Enhanced Emission and Accumulation of Antiprotons and Positrons from Supersymmetric Dark Matter

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We estimate the amount of antiprotons and positrons in cosmic rays due to neutralino annihilations in the galactic halo assuming that dark matter tends to cluster and that these clusters are not disturbed by tidal forces. We find that, assuming neutralinos annihilate mostly to gauge bosons, the amount of antiprotons should exceed the number seen at BESS, whereas the increase in positron flux is below the present detection threshold.

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I. INTRODUCTION

The nature of dark matter remains one of nature’s puzzles. Supersymmetry with conserved \( R \)-parity, besides having many desirable properties for particle physicists, provides a natural candidate for cold dark matter, since if \( R \)-parity is conserved, then the lightest supersymmetric partner is stable. In most models, the lightest supersymmetric partner is the lightest neutralino, a linear combination of the neutral supersymmetric partners: the Bino \( B \), the Wino \( W \), and the two neutral Higgsinos \( h_1 \) and \( h_2 \).

Detection of supersymmetric dark matter can be achieved indirectly through its effect on cosmic rays, and more specifically on antiprotons and positrons in the cosmic rays [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14]. (See also ref. [11, 12, 13, 14] for discussion on the effects of WIMPs on cosmic rays [1, 2, 3, 4, 5, 6, 7, 8, 9, 10].) Unlike hot dark matter with light constituents, which are relativistic throughout most of the relevant history, or baryons, which via electromagnetic interactions with the cosmic microwave background radiation tend to maintain their temperature until late times, cold dark matter clusters in the early universe, once the perturbations \( \delta(\rho)/\rho \) on the scale considered enter the horizon. Structures then form in a down-up hierarchical fashion: smaller structures form first and merge into bigger ones.

This culminates in forming galaxies with local dark matter density in our neighborhood of

\[
\rho_{\chi, \text{local}} \approx 0.4 \text{GeV cm}^{-3},
\]

clusters thereof and even larger structures.

At some red-shift \( z \), certain autonomous structures form in the initially almost smooth cold dark matter [16]. Those become gravitationally bound and decouple (except for the center of mass motion) from the Hubble expansion. The local dark matter density within these first mini-halos, is enhanced relative to the average co-moving number density, i.e., the present cosmological dark matter density, and becomes

\[
n_{\chi, \text{mini-halo}} \approx (6z)^3 \cdot n_{\chi, \text{cosmological}}.
\]

The factor \( z^3 \) reflects the hubble stretching and \( n_\chi \) dilution which operates cosmologically but not inside the mini-halos and the \( 6^3 \) factor is due to the extra factor 6 shrinkage of the virialized mini-halo.

Thus, if the first structures form at \( z = 100 - 20 \) we have enhancement factors of

\[
e_f \approx (6z)^3 \sim 2 \cdot 10^8 - 2 \cdot 10^6
\]

over the co-moving average density of neutralinos.

Recent detailed \( N \) body simulations with initial fluctuations extrapolated down from WMAP to galaxies to the \( 10^{-15} \) less massive dark matter mini-halos suggest indeed that [15]:

\[
\begin{align*}
\delta \rho & \approx 10^{-6} \quad \text{for} \quad z > 100, \\
\delta \rho & \approx 10^{-8} \quad \text{for} \quad z < 100.
\end{align*}
\]
1. These first structures formed early on at $z=100-20$ so that the neutralino concentration therein is enhanced by $e_f \sim 2 \cdot 10^8 - 2 \cdot 10^6$ over the cosmological:

$$n_X^{\text{cosmological}} = \frac{\Omega_X}{\Omega_C} \rho_C \sim 1.3 \text{ keV/cm}^3.$$  

Hence, the neutralino mass density inside the mini-halo is approximately $3 - 300 \text{ GeV/cm}^3$, i.e., $5 - 750$ times larger than the average dark matter density in our local neighborhood.

2. More specifically, the masses of the smallest mini-halos were found to be

$$m_{\text{mini-halo}} \sim 10^{-6} m_\odot,$$

and sizes

$$r_{\text{mini-halo}} \sim 0.01 \text{ pc} \sim 3 \cdot 10^{16} \text{ cm}.$$  

The average density inside these structures is approximately $40 \text{ GeV/cm}^3$, i.e., $100$ times that of the average local dark matter density. The density profile of these mini-halos can be described by a power law

$$\rho(r) \propto r^{-\gamma},$$

with $\gamma$ in the range from 1.5 to 2.

3. Let $f_{\text{mini-halo}}$ be the fraction of all the cosmological dark matter clustered inside these first mini-halos. It is important for our present purpose that subsequent incorporation of mini-halos alongside some of the background initially unclustered dark matter, into later, bigger mini-halos, keeps the smaller, more compact, first mini-halos intact. The authors of ref. [15] find that this is indeed the case. More specifically, tidal disruption by stars and by the collective gravitational field does not destroy the above first mini-halos even inside the galactic disc at distances larger than 3 kpc from the center of our galaxy and, in particular, at our location 7 kpc from the center. The question of the stability of these structures has been further discussed in [17, 18, 19, 20, 21] and thus the mass of the lightest neutralino will be taken as

$$m_{\chi} \sim 10^{-6} m_\odot,$$

or more precisely, 500 mini-halos within a $(\text{pc})^3$.

This is equivalent to a local average density of

$$500 \cdot 10^{-6} m_\odot \text{pc}^{-3} \sim \frac{1}{20} \cdot 0.4 \text{ GeV/cm}^3,$$

namely, approximately 5% of the local dark matter density, which implies equal enrichment in the galaxy of the unclustered neutralinos and the initial mini-halos. This seems a conservative estimate of the density of the initial mini-halos as larger structures are likely to form near the previous, slightly smaller structures.

### III. THE SUPERSYMMETRIC MODEL

We work here in the framework of $N = 1$ minimal supergravity [22, 23, 24].

For our purposes, it is sufficient to describe the model using only four parameters and a sign. These parameters are $m_0$, the common scalar mass, $m_{1/2}$, the common gaugino mass and $A_0$, the common trilinear interaction term, all of which are evaluated at the GUT scale. The fourth parameter is $\tan \beta$, the ratio between the vacuum expectation values of the two Higgs doublets, and the final parameter is the sign of $\mu$, the parameter that appears in the Higgs superfields interaction.

We assume that the mass of the lightest neutralino is larger than the mass of the $W$ and the $Z$ bosons, but either smaller or not much larger than the mass of the lightest Higgs particle. If this is the case, and assuming that the neutralino is mostly Wino-like or Higgsino-like, annihilation of neutralinos will be dominated by annihilation to two gauge bosons (fig. 1).

![FIG. 1: Neutralino annihilation into two gauge bosons](image)

The authors of ref. [25] estimate that the mass of the lightest neutralino boson most likely lies within the range

$$114 \text{ GeV} < m_{h_1} < 127 \text{ GeV},$$

and thus the mass of the lightest neutralino will be taken as

$$m_\chi = \eta \cdot 100 \text{ GeV},$$

with $\eta \gtrsim 1$.

The next to lightest supersymmetric particle is assumed to be much heavier (several hundreds of GeV), and thus effects of co-annihilations involving almost degenerate supersymmetric particles can be neglected.
IV. PRODUCTION OF ANTIPROTONS FROM NEUTRALINO ANNIHILATION

Our discussion of the enhanced flux of antiparticles is based on the standard mini-halos of mass $m = 10^{-6}m_\odot$, and size $r \sim 0.01$ pc \[12\].

We assume a local mini-halo density in our galactic neighborhood of $500$ pc$^{-3}$. The average neutralino mass density in such a mini-halo is

$$\rho_\chi \sim 10^{57} GeV pc^{-3}, \tag{12}$$

and a number density of

$$n_\chi \sim \eta^{-1} \cdot 10^{55} pc^{-3}, \tag{13}$$

where $\eta$ is defined in eq. \[11\].

The lifetime for $\chi\chi$ annihilations within these mini-halos is

$$\tau_{ann} = (\langle \sigma_{ann} v \rangle n_\chi)^{-1} \sim 3 \cdot 10^{26} \eta \text{ sec}, \tag{14}$$

where

$$\langle \sigma_{ann} v \rangle = 10^{-9} GeV^{-2}. \tag{15}$$

The differential production rate per unit of volume of antiprotons can be written as

$$q_\bar{p} = \langle \sigma_{ann} v \rangle g(T_\bar{p}) \left( \frac{\rho_\chi}{m_\chi} \right)^2, \tag{16}$$

where $g(T_\bar{p})$ denotes the antiproton differential energy spectrum.

Assuming that neutralinos annihilate mostly to gauge bosons, one antiproton is produced on average per annihilating neutralino through decay of $W$ or $Z$ bosons \[20\], leading to about $10^{-27}$ antiprotons per cm$^3$ per second which are injected in the galactic disc and in the halo in our neighborhood.

Let the effective residence time of the antiprotons before slowing down and annihilating be

$$t_{res} = \tau_r \cdot 10^7 \text{years} \sim \tau_r \cdot 3 \cdot 10^{14} \text{sec}. \tag{17}$$

The antiprotons’ density builds up to

$$n_\bar{p} \sim \eta^{-1} \cdot \tau_r \cdot 3 \cdot 10^{-13} \text{cm}^{-3} \tag{18}$$

The antiprotons of interest with energy above 1 GeV move with velocities $v \approx c$ making a flux:

$$\Phi_\bar{p} \sim c \cdot n \sim \eta^{-1} \tau_r \cdot 10^{-2} \text{cm}^{-2} \text{sec}^{-1}, \tag{19}$$

yielding an angular differential flux of

$$\eta^{-1} \tau_r 8 \cdot 10^{-4} \text{ cm}^{-2} \text{sec}^{-1} \text{sr}^{-1}. \tag{20}$$

If, as we argue in section V, the residence time is indeed $10^7$ years, then the expected range of antiproton fluxes from neutralino annihilations in mini-halos exceeds the experimental values seen at BESS \[27\] (fig. 2).

The angular differential flux integrated from 0.1 GeV to 10 GeV using the data from BESS is

$$\sim 10^{-5} \text{cm}^{-2} \text{sec}^{-1} \text{sr}^{-1} \tag{21}$$

It has been known for some time that cosmic ray antiprotons are a sensitive indicator for supersymmetric dark matter. This is even more so with the enhanced annihilation rates inside the mini-haloes in our galaxy. The local unclustered dark matter of 0.4 GeV/cm$^3$ in our neighborhood is 0.25 - 10$^6$ times that of the cosmological 1.5 keV/cm$^3$ as opposed to about a 100 times larger enhancements inside the mini-halos.

Since the fraction of neutralinos in our galactic neighborhood residing in mini-halos is $\sim 0.05$, the net effect of the local mini-halos is to enhance the antiproton flux (relative to the expectation for a uniform neutralino density of 0.4 GeV/cm$^3$) by more than 100. Thus, independently of any detailed estimate of the actual antiproton flux in the two scenarios, the neutralino clustering within mini-halos can help the signal of antiprotons from neutralino annihilations cross the detectibility threshold.

V. PROPAGATION OF ANTIPROTONS

Let us briefly review the estimate of the lifetime of the antiprotons. The antiprotons, like other components
of the cosmic rays, can disappear from the reservoir of cosmic rays in two ways:

1. by literally "leaking" out into the intergalactic space along magnetic field lines which do not close inside the galaxy or the halo.

2. While traversing the disc and to some extent also in the halo, the antiprotons lose energy via collisions with electrons and protons in the ambient plasma. Such antiprotons with too low an energy cannot penetrate the stellar wind and attendant magnetic fields and thus do not arrive at (ant)arctic balloons with minimal geomagnetic cutoff.

In the special case of antiprotons, losses via annihilation are most important. Indeed using:

\[ \sigma_{pp}^{\text{ann}} \sim 10^{-25} \text{cm}^2, \]  

we find the lifetime for annihilation is

\[ \tau_{p}^{\text{ann}} = (n_p \cdot \sigma_{pp}^{\text{ann}})^{-1} \sim 10^7 \text{ years}, \]  

and thus, the total traversed grammage is

\[ \sim 10^{25} \text{protons/cm}^2 \sim 10^{gr}/\text{cm}^2. \]  

The magnetic fields in the disc which are of the order of \( 3 \times 10^{-6} \) gauss are stronger by a factor of about 10 than those in the halo, and the latter are a 100 times larger than the intergalactic magnetic fields. Thus only a small fraction of the magnetic field lines in the disc connect to the halo and a smaller fraction yet of the magnetic fields in the halo connect to the outside thereby slowing down the leakage. Indeed the overall residence time (in the disc and the halo together) of protons with energy of the order of 1 GeV is estimated using isotopic composition data to be 30 millions years, allowing 1000 traversals of the disc or 100 traversals of the halo.

We also need to restrict the total grammage traversed by the cosmic ray particles to be less than \( 5gr/cm^2 \). This yields:

\[ t_{\text{disc}} \sim 5 \cdot 10^6 \text{years}, \]  

namely,

\[ \tau_r \sim 1/2, \]  

roughly consistent with \( 10^7 \) years (or \( \tau_r \sim 1 \)) used in estimating the antiproton signal from neutralino annihilation.

Note that in the present scenario antiprotons are produced not only in the disc as most cosmic rays but even more within the mini-halos. This enhances the signal as antiprotons originating in the halo can go into the disc and arrive to us as well.

The following comments are in order:

1. The estimated antiproton flux is reduced by a factor of about 0.7, the fraction of hadronic \( Z^0 \) (and/or \( W^+ \)) decays. With the smaller \( \tau_r \sim 1/2 \) this reduces the expected flux by factor 3, yielding a differential antiproton flux of

\[ 2.7 \cdot 10^{-4} \text{ cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}. \]  

2. By and large, the observed antiproton signal agrees with that computed from interaction of cosmic ray protons with momenta \( \gtrsim 8 \text{ Gev} \) with interplanetary protons suggesting more stringent limits on the supersymmetric dark matter scenario from antiprotons. The background antiprotons are relatively energetic. It was therefore suggested that the excess at energies lower than a GeV indicates supersymmetric dark matter annihilations.

3. As noted above, the multiplicity of antiprotons produced (particularly those at the more interesting lower energies) grows rapidly with the mass of the neutralino if the mix of Wino, Bino and Higgsino in \( \chi^0 \) optimizes the annihilation via a virtual \( Z^0 \) (and to \( Z^0 \to q \bar{q} \), in particular). This will enhance the desired signal of antiprotons from neutralino annihilations. On the other hand, if annihilation to \( W^+W^- \) dominates, the multiplicity is fixed but the energy spectrum shifts upward with \( m_\chi \), diminishing the signal of low energy antiprotons.

4. If the mass of the neutralino is large enough, annihilations into either a higgs boson and a gauge boson or into two higgs bosons are possible. The higgs bosons will then decay to \( b \) quarks, and the production of antiprotons is suppressed.

5. The cross section for annihilation of antiprotons with energies of the order of 1 GeV is larger than the corresponding elastic cross section. Further, already at these energies the momentum transferred in these scattering, \( t \), and the attendant recoil kinetic energy loss, \( t/2m_p \), are relatively small. Thus the detected antiprotons manifest the energy spectrum from neutralino annihilations.

VI. NEUTRALINO DETECTION THROUGH POSITRONS

We next consider positrons. Could their observation be a better indicator for supersymmetric dark matter?

The answer is clearly negative in so far as the lower energy part of the spectrum with energy less than 1 GeV is concerned. The background from \( pp \to pm \pi^+ \) with the charged pion decaying to muon and then to a positron is huge compared to the antiproton background: first the threshold in this case is lower and it is possible to utilize the lower and much stronger part of the cosmic radiation spectrum. Also the inclusive pion production cross section is about 1000 times larger than that for antiprotons.
The multiplicity of positrons from neutralino annihilation is larger by a factor of 15 than that of the antiprotons but this cannot compensate the above larger factors.

The situation is clearly better if we focus on the more energetic positrons, for instance, those with \( E_{e^+} \approx 8 \) GeV or higher originating from charged pions of \( E_\pi > 20 \) GeV. The multiplicity of those in neutralino annihilations is still \( O(1) \) whereas their production in proton-proton collisions requires now protons of energies greater than 30 GeV. This is strongly suppressed by the power fall-off of the background, proportional to \( \gamma^2 \), whereas their production in proton-proton collisions requires now protons of energies greater than 1 GeV. The multiplicity of those in neutralino annihilations is larger by a factor of 15 than that of the antiprotons.

is larger by a factor of 15 than that of the antiprotons

The various losses on some existing electromagnetic background, proportional to \( \gamma^2 \), are \( 2.5 \cdot 10^8 \) faster for the energetic positrons than for the 1 GeV antiprotons. The actual energy loss rate is

\[
dW/dt = \gamma^2 \cdot \sigma_{\text{Tompson}} \cdot U \cdot c \sim 5 \cdot 10^{-6} U,
\]

where \( U \) is the energy density due to the magnetic fields, and

\[
U = B^2/(8\pi) \sim 0.22 \ eV \cdot (cm)^{-3}.
\]

Thus 8 GeV positrons lose 1/2 of their energy via synchrotron radiation in 3.5 \( \cdot 10^{15} \) sec. This is more than ten times longer than the lifetimes of the antiprotons. Roughly the same loss occurs on the equal energy density cosmic microwave radiation via inverse Compton scattering. Finally the standard Coulombic losses are very similar for the minimally ionizing relativistic positrons and antiprotons and in any case are less than those of nuclear interactions and annihilations at these energies. Using a similar analysis as in section IV we get a positron angular flux of

\[
0.4 \ cm^{-2} \ sec^{-1} \ sr^{-1}.
\]

This is an order of magnitude smaller than the observed amount.

The authors of ref. [6] assert that the positron excess observed on both flights of the HEAT balloon experiment [29, 30] can be explained by a single nearby mini-halo. This scenario is very unlikely, as shown in [7].

VII. CONCLUSIONS

In this paper we have shown that if neutralinos annihilate mostly to gauge bosons there should be an excess of antiprotons over the observed amount in BESS due to the enhanced neutralino density in the mini-halos over the cosmological density. This fact may imply that the mass of the neutralinos is larger than the mass of the lightest higgs boson, in which case annihilations into higgs bosons suppress the number of antiprotons produced, or that it is smaller than the mass of the gauge bosons.

We have also shown, that although antiprotons are strong indicators for dark matter, this is not the case for positrons. The low energy positrons coming from neutralino annihilation cannot be distinguished from the large background signal and the contribution of neutralino annihilation to the positron signal with high energies is too small to make any predictions.

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