation (sign-of-charge, *spectrometer*)
- antiproton/e$^-$ (and p/e$^+$) separation from *calorimeter*

- Dominant background - *spillover protons.*
  - Finite deflection resolution of spectrometer - wrong assignment of sign-of-charge at high energy

Antiproton (NB: e$^-$/p $\sim 10^2$)
Antiproton identification

proton-consistency cuts
\((dE/dx -vs- R \text{ and } \beta -vs- R)\)

electron rejection cuts based on calorimeter interaction topology

antiprotons

"spillover" p

\((-1) \leftrightarrow Z \rightarrow +1\)
**Selected antiprotons**

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

- Ultimate spillover limit for antiprotons expected to be ~200 GeV.
Antiproton-to-proton flux ratio

\( \frac{\bar{p}}{p} \approx 5 \text{ g/cm}^2 \)

t \approx 24 \text{ h}
Antiproton-to-proton flux ratio

* preliminary *

P. Hofverberg,
KTH PhD Thesis

Phys. Rev. Lett. 102, 051101
(2nd Feb. 2009)
Secondary production models

$\frac{\vec{p}}{p}$ vs kinetic energy (GeV)

- Donato 2001 (DRC, $\phi=500\text{MV}$)
- Moskalenko 2002 ($\Lambda<0, \alpha=15'$)
- Ptuskin 2006 (PD, $\phi=550\text{MV}$)
- Donato 2001 (DRC, $\phi=500\text{MV}$)

* preliminary *

P. Hofverberg,
KTH PhD Thesis

Phys. Rev. Lett. 102, 051101
(2nd Feb. 2009)
Antiproton-to-proton flux ratio

New! (preliminary)

Spillover limit
Antiproton flux

Preliminary
High energy positron analysis

- Data-set: July 2006 – February 2008 (~500 days)
- Collected triggers \( \sim 10^8 \)
- Identified \( \sim 150 \times 10^3 \) electrons and \( \sim 9 \times 10^3 \) positrons between 1.5 and 100 GeV (180 positrons above 20 GeV)

### Electron/positron identification:
- R rigidity from spectrometer
- \(|Z|=1\) \((dE/dx=MIP)\) - spectrometer and ToF
- \(\beta=1\) - ToF
- \(e^-/e^+\) separation (sign-of-charge) - spectrometer
- \(e^+/p\) (and \(e^-/\text{antiproton}\)) separation - calorimeter

- Dominant background - **interacting protons**.
Rigidity: 20-30 GV

Fraction of charge released along the calorimeter track (left/hit/right): ~0.6 \( R_m \)

Energy - momentum match

Starting point, lateral / longitudinal profile

NB: background determined from data
Cross-check: neutron yield

Rigidity: 42-65 GV

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

Neutrons detected by ND

- Energy-momentum match
- Starting point of shower
Pre-PAMELA positron fraction
PAMELA positron fraction


![Diagram showing positron fraction vs energy with solar modulation indicated.](image-url)
Secondary production expectation

Nature 458 (2009) 607
Quite a difference between antiproton and positron results!

A smörgåsbord of papers have offered interpretations

The majority focus on dark matter, e.g. L. Bergström, arXiv:0903.4849 (30 March 2009):

DM interpretation of positron excess

- ‘Leptophilic’ decays are favoured.
- Sharp rise! DM annihilation spectrum from SUSY is too soft (qq or WW dominant final states).
- The required DM annihilation rate is much higher ($\times 10^{2-3}$) than predicted for a thermal relic from Big Bang.
  - Inhomogeneous DM distribution?
  - Enhanced $\sigma_{\text{ann.}}$, e.g. Sommerfeld effect?

**NB:** model builders must not overproduce antiprotons (or gammas)
**Dark Matter examples**

**Majorana DM** with new internal bremsstrahlung correction. **NB:** requires annihilation cross-section to be ‘boosted’ by >1000. *Does not affect antiproton fluxes, but would give large gamma-ray excess around WIMP mass (Fermi)!*

**Hooper and Zurek**  
*arXiv:0902.0593*

- Propose a new light boson \(m_\Phi \leq \text{GeV}\), such that \(\chi \chi \to \Phi \Phi\); \(\Phi \to e^+e^-, \mu^+\mu^-, \ldots\)
- Light boson, so decays to antiprotons are kinematically suppressed. **Leptophilic!**

**Kaluza-Klein dark matter**

**Cholis et al., arXiv:0810.5344**
An astrophysical explanation?

• Dark matter provides a spectacular solution to the rising positron fraction

• However, **pulsars** offer a standard astrophysical solution...

• Strong spinning $\mathbf{B} \rightarrow$ accelerated electrons $\rightarrow$ synchrotron emission $\rightarrow$ electromagnetic showers produced in pulsar magnetosphere $\rightarrow e^+$

• Efficient energy loss from synchrotron and inverse Compton energy losses, so source must be ‘close’ (< few kpc) and ‘young’ (~$10^5$ years)

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... and Fermi is updating the catalogue!

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**Already considered 20 years ago!**
Pulsar examples

Geminga (d $\sim$ 250 $^{+250}_{-62}$ pc)

- Different distance, age and pulsar energy considered

Fit to Fermi and PAMELA data with known (ATNF catalogue) nearby, mature pulsars and with nominal e+/e- injection parameters
• **PAMELA** results herald a new era of precision studies of charged cosmic rays in space

• **Antiproton-to-proton flux ratio** (~100 MeV - ~100 GeV) shows no significant deviations from secondary production expectations.

• **High energy positron fraction** (>10 GeV) increases significantly with energy. **Nearby primary source?** Additional data in preparation (spillover limit ~300 GeV).

• Absolute fluxes (e\(^+\), e\(^-\)) in preparation. e\(^-\) (~500 GeV), e\(^\pm\) (~1 TeV).

• A plethora of interpretations are on the market. Take your pick! More data needed (watch this space!). Synergy with other instruments (e.g. Fermi) very important.

• **PAMELA** mission recently approved until 2011