Sneutrino Dark Matter and PAMELA

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Recent Results on the Anti-particle Flux:

PAMELA has reported an excess of positrons up to 100 GeV, but no excess in the antiproton flux:

In addition, ATIC has reported excess in $e^+ + e^-$ spectrum with a peak around 600 GeV.  

Not confirmed by the latest Fermi and H.E.S.S. results.
Fermi: Abdo, et al., arXiv:0905.0025
Dark matter annihilation and positron excess:

WIMPs annihilate to particle-antiparticle pairs today.

Annihilation rate is given by:

\[ \Gamma_{\text{today}} = nB\langle \sigma v \rangle_f \]

- **B** Overall factor (branching ratio, enhancement, …)
- **n** Local dark matter density (NFW profile)
- **\( \langle \sigma v \rangle_f \)** Thermal freeze-out cross section

\[ \langle \sigma v \rangle_f = 3 \times 10^{-26} \frac{cm^3}{s} \]
Model-independent analysis shows $B \gg 1$ needed:

Barger, *et. al.*, arXiv:0809.0162

$B \sim O(10)$ for electron-positron final state

$B \sim O(100)$ for W boson final states

In MSSM, usually a much larger $B$ required because of the P-wave suppression of annihilation:

$$\langle \sigma v \rangle \propto v^2 \Rightarrow \langle \sigma v \rangle_{today} \sim 10^{-5} \langle \sigma v \rangle_f$$

Even in the best case scenario:

$$\langle \sigma v \rangle_{today} \sim 10^{-2} \langle \sigma v \rangle_f$$
How to get a large enhancement in annihilation NOW?

Astrophysics:
Enhancing the number density, astrophysical boost factor due to local substructure in the halo.

But it is difficult to imagine a boost factor of $10^4$. May get $10^{-10}$ in our vicinity.
Afshordi, Mohayaee, Bertschinger, arXiv:0811.1582

Particle Physics:
Enhancing the cross section, microphysical boost factor.

We need a large cross section today as compared with the freeze-out time.

How?
Sommerfeld Effect:  

Cirelli, et. al., arXiv:0809.2409

Enhancement of S-wave processes in the non-relativistic limit due to attractive force from exchange of a boson:

\[ V(r) \sim -\alpha \frac{e^{-m\phi r}}{r} \]

Works if \( m_\phi \ll m_\chi \).

Enhancement factor saturates at \( \sim \frac{m_\chi}{\alpha m_\phi} \).
Requirements:

1) S-wave annihilation.

2) Light boson to generate an attractive force.

3) Annihilation mainly to lepton final states (to be compatible with antiproton data).

Donato, *et. al.*, arXiv:0810.5292

Beyond MSSM —> New dark matter model!

…
Explicit Model:

Are there well motivated models that can lead to Sommerfeld enhancement?

MSSM plus gauged $U(1)_{B-L}$.


Explaining neutrino masses and having supersymmetric dark matter at the same time requires RH neutrinos.

$U(1)_{B-L}$ implies the existence of 3 RH neutrinos (anomaly cancellation).
Field content and B-L charge assignments:

\[
\begin{array}{cccccc}
Q & L & N & H_1' & H_2' & (+ \text{ SUSY Partners}) \\
\end{array}
\]

\[
Q_{B-L} \quad +1/6 \quad -1/2 \quad -1/2 \quad +3/2 \quad -3/2
\]

\[
\mathcal{g}_{B-L} \sim 0.4
\]

The bounds from Tevatron and LEP on the $Z'$ require:

\[
m_{Z'} > 1.5 \text{TeV}
\]

The B-L spontaneously broken by the new Higgs VEVs:

\[
\left\langle H_1' \right\rangle, \left\langle H_2' \right\rangle \quad \tan \beta' \equiv \frac{\left\langle H_2' \right\rangle}{\left\langle H_1' \right\rangle}
\]
There are three Higgs fields in the B-L sector:

\[ \phi \quad m_\phi^2 < m_Z^2 \cos^2 2\beta' \]

\[ \Phi, A \quad m_\Phi, m_A \sim m_Z' \]

\[ \tan \beta' \approx 1 \Rightarrow m_\phi \ll m_Z' \]

One of the B-L Higgses can be very light.

Sneutrino \( \tilde{N} \) is the LSP in parts of the parameter space.
Exchange of the light Higgs leads to an attractive force between the sneutrinos (in the non-relativistic limit):

\[ V(r) = -\alpha \frac{e^{-m_{\phi}r}}{r} \]

Where:

\[ \alpha = \frac{g_{B-L} m_Z \sin(\alpha' + \beta')} {4m_{\tilde{N}}} \]

This results in the Sommerfeld enhancement in S-wave annihilation modes in this model.
Sneutrino annihilation channels:

\[ \tilde{N}\tilde{N}^* \rightarrow \phi\phi \quad \text{S-wave, dominant mode} \]
\[ \tilde{N}\tilde{N} \rightarrow NN \quad \text{S-wave, subdominant (~10%)} \]
\[ \tilde{N}\tilde{N}^* \rightarrow \bar{f}f \quad \text{P-wave, negligible} \]

(There are also modes with \( \Phi, A \) final states, but they are kinematically forbidden or suppressed)

The annihilation cross section is governed by D-term interactions, increase as \( m_{Z'} \) increases.
The produced $\phi$ quanta decay to fermion-antifermion pairs:

$$\Gamma_{\phi \rightarrow \bar{f}f} = \frac{C_f}{2^7\pi^5} \frac{g_{B-L}^6 Q_f^4 Q_\phi^2 m_\phi m_F}{m_{Z'}^6} \left(1 - \frac{4m_f^2}{m_\phi^2}\right)^{3/2}$$

Leptons favored by the virtue of B-L charges.

No antiproton excess automatically implied by B-L symmetry.

\[m_\phi < 15\text{GeV}\] tau final states dominate

\[m_\phi < 4\text{GeV}\] muon final states dominate
\( \mathcal{E}_\phi \equiv \frac{m_\phi}{\alpha m_{\tilde{N}}} \)
Fit to PAMELA

- Tau final state
- Muon final state

Dark matter mass 1 TeV, 1.5 TeV, 2 TeV (bottom to top)

Enhancement factor 1000
Electron+positron spectrum

muon final state

tau final state compatible with Fermi results
Direct Detection:

\( \tilde{N} \) interacts with quarks via \( Z' \) exchange.

No spin-dependent contribution (B-L is vector like).


\[
\frac{m_{Z'}}{g_{B-L} Q_L} > 6 \text{TeV}
\]

\[\Rightarrow \sigma_{\text{sneutrino-nucleon}} \propto \left( \frac{g_{B-L} Q_L}{m_{Z'} + m_{\tilde{N}}} \right)^4 \leq 8 \times 10^{-9} \text{ pb} \]
Summary and Outlook:

• PAMELA seems to indicate and excess in the positron flux.

• Could be due to dark matter annihilation. This would require new cosmology and/or particle physics.

• Microphysical origin for enhanced annihilation implies new dark matter models.

• A minimal and well motivated model is B-L extension of MSSM with RH sneutrino as the dark matter. Can explain PAMELA, and be compatible with Fermi (tau final states).

• Can be probed by the upcoming and future direct detection experiments. Has other interesting signals (Fermi, IceCube).
Outline:

• Introduction.

• Recent results from PAMELA (and ATIC, H.E.S.S., Fermi).

• Dark matter explanation and challenges.

• Minimal model: B-L symmetry.

• Prospect for direct detection.

• Summary.
Introduction:
For thermal dark matter, the relic abundance is governed by thermal freeze-out.

Happens when temperature is:

\[ T_f \sim \frac{m_\chi}{20} \]

To have the correct dark matter abundance:

\[ \langle \sigma v \rangle_f = 3 \times 10^{-26} \frac{cm^3}{s} \]

This is the nominal value of annihilation cross-section.
Introduction:

Most of the matter in the universe is dark.

What is the dark matter?

WIMPs are natural candidates, arise in particle physics models:

LSP, LKP, Axion, …

Have a natural place in extensions of the SM, not introduced to address dark matter.
Experimental Searches for WIMP Dark Matter:

1) Direct detection: WIMP-nucleus scattering (CDMS, XENON, LUX, ...).

2) Indirect detection: WIMP annihilation to Gamma rays (Fermi), Neutrinos (IceCube) Antiparticles (PAMELA).

3) Collider signal: Missing energy (LHC, ILC).

Complementarity: different experiments probe different Interactions of dark matter.

Consistency: results must agree (the same particle).
Lets focus on the positron excess.

How can the anomaly be explained?

**Astrophysical sources:**
Pulsars could explain the positron excess.

Hooper, Blasi, Serpico, arXiv:0810.1527
Yuksel, Kistler, Stanev, arXiv:0810.2784
Profumo, arXiv:0812.4457

Positrons produced from gamma annihilation, accelerated by the electric field in the magnetosphere.

Young and nearby pulsars needed.
Fermi will play an important role.
\[ D_{B-L} \supset \frac{1}{2} g_{B-L} \left[ Q_\phi \left( |H'_1|^2 - |H'_2|^2 \right) + \frac{1}{2} |\bar{N}|^2 + \ldots \right] \]

\[ H'_1 = \frac{\langle H'_1 \rangle + \cos \alpha' \Phi - \sin \alpha' \phi}{\sqrt{2}} + \frac{H'_{1,I}}{\sqrt{2}} \]

\[ H'_2 = \frac{\langle H'_2 \rangle + \sin \alpha' \Phi + \cos \alpha' \phi}{\sqrt{2}} + \frac{H'_{2,I}}{\sqrt{2}} \]

\[ V \supset -\frac{1}{2} g_{B-L} m_Z \sin(\alpha' + \beta') \phi \bar{N}^* \bar{N} \]
\( \phi \) must be kept light (< 15 GeV) after radiative corrections.

But, corrections from superpotential terms should be sufficiently large for radiative breaking of B-L.

With the chosen B-L charges, we can have:

\[
W_{B-L} = f H'_2 N^c N^c + \mu' H'_1 H'_2
\]

\[
\Delta m^2_\phi \sim \frac{1}{16\pi^2} f^2 m_N^2 \ln \left[ \frac{m_N^2}{m_{\tilde{N}_R} m_{\tilde{N}_I}} \right]
\]

\( f \sim 0.2 \) large enough for both purposes.