Precision research of cosmic rays from space with PAMELA detector: Results and perspectives

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Pamela Collaboration

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

Germany:
- Siegen

Sweden:
- KTH, Stockholm

Russia:
- Moscow
- St. Petersburg
Launch on June 15th 2006  Soyuz-U rocket

70 degrees polar orbit
350*600km i,
now 600km
Pamela Instrument

- **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)
Principle of detection

Electrons  Positrons  Protons

S1  S2  S3  S4

e-  171 MV  e+  169 MV  p  36GV

Tracker  Calorimeter
High precision cosmic ray measurements challenge and constrain models of production, acceleration and propagation of cosmic ray in the Galaxy and the heliosphere.

On several different scales

→ Modeling

→ Dose and risk estimation for astronauts on ISS and Moon/Mars
Cosmological scale,
(beyond Cosmic Microwave Background)

Matter / Antimatter Asymmetry in the Universe

Sakharov conditions

1) Direct violation of baryonic number
   particle “X” decays breaking baryon symmetry

2) CP violation
   to avoid specular antiparticle decay

3) Non thermal equilibrium at a given time
   To avoid baryon compensation through inverse processes

“Violation of CP Invariance, C Asymmetry, and Baryon Asymmetry of the Universe”
Search for antinuclei

Antihelium also from primordial nucleosynthesis

Antinuclei only from antistars

PAMELA (2006-2009)

JEPT letters 93, 11, 628-631, 2011

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PAMELA (2006-2009)
Search for exotic matter: Strangelets
(Lumps of Strange Quark Matter)

Roughly equal numbers of u,d,s quarks in a single ‘bag’ of cold hadronic matter.

Z = 2, A = 4 (He)
Z/A = 0.5

Z = 2, A = 7
Z/A = 0.286

u,d,s quark matter might be stable
Not limited in A
A = 100, 1000….
Z is almost zero due to cancellation of quark charge
Could account for a (small) part of DM
Also candidate of UHECR
Strangelet upper limit

FIG. 4. Integral upper limit in terms of rigidity, as measured by PAMELA, for nuclei up to Z=8.

predicted:

relic searches:
- b) PRL 92, 022501 (2004)
- c) PRL 81, 2416 (1998)
- d) PRL 43, 429 (1979)

heavy ion bombarding experiments:
- g) satellite-based searches:
  - ARIEL-6 APJ 314, 739 (1987)
  - HEAO-3 APJ 346, 997 (1989)
  - Skylab APJ 220, 719 (1978)

Strangelet-like events detected by:
- i) HECRO-81 PRL 65, 2094 (1990)
Cosmic rays on Galactic scale: Nuclei, protons, antiprotons, isotopes
Cosmic rays are accelerated in Supernova explosions (probably)

- Meet energy criteria
- First order Fermi shock acceleration produces power law spectrum
- Observed in gamma by Agile and Fermi

- Fermi: Shell of SNR W44 have → decay of π10 produced in the interaction of hadrons accelerated in the shock region with the interstellar medium *A. Abdo, et al.*, Science 327, 1103 (2010).
- Starburst galaxies (SG), where the SN rate in the galactic center is much higher than in our own, the density of cosmic rays in TeV gamma-rays (H.E.S.S infers cosmic rays density in SG NGC 253 three orders of magnitude higher than in our galaxy *F. Acero, et al.*, Science 326, 1080 (2009).
- VERITAS: SG M82 cosmic rays density is reported to be 500 times higher than in the Milky Way *VERITAS Collaboration, et al.*, Nature 462, 770 (2009).
Pamela galactic proton and He

- Different spectral index for proton and helium.
- Helium percentage is growing with rigidity.
- Challenges Supernova only origin of cosmic ray and/or acceleration/propagation models.

\[ \gamma_{30-1000\text{GV}, p} = 2.820 \pm 0.003 \text{ (stat)} \pm 0.005 \text{ (syst)} \]

\[ \gamma_{30-1000\text{GV}, \text{he}} = 2.732 \pm 0.005 \text{ (stat)} + 0.008 - 0.003 \text{ (syst)} \]

Science 2011, 332 no. 6025 pp. 69-72
AMS-02 @ ICRC 2013

the importance of systematics

Proton flux: search for structures

Helium flux: search for structures
Global picture: PAMELA vs AMS-02 proton spectrum

Solar modulation

Global picture: PAMELA vs AMS-02 helium nuclei spectrum

Solar modulation

χ²/ndf: 10.94 / 30
Prob: 0.9994
p0: 1.036 ± 0.008654
1. Acceleration is a rigidity dependent effect
2. The ratio decreases $\rightarrow$ More He at high energies $\rightarrow$ Acceleration mechanisms or sources are different?
3. Measurement valid also below the (low) solar modulation

$$\Delta \gamma = -0.101 \pm 0.002$$
Conclusion from Proton and Helium

- Proton and Helium undergo different processes even in GeV-TeV scale
- Change in spectral index around 230-240GV

Needed to bridge to high energy
Various hypotheses to explain Pamela data

- Additional Sources Wolfendale 2011, 2012
- Spallation, Propagation Blasi & Amato 2011, 2013
- Weak local component (+ others) Vladimirov, Johanesson, Moskalenko 2011
- Reacceleration Thoudam & Horandel, 2013
- Various models, Moskalenko 1108.1023
B/C ratio

Propagation in the Galaxy


- B/C ratio
- Secondary/primary

CNO+ISM → B

\[ \frac{N_B}{N_C} \propto \lambda_{\text{esc}} \cdot \sigma_{\text{CNO} \rightarrow B} \]

→ Propagation in the Galaxy

Time of permanence of cr

Puzzle of production and propagation in the galaxy
H and He Isotopes

Propagation in the Galaxy

- Flux depends on solar modulation
- Ratio is less dependent
- Strong tool for evaluating secondary particle production in the galaxy
- Complementary to B/C

Antiprotons

- Secondary production, kinematics well understood
- Probe for extra sources
- Galactic scale
Indirect Dark matter search in space
Antiproton/proton ratio

Low Energy ➔
Confirms charge dependent solar modulation

High Energy ➔
Consistent with models (Galprop, Donato...)

PRL. 105, 121101, 2010
PRL 102:051101, 2009
Antiproton absolute flux

Apparently no extra sources

Rule out and strongly constrain many models of DM

M. Garny et al, JCAP 1204 (2012) 033
Galactic neighborhood: e+, e- (1-2 kpc)

Synchrotron Radiation and Inverse Compton Limit propagation to 1-2 kpc

\[ \tau \simeq 5 \cdot 10^5 \text{yr} \left( \frac{1 \text{ TeV}}{E} \right) \]
Pamela positron fraction

Charge dependent solar modulation increase over background

Pamela positron fraction: comparison with other data

Nature 458, 607-609 (2 April 2009)
AMS & FERMI confirm PAMELA data

Anomalous source at high energy

Charge dependent solar modulation at low energy
→ Need 3D model of heliosphere

Charge dependent solar modulation

L. Maccione, PRL 110 (2013) 081101
Absolute positron spectrum

Propagation Charge dependent solar modulation

PRL111, 081102 (2013)
Secondary production

- relativistic proton (cosmic ray)
- proton at rest (interstellar gas)
- collision
- secondary antiproton

Dark Matter Annihilation

- quarks
- annihilation
- electrons
- positrons
- leptons
- neutrinos $\nu_e, \nu_\mu$
- antiprotons
- protons
- bosons

Astrophysical sources, SNR...

- positron
- electron
- (c) M. Casolino, INFN & University Roma Tor Vergata

2. Example of DM solution: SUSY with internal bremsstrahlung and large boost factors, or Winos with unusual propagation parameters can give the right spectrum.

However, does not explain new electron plus positron data (see later)

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Heliosphere and long term solar modulation (100 AU)

Three boundaries:
- Solar wind termination shock (R~160 AU)
- Heliopause
- Bow shock

\[ B_{gal} \approx 2.5 \times 10^{-10} T \]
Charge dependent solar modulation of 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
Solar modulation of protons and nuclei: monthly

Very long and peculiar solar minimum.

Current solar cycle (24) late and weak.

Closer to interstellar medium.

Good reference field for dosimetry.

Charge dependent solar modulation: PAMELA electron and positron spectra over the last solar minimum
Charge dependent solar modulation: PAMELA electron and positron spectra over the last solar minimum

Variation of the $e^-$, $e^+$ and $p$ flux between Jul 2006 and December 2009
Solar particle events (1 AU)
December 13th 2006 event

No simple modeling of acceleration and propagation

Preliminary PAMELA SEP Spectra

Completing the spectrum

PAMELA bridges the gap between low energy space-based and ground-based measurements to obtain a complete spectrum.
Forbush decrease

[Diagram showing solar activity and cosmic rays affecting Earth's proton flux]

- Quiet proton flux
- 2006/12/15

Graphs showing proton flux and red to black ratio over a range of values.
Time and rigidity dependence of Forbush decrease

Protons Ratio vs time

From Mergè Martucci Sotgiu
GEOMAGNETOSPHERE, VAN ALLEN BELTS
Geomagnetosphere, Van Allen Belts (1000 km)

http://www.youtube.com/watch?v=OaoiPw5Pqbg
Discovery of stably trapped antiprotons in Earth’s radiation belt

Total mass
Less than ng
Negligible but replenishable

Saturn, Jupiter mass $m_g$

Pamela is operating successfully in space

- Expected three years of operations – survived >9!
- Mission prolonged at least 1 more year

- Hope to continue measure deep in the 24th solar cycle

http://pamela.roma2.infn.it
http://www.casolino.it