Testing astrophysical models for the PAMELA positron excess with cosmic ray nuclei

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Connecting Quarks with the Cosmos
INT, Seattle, 7 July 2009
Which DM can fit the data?

The PAMELA Anomaly

PAMELA has measured positron fraction,

\[
\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}
\]

Anomaly: excess above astrophysical background

Source of anomaly?
- DM decay/annihilation
- Pulsars
- Other astrophysics

Secondary $e^{\pm}$ during Propagation

source of CR protons, e.g. SNR

Interstellar Medium
90% H, 10% He

$\pi^0 \rightarrow \gamma \gamma$

$\pi^\pm \rightarrow \mu^\pm, \nu_e, \nu_\mu, \nu_\mu$

$p$

...
The Simple Leaky Box Model

Cosmic rays confined in galaxy but with small, constant escape probability

⇒ Exponential path length distribution with average column depth

If the average column depth is energy/rigidity dependent,

\[ \lambda(E) = \lambda_0 E^{-\delta}, \]

one can explain:
• nuclear secondary-to-primary ratios and
• spectral index of ambient cosmic rays.

GALPROP which solves the full diffusion equation gives same results.
Secondary-to-Primary Ratios

Transport equation in Leaky Box Model:

\[
0 = -\frac{N_i}{\tau_i^{\text{esc}}} - \Gamma_i^{\text{inel}} N_i + \sum_{j < i} \Gamma_{j \rightarrow i} N_j + Q_i
\]

Primary spectrum:

\[
N_1 = \frac{Q_1 \tau_1^{\text{esc}}}{1 + \lambda_1^{\text{esc}} / \lambda_1^{\text{inel}}}
\]

Secondary spectrum:

\[
N_2 = \left( \frac{1}{\lambda_2^{\text{esc}}} + \frac{1}{\lambda_2^{\text{inel}}} \right)^{-1} \frac{N_1}{\lambda_{1 \rightarrow 2}}
\]

Secondary-to-primary ratio:

\[
\frac{N_2}{N_1} = \left( \lambda_2^{\text{esc}} + \lambda_2^{\text{inel}} \right)^{-1} \propto E^{\delta}
\]

\[
\log \frac{N_2}{N_1} \propto E^{-\delta}
\]
Dark Matter as Source of $e^{\pm}$

**Dark matter annihilation**

Annihilation rate $\propto n_{DM}^2$

Leads eventually to SM particles, e.g. $e^{\pm}$

If WIMPs produced thermally, need astrophysical or particle physics boost factor

**Dark matter decay**

Similar, but decay rate $\propto n_{DM}$

Lifetime $\sim 10^9$ times age of universe from dim-6 operator suppressed by $M_{pl}$

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Nardi et al., JCAP 0901:043, 2009

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![Graph showing Positron fraction vs. Positron energy in GeV with data points and shaded regions indicating PAMELA 08 results.](https://example.com/graph.png)
Pulsars as Source of $e^\pm$

- Combination of global, galactic contribution and two nearby mature pulsars, Geminga (157 pc) and B0656+14 (290 pc), could fit PAMELA excess
- Parameters of pulsars, however, poorly known
- FERMI could possibly find anisotropy of nearby B0656+14 pulsar after five years
Astrophysical Source of $e^\pm$

Rise in positron fraction could be due to secondary positrons produced during acceleration and accelerated along with primary electrons

Blasi, arXiv:0903.2794

Assuming production of galactic CR in old SNR, PAMELA positron fraction can be fitted

This is a general feature of every stochastic acceleration process, i.e. if $\tau_{1\rightarrow 2} < \tau_{\text{acc}}$

DSA with Secondaries

Acceleration determined by compression ratio:
\[ r = \frac{u_ -}{u_ +} = \frac{n_ +}{n_ -} \]

Solve transport equation,
\[ u \frac{\partial f_{e \pm}}{\partial x} = D \frac{\partial^2 f_{e \pm}}{\partial x^2} + \frac{1}{3} \frac{\partial u}{\partial x} p \frac{\partial f_{e \pm}}{\partial p} + q_{e \pm} \]
\[ f_{e \pm} \xrightarrow{x \to -\infty} 0, \quad \lim_{x \to \infty} f_{e \pm} \ll \infty \]

Solution:
\[ f_{e \pm}^0 (x, p) = \begin{cases} (f_{e \pm}^0 (p) - F) e^{(u_ - / D_{e \pm})x} + F e^{(u_ - / D)x} & \text{for } x < 0 \\ f_{e \pm}^0 (p) + \frac{q_ {e \pm}^+ (x = 0)}{u_ +} x & \text{for } x > 0 \end{cases} \]

where
\[ f_{e \pm}^0 (p) = \gamma (1 + r^2) \int_0^p \frac{dp'}{p'} \left( \frac{p'}{p} \right)^\gamma \frac{D_{e \pm} (p') q_{e \pm}^-(x = 0)}{u_-^2} , \quad D_{e \pm} (p) \propto p^d \]
Acceleration of Secondary $e^{\pm}$

**Total electron + positron flux**

- primary electrons:
  \[ \sim E^{-3} \]

- secondary $e^{\pm}$ from propagation:
  \[ \sim E^{-3-\delta} \]

- secondary $e^{\pm}$, accelerated in source:
  \[ \sim E^{-3} + E^{-3+d} \]

**Positron ratio**

\[
\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}} \sim \frac{\phi_{e^+}}{\phi_{e^-}} \\
\sim \frac{E^{-3-\delta} + E^{-3+d}}{E^{-3}} \sim E^{-\delta} + E^d
\]
# Explanations for PAMELA Excess

<table>
<thead>
<tr>
<th>$e^+ / e^-$</th>
<th>DM</th>
<th>Pulsars</th>
<th>Acceleration of Secondaries</th>
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</thead>
<tbody>
<tr>
<td>✔️</td>
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Antiproton-to-proton Ratio

$\bar{p}/p$

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<td>DM</td>
<td>(✓)</td>
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<tr>
<td>Pulsars</td>
<td>✗</td>
</tr>
<tr>
<td>Acceleration of Secondaries</td>
<td>✓</td>
</tr>
</tbody>
</table>

Blasi, Serpico, arXiv0904.0871

$\bar{p}/p$ vs. Kinetic Energy, $T$ [GeV]

- Bohm-like
- ISM
- ISM+B term
- Total

- B term
- A term

$10^{-5}$ to $10^{-4}$
Nuclear Secondary-to-Primary Ratios

<table>
<thead>
<tr>
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<th>nuclei</th>
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<tbody>
<tr>
<td>DM</td>
<td>x</td>
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<tr>
<td>Pulsars</td>
<td>x</td>
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</tbody>
</table>

DM and pulsars do not produce nuclei!

Nuclear secondary-to-primary ratios used for testing and calibrating propagation models

Panov et al. (ATIC), ICRC 2007

![Graph showing B/C ratio vs. Energy per nucleon, GeV]
Nuclear Secondary-to-Primary Ratios

If nuclei are accelerated in the same sources as electrons and positrons, nuclear ratios *must* rise eventually.

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</table>

This would be a clear indication for acceleration of secondaries!

Panov *et al.* (ATIC), ICRC 2007

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<td>ATIC, experiment</td>
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<tr>
<td>HEAO-3, experiment [1]</td>
<td></td>
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<tr>
<td>Osborn &amp; Ptuskin, leaky box model [4]</td>
<td></td>
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<td>HEAO-3 model, leaky box model [1]</td>
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Graph showing B/C ratio against energy per nucleon in GeV.
Calculation

• Transport equation

\[ u \frac{\partial f_i}{\partial x} = D_i \frac{\partial^2 f_i}{\partial x^2} + \frac{1}{3} \frac{du}{dx} p \frac{\partial f_i}{\partial p} - \Gamma_i f_i + q_i \]

with boundary condition

\[ f_i(x, p) \xrightarrow{x \to -\infty} Y_i \delta(p - p_0) \]

• Solution:

\[ f_i^+ = f_i^0 + \frac{q_i^+(x = 0) - \Gamma_i f_i^0}{u_+} x \quad \text{for} \quad x > 0 \]

where

\[ f_i^0(p) = \int_0^p \frac{dp'}{p'} \left( \frac{p'}{p} \right) \gamma e^{-\gamma(1+r^2)(D_i^- (p')-D_i^- (p'))} \Gamma_i^- / u_-^2 \]

\[ \times \gamma \left[ (1 + r^2) \frac{D_i^- (p')q_i^- (x = 0)}{u_-^2} + Y_i \delta(p' - p_0) \right] \]

\[ f_i^+ \sim q_i^- (p) + D_i^- q_i^- (p) \]
Diffusion Coefficient

- Diffusion coefficient not known \textit{a priori}

- Bohm diffusion sets lower limit

\[ D^{\text{Bohm}} = r_\ell \frac{c}{3} \propto \frac{E}{Z} \]

- Difference parametrised by fudge factor \( \mathcal{F}^{-1} \)

\[ D = D^{\text{Bohm}} \mathcal{F}^{-1} \]

- \( \mathcal{F}^{-1} \) determined by fitting to one ratio, allows prediction for other ratio
Titanium-to-Iron Ratio

PM and Sarkar, arXiv:0905.3152

![Graph showing the Titanium-to-Iron ratio versus energy per nucleon.]

Titanium-to-iron ratio used as calibration point for diffusion coefficient:

$$\mathcal{F}^{-1} \approx 40$$
Boron-to-Carbon Ratio

PAMELA is currently measuring B/C with unprecedented accuracy

A rise would rule out the DM and pulsar explanation of the PAMELA $e^+/e^-$ excess.
Summary

1. Background for secondary-to-primary ratios in Leaky Box Model

2. Model for acceleration of secondary positrons and electrons in source

3. Nuclear secondary-to-primary ratios as a unique test of these models