Cosmic–Ray Antideuterons as a Signature for Neutralino Annihilation in the Galactic Halo

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Abstract

Once the energy spectrum of the secondary component is well understood, measurements of the antiproton cosmic–ray flux at the Earth will be a powerful tool to indirectly probe for the existence of supersymmetric relics in the galactic halo. Unfortunately, it is still spoilt by considerable theoretical uncertainties. As shown in this work, searches for low–energy antideuterons appear in the mean time as a plausible alternative, worth being explored. Above a few GeV/n, a dozen spallation antideuterons should be collected by the future AMS experiment on board ISS. For energies less than $\sim$ 3 GeV/n, the $\bar{\rm D}$ spallation component becomes negligible and may be supplanted by a possible supersymmetric signal. If a few low–energy antideuterons are discovered, this should be seriously taken as a clue for the existence of massive neutralinos in the Milky Way.

1 Introduction:

Cosmic ray fluxes are about to be measured with unprecedented precision both by balloon borne detectors and by space instruments. The various ongoing experiments are also hunting for traces of antimatter in the cosmic radiation. The BESS collaboration (Matsunaga et al. 1998) plans to push the limit on the $\bar{\rm He}/{\rm He}$ ratio down to 10^{-8} whereas the AMS spectrometer should reach a sensitivity of $\sim 10^{-9}$ once it is installed on the International Space Station (ISS) (Ahlen et al. 1994). The search for antinuclei has profound cosmological implications. The discovery of a single antihelium or anticarbon would actually be a smoking gun for the existence of antimatter islands in our neighborhood. However, light antinuclei, mostly antiprotons but also antideuterons, are actually produced in our Galaxy as secondaries. They result from the interaction of high–energy cosmic–ray protons with the interstellar gas of the Milky Way disk. In a previous analysis, Chardonnet, Orloff, and Salati (1997) have estimated the flux of antideuterium $\bar{\rm D}$ and antihelium $^3\bar{\rm He}$ secondaries. The $\bar{\rm D}$ signal is very weak but may marginally be detected by forthcoming experiments. The case of antihelium is, at least for the moment, hopeless.

The dark matter of the Milky Way could be made mostly of elementary particles such as the heavy and neutral species predicted by supersymmetry. The mutual annihilations of these relics, potentially concealed in the halo of our Galaxy, would therefore produce an excess in the cosmic radiation of gamma rays, antiprotons and positrons. In particular, supersymmetric antiprotons should be abundant at low energy, a region where the flux of $\bar{\rm p}$ secondaries is a priori negligible. There is quite an excitement trying to extract from the observations a possible $\bar{\rm p}$ exotic component which would signal the presence of supersymmetric dark matter in the Galaxy. Unfortunately, it has been recently realized (Bottino et al., 1998; Bergström, Edsjö, & Ullio, 1999; Bieber et al. 1999) that a few processes add up together to flatten out, at low energy, the spectrum of secondary antiprotons. Ionisation losses as well as inelastic but non-annihilating scatterings on the hydrogen atoms of the galactic disk result into the decrease of the antiproton energy. The low–energy tail of the $\bar{\rm p}$ spectrum is replenished by the more abundant population from higher energies. That effect is further strengthened by solar modulation which also shifts the energy spectrum towards lower energies. As a result of these effects, the secondary $\bar{\rm p}$'s are much more abundant at low energy than previously thought. Disentangling an exotic supersymmetric contribution from the conventional component of spallation antiprotons may turn out to be a very difficult task. The antiproton signal of supersymmetric dark matter seems therefore to be in jeopardy.

Antideuterons, *i.e.*, the nuclei of antideuterium, are free from such problems. As explained in Sect. 2, they form when an antiproton and an antineutron merge together. The two antinucleons must be at rest with respect to each other in order for fusion to take place successfully. As discussed in Sect. 3, this implies that the distribution of spallation antideuterons is significantly suppressed below ~ 3 GeV/n, a region where primary $\bar{\mathrm{D}}$'s from neutralino annihilation could potentially take over as shown by Donato, Fornengo, and Salati (1999). Conclusions are drawn in Sect. 4.

2 Production of antideuterons:

The processes at stake are both the spallation of a cosmic–ray high–energy proton on an hydrogen atom at rest (secondary production) and the annihilation of a neutralino pair (primary production). For each of these reactions, the differential probability for the production of an antiproton or an antineutron may be derived. The calculation of the probability for the formation of an antideuteron can therefore proceed in two steps. We first need to estimate the probability for the creation of an antiproton–antineutron pair. Then, those antinucleons merge together to yield an antinucleus of deuterium.

The production of two antinucleons is assumed to be proportionnal to the square of the production of one of them. The hypothesis that factorization of the probabilities holds is fairly well established at high energies. For spallation reactions, however, the bulk of the antiproton production takes place for an energy $\sqrt{s} \sim 10$ GeV which turns out to be of the same order of magnitude as the antideuteron mass. Pure factorization should break in that case as a result of energy conservation. It needs to be slightly adjusted. We have therefore assumed that the center of mass energy available for the production of the second antinucleon is reduced by twice the energy carried away by the first antinucleon. In the antideuteron frame, the antinucleons merge together if the momentum of the corresponding two–body reduced system is less than some critical value P_{coal}. A value of $P_{\mathrm{coal}} = 58$ MeV has been derived by Chardonnet, Orloff, and Salati (1997), not too far from what may be naively expected from the antideuteron binding energy, *i.e.*, $\sqrt{m_{\mathrm{p}}\, B} \sim 46$ MeV.

The Lorentz invariant cross section for the production of antideuterons resulting from the impact of a high–energy cosmic–ray proton on a proton at rest may be expressed in terms of the Lorentz invariant cross sections for the production of antineutrons and antiprotons

$$\begin{aligned} E_{\bar{\mathrm{D}}} \frac{d^3\sigma_{\bar{\mathrm{D}}}}{d^3\vec{k_{\bar{\mathrm{D}}}}} &= \left(\frac{m_{\bar{\mathrm{D}}}}{m_{\bar{\mathrm{p}}}\, m_{\bar{\mathrm{n}}}}\right) \left(\frac{4}{3}\pi {P_{\mathrm{coal}}}^3\right) \times \frac{1}{2\sigma^{\mathrm{tot}}_{\mathrm{p-p}}} \times \\ &\times \left\{ E_{\bar{\mathrm{p}}} \frac{d^3\sigma_{\bar{\mathrm{p}}}}{d^3\vec{k_{\bar{\mathrm{p}}}}} \left(\sqrt{s}, \vec{k_{\bar{\mathrm{p}}}}\right) \, E_{\bar{\mathrm{n}}} \frac{d^3\sigma_{\bar{\mathrm{n}}}}{d^3\vec{k_{\bar{\mathrm{n}}}}} \left(\sqrt{s} - 2E_{\bar{\mathrm{p}}}, \vec{k_{\bar{\mathrm{n}}}}\right) \;+\; \left(\vec{k_{\bar{\mathrm{p}}}} \leftrightarrow \vec{k_{\bar{\mathrm{n}}}}\right) \right\} \quad . \end{aligned} \tag{1}$$

In the case of a neutralino annihilation, the differential multiplicity for antideuteron production may be expressed as a sum, extending over the various quarks and gluons h as well as over the different annihilation channels F, of the square of the antiproton differential multiplicity (Donato, Fornengo, & Salati, 1999)

$$\frac{dN_{\bar{\mathrm{D}}}}{dE_{\bar{\mathrm{D}}}} = \left(\frac{4\, {P_{\mathrm{coal}}}^3}{3\, k_{\bar{\mathrm{D}}}}\right) \left(\frac{m_{\bar{\mathrm{D}}}}{m_{\bar{\mathrm{p}}}\, m_{\bar{\mathrm{n}}}}\right) \sum_{\mathrm{F,h}} B^{(\mathrm{F})}_{\chi\mathrm{h}} \left\{ \frac{dN^{\mathrm{h}}_{\bar{\mathrm{p}}}}{dE_{\bar{\mathrm{p}}}} \left(E_{\bar{\mathrm{p}}} = E_{\bar{\mathrm{D}}}/2\right) \right\}^2 \quad . \tag{2}$$

That sum is weighted by the relevant branching ratios $B^{(\mathrm{F})}_{\chi\mathrm{h}}$.

3 The supersymmetric antideuteron signal against its background:

For kinematic reasons, a spallation reaction creates very few low–energy particles. Low–energy secondary antideuterons are even further suppressed. Energy loss mechanisms are also less efficient in shifting the antideuteron energy spectrum towards low energies. The corresponding interstellar (IS) flux reaches a maximum of $2-5\times10^{-8}$ $\bar{\mathrm{D}}$ m^{-2} s^{-1} sr^{-1} GeV^{-1} for a kinetic energy of ~ 4 GeV/n, depending on the input cosmic–ray proton spectrum. A dozen of secondary antideuterons should be collected by the AMS/ISS experiment.

On the other hand, supersymmetric $\bar{\mathrm{D}}$'s are manufactured at rest with respect to the Galaxy. In neutralino annihilations, antinucleons are predominantly produced with low energies. This feature is enhanced by their

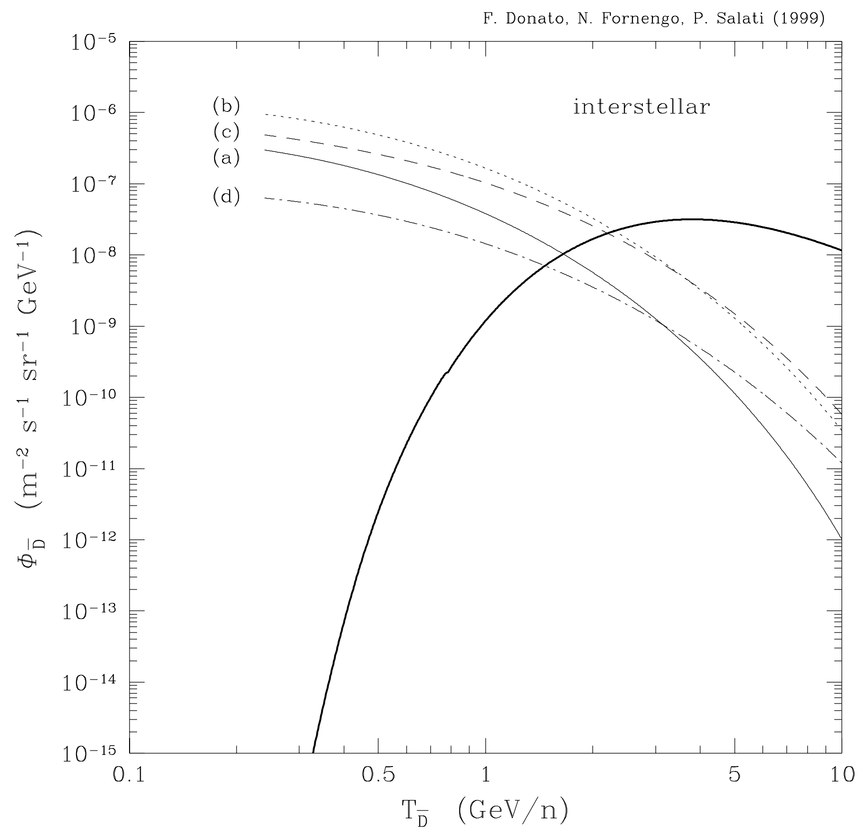

Figure 1: The IS flux of secondary antideuterons (heavier solid curve) decreases at low energy whereas the energy spectrum of the antideuterons from supersymmetric origin tends to flatten. The four cases discussed in Donato, Fornengo, and Salati (1999) are respectively featured by the solid (a), dotted (b), dashed (c) and dot-dashed (d) curves.

subsequent fusion into antideuterons, hence a fairly flat spectrum for supersymmetric antideuterium nuclei as shown in Fig. 1. Below a few GeV/n, secondary antideuterons are quite suppressed with respect to their supersymmetric partners. That low–energy suppression is orders of magnitude more effective for antideuterons than for antiprotons. This makes cosmic–ray antideuterons a much better probe of supersymmetric dark matter than antiprotons.

Unfortunately, antideuteron fluxes are quite small with respect to $\bar{\rm p}$'s. Donato, Fornengo, and Salati (1999) have shown that a significant portion of the supersymmetric parameter space may nevertheless be explored by measuring the cosmic–ray $\bar{\rm D}$ flux at low energy. In particular, an AMS/ISS caliber experiment should reach a sensitivity of 4.8×10^{-8} $\bar{\rm D}$ $\rm m^{-2}\ s^{-1}\ sr^{-1}\ GeV^{-1}$ at solar minimum, pushing it down to 3.2×10^{-8} $\bar{\rm D}$ $\rm m^{-2}\ s^{-1}\ sr^{-1}\ GeV^{-1}$ at solar maximum, for a modulated energy of 0.24 GeV/n.

4 Conclusions:

Supersymmetric antiprotons are four orders of magnitude more abundant in cosmic–rays than antideuterons. However, they may be swamped in the background arising from their secondaries. Future experiments will collect a large number of antiprotons. Our concern is whether an hypothetical supersymmetric $\bar{\rm p}$ signal may be disentangled from the background. Because the latter still suffers from large theoretical uncertainties, we are afraid that antiproton searches in cosmic–rays are not yet the ultimate probe for the existence of supersym-

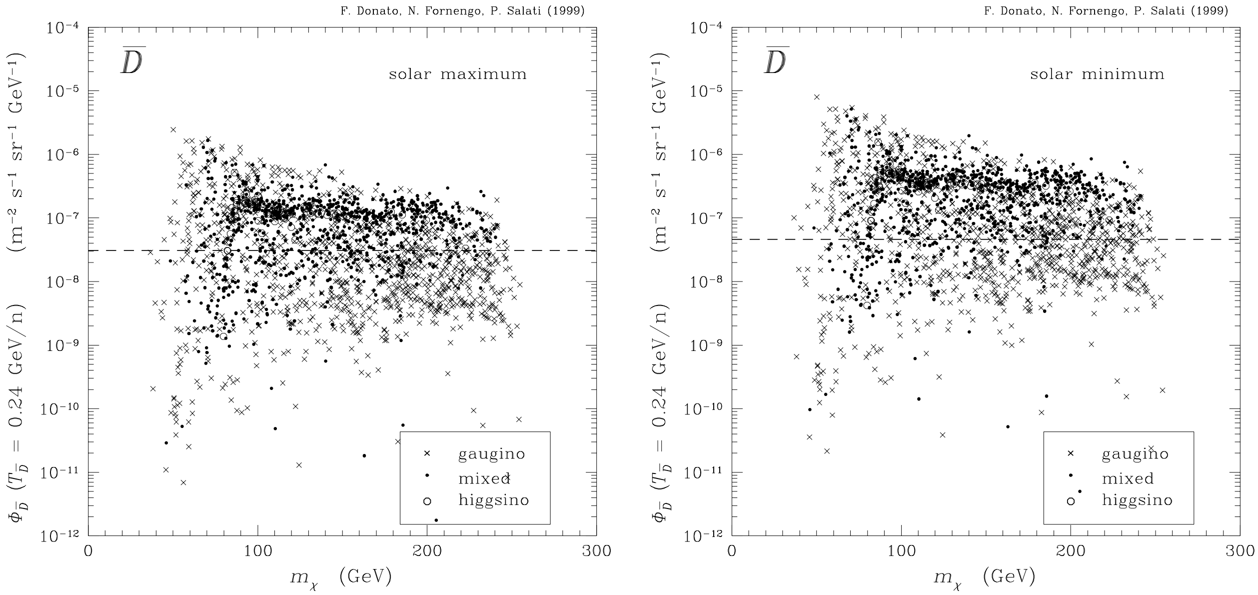

Figure 2: Scatter plots in the plane m_χ–$\Phi_{\bar{\mathrm{D}}}^{\mathrm{TOA}}$. The Earth antideuteron flux $\Phi_{\bar{\mathrm{D}}}^{\mathrm{TOA}}$ has been computed at solar maximum (`left`) and minimum (`right`), for a modulated energy of 0.24 GeV/n. Configurations lying above the horizontal lines correspond to the detection of at least one antideuteron in the range of interstellar energies 0.1 – 3 GeV, by an experiment of the AMS caliber on board ISS.

metric relics in the Milky Way. The distribution of secondary antiprotons turns out to be flatter than previously estimated. Therefore, it is still a quite difficult task to ascertain which fraction of the measured antiproton spectrum may be interpreted as a supersymmetric component. Notice however that as soon as the secondary $\bar{\mathrm{p}}$ flux is reliably estimated, low–energy antiproton searches will become a more efficient tool.

In the mean time, searches for low–energy antideuterons appear as a plausible alternative, worth being explored. A dozen spallation antideuterons should be detected by the future AMS experiment on board ISS above a few GeV/n. For energies less than $\sim$ 3 GeV/n, the $\bar{\mathrm{D}}$ spallation component becomes negligible and may be supplanted by a potential supersymmetric signal. We conclude that the discovery of a few low–energy antideuterons should be taken seriously as a clue for the existence of massive neutralinos in the Milky Way.

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