PAMELA results and challenges

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PAMELA
The Dawn of the Physics of PAMELA

Antiproton/proton ratio vs. Kinetic Energy (GeV)

- LEAP90
- PBAR90
- Bogomolov 1987–1990
- Buffington 1981
- Golden 1984
Antiproton/proton ratio before 1990

Stecker et al. 85
extragalactic antimatter
Stecker & Wolfendale

$m_\chi = 20$ GeV
Stecker et al. 85

$m_\chi = 15$ GeV

Kinetic Energy (GeV)
Balloon data: Positron fraction before 1990

Charge ratio ($e^+ / e^+ + e^-$)

Energy (GeV)

$m_\chi = 20$ GeV

Tilka 89

dinamic halo

leaky box

Golden et al. 1987
Muller & Tang 1987
Buffington 1975
Daugherty 1975
Fanselow 1969
Antimatter Search

Wizard Collaboration

- MASS - 1,2 (89,91)
- TrampSI (93)
- CAPRICE (94, 97, 98)

- BESS (93, 95, 97, 98, 2000)
- Heat (94, 95, 2000)
- IMAX (96)
- AMS-01 (1998)
ANTIMATTER LIMITS
Cosmic Ray Antimatter

Antiprotons

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

Positrons

CR + ISM → π± + x → μ± + x → e± + x
CR ISM → π0 + x → γγ → e±
Space Missions and LDF

**PAMELA**
15-06-2006

**ATIC**
2002 - 2007

**BESS**
13-12-2004  23-12-2007

**AMS-02**
16 -5-2011

**Fermi/GLAST**
11-6-2008
PAMELA
Payload for Antimatter Matter Exploration and Light Nuclei Astrophysics
PAMELA Instrument

GF $\sim 21.5 \text{ cm}^2\text{sr}$
Mass: 470 kg
Size: 130x70x70 cm$^3$
PAMELA Instrument

- S1, S2, S3; double layers, x-y
- Plastic scintillator (8mm)
- ToF resolution ~300 ps (S1-3 ToF > 3 ns)
- Lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

- Permanent magnet, 0.43 T
- 21.5 cm² sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view → MDR

MDR 1.2 TeV

- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm² sr

- 36 ³He counters
- ³He(n,p)T; E_p = 780 keV
- 1 cm thick poly + Cd moderator
- 200 μs collection
Orbit Characteristics

- Low-earth elliptical orbit
- 350 – 610 km
- Quasi-polar (70° inclination)
- SAA crossed
Antiparticles

Antimatter and Dark Matter Search
Antimatter limits
Antiproton Flux


AMS (M. Aguilar et al.)
BESS1999 (Y. Asaoka et al.)
PAMELA new analysis
CAPRICE1994 (M. Boezio et al.)
BESS-POLAR II (K. Abe et al. 2011)
CAPRICE1998 (M. Boezio et al.)
BESS2000 (Y. Asaoka et al.)
BESS-polar04 (K. Abe et al.)

Antiproton to proton ratio
(0.06 GeV - 180 GeV)


Donato et al. (PRL 102 (2009) 071301)
Positron ratio

![Graph showing the positron fraction vs energy (GeV).]
Electron flux

Flux \times E^3 (s^{-1} sr^{-1} m^{-2} GeV^{-1}) \times GeV^3

Energy (GeV)

- Fermi e^-
- PAMELA
- HEAT94+95
- AMS
- CAPRICE94
- MASS91
PAMELA and FERMI electrons
Positron flux

Flux \times E^3 [s^{-1} \text{sr}^{-1} \text{m}^{-2} \text{GeV}^2]

Energy [GeV]
DM annihilations

DM particles are stable. They can annihilate in pairs.

$\chi$ annihilations

Primary annihilation channels

Decay

Final states

$\sigma_a = \langle \sigma v \rangle$

reference cross section:

$\sigma = 3 \cdot 10^{-26} \text{cm}^3/\text{sec}$
A Challenging Puzzle for Dark Matter Interpretation
Majorana DM with **new** internal bremsstrahlung correction. NB: requires annihilation cross-section to be `boosted` by >1000.
A NEUTRON STAR WITH A STRONG MAGNETIC FIELD:

FAST ROTATING PULSAR (P = 33 msec)

\[ L(\text{spindown}) = 5 \times 10^{38} \text{ erg/s} \]
Example: pulsars

H. Yüksak et al., arXiv:0810.2784v2
Contributions of e- & e+ from Geminga assuming different distance, age and energetic of the pulsar

Hooper, Blasi, and Serpico arXiv:0810.1527
A Challenging Puzzle for CR Physics

Positrons (and electrons) produced as secondaries in the sources (e.g. SNR) where CRs are accelerated. Nearby sources
But also other secondaries are produced: significant increase expected in the p/p and B/C ratios.

P. Blasi, PRL 103 (2009) 051104; 4
S: Sarkar
arXiv:1108.1753. Nearby sources

Y. Fujita

N.J. Shaviv et al.,
PRL 103 (2009) 111302;
Proton and Helium Spectra
Proton and Helium fluxes

Science 332,69 (2011)
Proton and Helium fluxes
Proton to Helium ratio

\[
\Delta \gamma^R = \gamma^R_p - \gamma^R_{\text{He}} = 0.101 \pm 0.0014 \text{(stat)} \pm 0.0001 \text{(sys)}
\]
Proton and Helium fluxes

\[ \frac{dN}{dE} \times E^{27/2} \text{, (m s sr GeV/n)} \]

Energy, GeV/n

CREAM
JACEE
ATIC-2
PROTON
PAMELA
Ryan
SOKOL

ICRC#196
Hydrogen and Helium Isotopes
Ratios

![Graph 1: $^2\text{H}/^1\text{H}$ vs. E (GeV/N)]

- Galprop RD Model $\phi = 415$ MV
- Galprop PD Model $\phi = 470$ MV
- BESS
- IMAX
- PAMELA

![Graph 2: $^3\text{He}/^4\text{He}$ vs. E (GeV/N)]

- Galprop RD Model $\phi = 290$ MV
- Galprop PD Model $\phi = 236$ MV
- BESS
- IMAX
- SMILI
- SMILI-2
- MASS
- AMS-01
- PAMELA
Boron and Carbon nuclei Spectra

Carbon

Boron

ICRC##1079
C/O ratio

![Graph showing the C/O ratio against kinetic energy, GeV/n. The graph includes data points from various sources such as ATIC, Panov et al., CREAM, Ahn et al., HEAO-3, Engelmann et al., and PAMELA (2009).]
Solar Modulation of galactic cosmic rays

- Study of solar modulation
- Study of charge sign dependent effects

Asaoka Y. et al. 2002, Phys. Rev. Lett. 88, 051101,
J. Clem et al. 30th ICRC 2007
Cosmic-Ray Antiprotons and DM limits


Antiproton flux predictions for a 12 GeV WIMP annihilating into different mass combinations of an intermediate two-boson state which further decays into quarks.

See also:
• M. Garny, A. Ibarra & S. Vogl, arXiv:1112.5155
• R. Kappl & M. W. Winkler, arXiv:1140.4376
Time Dependence of PAMELA Proton Flux

- Increasing GCR flux
- Decreasing solar activity

[Graph showing proton flux over energy with curves for 2006, 2007, 2008, and 2009]
range: 0.4 - 0.71 GeV
PAMELA Positron Fraction

Preliminary

Secondary production Moskalenko & Strong 98

Positron fraction $\phi(e^+/ (\phi(e^+) + \phi(e^-))$ vs Energy [GeV]

GALPROP


PAMELA (MLP) 2006

PAMELA (MLP) 2007

PAMELA (MLP) 2008

PAMELA (MLP) 2009
December 2006 Solar particle events

Dec 13th largest CME since 2003, anomalous at sol min

X3.4 solar flare.
December 13th 2006 event

Protons

1/1/07 00:00 - 05:30

- a 0:00 - 2:10
- b 3:00 - 3:45
- c 3:45 - 4:30
- d 4:30 - 5:00
- e 8:00 - 10:00

Arbitrary units

GOES Space Environment Monitor

Preliminary!
December 13th 2006 He differential spectrum
December 14th 2006: Forbush decrease

- Low energy tail of Dec 13th event
- Below galactic spectrum: Start of Forbush decrease
- Decrease of primary spectrum
- Arrival of magnetic cloud from CME of Dec 13th
- Shock 1774 km/s (gopalswamy, 2007)

Graph showing:
- Protons on the Y-axis (Arbitrary units)
- Decrease of Neutron Monitor Flux
- Solar Quiet spectrum
- Magnetic Field
- Neutron Monitor
- X-ray
- P_e
Forbush decrease – protons

Rigidity from 1.57 to 5.70 GV

Arbitrary units

Time (dd/mm/yy)

--- protons
Forbush decrease – protons, electrons and positrons

Rigidity from 1.57 to 5.70 GV

Arbitrary units

Time (dd/mm/yy)

- protons
- electrons
- positrons
 proton flux during the January 23rd flare

2012

 proton flux during the May 17th flare
Radiation Belts
Proton flux over the PAMELA orbit
PAMELA trapped antiprotons

O. Adriani et al., APJL 737 L29 (2011); arXiv:1107.4882
Distributions of sub-cutoff proton counts

\[ \alpha_{eq} \text{ vs L-shell} \quad \frac{B}{B_{eq}} \text{ vs L-shell} \quad \text{Geo. Lat vs Long} \]
Comparison of the proton flux measured between 1.5 and 1.57 GV by PAMELA and ULYSSES as a function of time.
Latitudinal gradients
Radial gradients
Thanks!

http://pamela.roma2.infn.it