Antimatter from supersymmetric dark matter

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Abstract. We propose low–energy antideuterons in cosmic rays as a new possible signature for indirect detection of supersymmetric dark matter. Since the energy spectrum of the antiproton secondary component is still spoilt by considerable theoretical uncertainties, looking for low–energy antideuterons seems a plausible alternative. We apply our calculation to the AMS experiment, when mounted on the International Spatial Station. If a few low–energy antideuterons will be discovered by AMS, this should be seriously taken as a clue for the existence of relic, massive neutralinos in the dark halo of our Galaxy.

1 Introduction.

The dark matter in the Universe and, in particular, in our Galaxy, could be mostly made of WIMPs (Weakly Interacting Massive Particles). The most appealing candidates to WIMPs are believed to be the heavy and neutral species predicted by supersymmetry, called neutralinos. The mutual annihilations of these relics in the halo of our Galaxy would 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 \( \bar{p} \) secondaries is a priori negligible. There is quite an excitement trying to extract from the observations a possible \( \bar{p} \) exotic component which would signal the presence of supersymmetric dark matter in the Galaxy. Unfortunately, it has been recently realized [1–3] that a few processes add up together to flatten out, at low energy, the spectrum of secondary antiprotons. Disentangling an exotic supersymmetric contribution from the conventional component of spallation antiprotons seems to be a very difficult task.

Antideuterons, i.e., the nuclei of antideuterium, are free from such problems. The two antinucleons must be at rest with respect to each other in order for fusion to take place successfully. For kinematic reasons, a spallation reaction creates very few low–energy particles and low–energy secondary antideuterons are very strongly suppressed. On the other hand, in neutralino annihilations, antinucleons are predominantly produced with low energies and supersymmetric \( \bar{D} \)'s are manufactured at rest with respect to the Galaxy. This feature is further enhanced by their subsequent fusion into antideuterons: a fairly flat spectrum for supersymmetric antideuterium nuclei is expected.

\[ \text{Report on work done in collaboration with N. Fornengo and P. Salati} \]
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 āp’s. We will nevertheless show in Sect. 3 that a significant portion of the supersymmetric parameter space may be explored by measuring the cosmic–ray āD flux at low energy, in particular by an AMS/ISS caliber experiment.

2 Production and propagation of antideuterons.

The processes at stake are both the spallation of a cosmic–ray high–energy proton on an atom at rest in the interstellar medium (secondary component) and the annihilation of a neutralino pair in the galactic dark halo (primary component). For each of the processes under concern, 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 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. A fully description of the processes at stake is carried in Ref. cite(no).

Here we only report the final formula which we obtained for the differential multiplicity of an antideuteron when originated from a neutralino pair annihilation:

\[
\frac{dN_{\bar{D}}}{dE_{\bar{D}}} = \left( \frac{4 P_{\text{coal}}}{3 k_{\bar{D}}} \right) \left( \frac{m_{\bar{D}}}{m_{\bar{p}} m_{\bar{n}}} \right) \sum_{F,h} B_{\chi h}^{(v)} \left( \frac{dN_{\bar{p}}}{dE_{\bar{p}}} \left( E_{\bar{D}} = E_{\bar{D}}/2 \right) \right)^2 .
\]

(1)

It 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. That sum is weighted by the relevant branching ratios. The antineutron and antiproton differential distributions have been assumed to be identical. Here \(m_{\bar{D}}, m_{\bar{p}}, m_{\bar{n}}\) are, respectively, the antideuteron, the antiproton and the antineutron mass, while \(k_{\bar{D}}\) is the antideuteron momentum. \(P_{\text{coal}}\) is a critical value for the two–body reduced system momentum and is linked to the fusion model.

The propagation of cosmic–rays inside the Galaxy is strongly affected by their scattering on the irregularities of magnetic fields, leading to a diffusive transport. Our Galaxy can be reasonably well modelled by a thin disk of atomic and molecular hydrogen, with radius \(R \sim 20\) kpc and thickness \(\sim 200\) pc. This gaseous ridge is sandwiched between two diffusion regions which act as confinement domains as a result of the presence of irregular magnetic fields. They extend vertically up to \(\sim 3\) kpc apart from the central disk. We address to Refs. [4,1]
Fig. 1. Secondary antideuteron spectrum: interstellar (solid curve), at solar maximum (dashed line) and solar minimum (dotted line).

for a careful description of the diffusion model we employed for the propagation of both the primary and secondary component.

In Fig. 1, the interstellar $\bar{D}$ spectrum (solid curve) has been modulated at solar maximum (dashed line) and solar minimum (dotted line). We have applied the forced field approximation [5] to estimate the effect of the solar wind on the cosmic–ray energies and fluxes. We can see that the antideuteron spectrum sharply drops below a few GeV/n. For kinematical reasons, the production of antinucleons at rest with respect to the Galaxy is extremely improbable. The manufacture of a low–energy antideuteron is even more improbable. It actually requires the creation of both an antiproton and an antineutron at rest. The momenta need to be aligned in order for fusion to succesfully take place. Low–energy antideuterons produced as secondaries in the collisions of high–energy cosmic–rays with the interstellar material are therefore extremely scarce, with a completely depleted energy spectrum below $\sim 1$ GeV/n. The spallation background is negligible in the region where supersymmetric $\bar{D}$’s are expected to be most abundant. This feature makes the detection of low–energy antideuterons an interesting signature of the presence of supersymmetric relics in the Galaxy.

To this aim, we have calculated the flux corresponding to four configurations (see Table 1 of Ref. [4] for details), aimed to illustrate the richness of the supersymmetric parameter space. As a theoretical framework, we use the Minimal Supersymmetric extension of the Standard Model (MSSM) (see [4] and references quoted therein) which conveniently describes the supersymmetric phenomenol-
ogy at the electroweak scale, without too strong theoretical assumptions. We present our results in Fig. 2.

We can see from this figure that the primary fluxes flatten at low energy where they reach a maximum. As the secondary $\bar{D}$ background vanishes, the supersymmetric signal is the largest. Neutralino annihilations actually take place at rest in the galactic frame. The fragmentation and subsequent hadronization of the jets at stake tend to favour the production of low–energy species. Therefore, the spectrum of supersymmetric antiprotons – and antineutrons – is fairly flat below $\sim 1$ GeV. For the same reasons, the coalescence of the primary antideuterons produced in neutralino annihilations predominantly takes place with the two antinucleons at rest, hence a flat spectrum at low energy.

In Fig. 3, the supersymmetric–to–spallation interstellar flux ratios for antiprotons (lower curves) and antideuterons (upper curves) are presented as a function of the kinetic energy per nucleon, for the same configurations as before. In the case of antiprotons, the primary–to–secondary ratio is much smaller than for antideuterons. The supersymmetric antiproton signal is swamped in the flux of the secondaries. This is not the case for antideuterons. At low energies, their supersymmetric flux is several orders of magnitude above background. Antideuterons appear therefore as a much cleaner probe of the presence of supersymmetric relics in the galactic halo than antiprotons. The price to pay however is a much smaller flux. It is therefore crucial to ascertain which portion of the supersymmetric configurations will be accessible to future experiments through the detection of low–energy cosmic–ray antideuterons.
3 Discussion and conclusions.

In order to be specific, we have estimated the amount of antideuterons which may be collected by the AMS experiment [6], once it is on board ISS. The future space station is scheduled to orbit at 400 km above the sea level, with an inclination of $\alpha = 52^\circ$ with respect to the Earth equator. A revolution takes about 1.5 hours so that ISS should fly over the same spot every day. The AMS detector may be pictured as a cylindrical magnetic field with diameter $D = 110$ cm. At any time, its axis points towards the local vertical direction.

Since the terrestrial magnetic field prevents particles from penetrating downwards, at any given geomagnetic latitude $\vartheta$ there exists a rigidity cut-off $R_{\text{min}}$ below which the cosmic-ray flux is suppressed. The value of the effective solid angle through which the arriving particles are potentially detectable depends on the cosmic-ray rigidity $p$ as well as on the precise location of the detector along the orbit (see [4] for any detail).

The net number of cosmic-ray species which AMS may collect on board ISS is actually a convolution of the detector acceptance $\mathcal{A}$ with the relevant differential flux at Earth. For antideuterons, this leads to

$$N_{\bar{D}} = \int \mathcal{A}(p_{\bar{D}}) \Phi_{\bar{D}}(p_{\bar{D}}) dT_{\bar{D}},$$

where the integral runs on the $\bar{D}$ modulated energy $T_{\bar{D}}$. 

Fig. 3. The supersymmetric–to–secondary IS flux ratio for antiprotons (lower curves) and antideuterons (upper curves) is presented as a function of the kinetic energy per nucleon. The supersymmetric configurations are those described in the text.
Integrating the secondary flux previously discussed leads respectively to a total of 12.3 and 13.4 antideuterons, depending on whether the solar cycle is at maximum or minimum. These spallation $\bar{D}$'s are mostly expected at high energies. As is clear from Fig. 2, the secondary flux drops below the supersymmetric signal below a few GeV/n. The transition typically takes place for an interstellar energy of 3 GeV/n. Below that value, the secondary antideuteron signal amounts to a total of only 0.6 (solar maximum) and 0.8 (solar minimum) nuclei. Most of the supersymmetric signal is therefore concentrated in a low–energy band extending from the AMS threshold of 100 MeV/n up to an upper bound of 3 GeV/n in interstellar space.

**Fig. 4.** The number $N_{\bar{D}}$ of antideuterons which AMS on board ISS can collect between 0.1 up to 3 GeV/n, plotted as a function of the neutralino mass $m_\chi$.

For each supersymmetric configuration, the $\bar{D}$ flux has been integrated over that low–energy range. The resulting yield $N_{\bar{D}}$ which AMS may collect on board ISS is presented as a function of the neutralino mass $m_\chi$ in the scatter plot of Fig. 4. During the AMS mission, the solar cycle will be at maximum. A significant portion of the parameter space is associated to a signal exceeding one antideuteron – horizontal dashed line.

A complementary information may be derived from Fig. 5, where the $\bar{D}$ modulated flux is featured as a function of the neutralino mass $m_\chi$. The antideuteron energy at the Earth has been set equal to 240 MeV/n. The flux $\Phi_{\bar{D}}^\oplus$ is larger at solar minimum – when modulation is weaker – than at maximum, the lower
The cosmic–ray energy, the larger that effect. The supersymmetric configurations which an antideuteron search may unravel are nevertheless more numerous at solar minimum. Between the left and the right panels, the constellation of representative points is actually shifted upwards and, relative to the limit of sensitivity, the increase amounts to a factor \( \sim 2 \). In spite of the low fluxes at stake, the antideuteron channel is sensitive to a respectable number of supersymmetric configurations.

As already discussed, 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 \( \bar{p} \) flux is reliably estimated, low–energy antiproton searches will become a more efficient tool. Meanwhile, we must content ourselves with using observations as a mere indication of what a supersymmetric component cannot exceed. The vertical shaded band of Fig. 6 corresponds actually to the \( 1–\sigma \) antiproton flux which the BESS 95 + 97 experiments [7] have measured at a \( \bar{p} \) kinetic energy of 0.24 GeV. In Fig. 6, the supersymmetric antideuteron yield \( N_{\bar{D}} \) has been derived at solar maximum. This corresponds to the conditions of the future AMS mission on board the space station. The antideuteron yield is plotted as a function of the associated supersymmetric \( \bar{p} \) flux at Earth. The latter is estimated at solar minimum to conform to the BESS data to which the vertical band refers. The scatter plot of Fig. 6 illustrates the strong correlation between the antideuteron and the antiproton signals, as may be directly guessed from Eq. 1. The horizontal dashed line indicates the level of sensitivity which AMS/ISS may reach. Points located above that line but on the left of the shaded vertical band are supersymmetric configurations that are not yet excluded by antiproton searches and for which the
Fig. 6. The antideuteron yield $N_D$ of Fig. 4 against the supersymmetric $\bar{p}$ flux. The antideuteron signal is estimated at solar maximum. This corresponds to the AMS mission on board the space station. The $\bar{p}$ flux is derived on the contrary at solar minimum, in the same conditions as the BESS 95 + 97 flights [7], whose combined measurements are indicated by the vertical shaded band for a $\bar{p}$ energy of 0.24 GeV. The correlation between the antiproton and antideuteron signals is strong.

antideuteron yield is potentially detectable. The existence of such configurations illustrates the relevance of an antideuteron search at low energies, appearing 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 $\bar{D}$ spallation component becomes negligible and may be supplanted by a potential supersymmetric signal. The discovery of a few low–energy antideuterons should be taken seriously as a clue for the existence of massive neutralinos in the dark halo of our Galaxy.

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