Antideuterons from decaying gravitino dark matter

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Abstract. From the point of view of Dark Matter searches, antideuteron are an interesting species of cosmic rays. In the past eighteen years much progress has been done in the understanding of these cosmic rays but this did not translate into experimental efforts to actually detect these particles. In this work, starting from a specific case of dark matter candidate with relatively generic features, we study some sources of theoretical uncertainties and show that the margin of improvement beyond the limits already set by cosmic-ray antiproton are quite narrow and anyway unachievable for the next generation of experiments.

1. Introduction
Most current cosmic-ray detectors have the ability to determine the mass of the incoming particles – and in some cases also their charge. However, some isotopes in the cosmic-ray particle spectrum still remain to be observed – among those antideuterons. Donato, Fornengo and Salati were the first who suggested that antideuterons would be an interesting species for the search of dark matter (DM) via cosmic rays [1]. Since this pioneering work, various authors have followed up on this idea [2–7]. Indeed, antimatter atoms like antideuterium cannot exist in stars. Therefore, they should not exist as astrophysical primary cosmic rays. The only astrophysical process that is expected to produce it is the spallation of cosmic rays off the interstellar medium (ISM). For kinematic reasons, this secondary flux is supposed to be very low at low energies [8]. If, however, DM annihilations or decays lead to the production of antideuterons, their spectrum would not exhibit this kinematic threshold. This leads to the conclusion that the observed antideuteron flux from DM annihilation or decay in the Galactic halo could be orders of magnitude higher than the astrophysical background at very low energies [1].

Even though it has been understood that because of tertiary production [9] and energy losses taking place during the cosmic-ray propagation [2] the difference between secondary and primary fluxes may not be as high as originally expected, antideuterons are still considered one of the most interesting species for DM searches.

In the present work, we investigate the case of gravitino DM within the framework of bilinear \(R\)-parity violation \([10,11]\). In this type of scenario the gravitino would be long-lived enough to be the DM in the Universe but would eventually decay and produce – among other species – antideuterons. A main motivation for this scenario is that it leads to a consistent cosmological...
scenario, explaining the baryon asymmetry of the Universe via thermal leptogenesis and avoiding any cosmological gravitino problems [11]. For a more detailed introduction of the model, please consult our previous work, where we studied constraints on the gravitino lifetime from cosmic-ray antiprotons in the same theoretical framework [12]. Note that this model has no extremely unusual features and the conclusions of this work can easily be generalised.

2. Cosmic-ray antideuterons
Galactic cosmic-ray propagation is a vast field of study still under investigation and for which many improvements are still expected. However, the diffusion model that is the most commonly used, is quite successful in reproducing the measured flux of secondary species such as antiprotons. This model takes into account diffusion off inhomogeneous interstellar magnetic fields, convection from stellar winds, diffusive re-acceleration and energy losses through interaction with the interstellar gas. The resolution of the diffusion equation is done through a semi-analytical methods that is fast enough to allow scans over the parameter space. A precise description of this model and of the cross-sections used in this work can be found in [13].

As for the case of antiprotons, no primary antideuterons are expected from astrophysical objects and the dominant background for DM searches are secondary antideuterons created in spallation processes of cosmic-ray protons and helium nuclei impinging on the ISM, i.e. hydrogen and helium gas. In order to estimate the background for the signal from gravitino decay, we employ here the same calculation of the astrophysical secondary antideuteron flux as used in [2]. As one can see in figure 1, various processes have to be taken into account for the calculation of the antiproton and antideuteron fluxes. These are summarised in table 1.

| Primaries          | $\psi_{3/2} \xrightarrow{\text{Decay}} \bar{p} + X$ |
|--------------------|--------------------------------------------------|
| Secondaries        | $p \xrightarrow{+\text{ISM}} \bar{p} + X$       |
| Tertiaries         | $\bar{p} \xrightarrow{+\text{ISM}} \bar{p} + X$ |

Table 1: Relevant processes for calculating the flux of antiprotons (left) and antideuterons (right).

Since both primaries and secondaries produce tertiaries, i.e. cosmic rays produced by the non-annihilating inelastic scattering of high-energy antideuterons on the ISM, we have not shown this component separately but rather added it directly to our estimates of the primaries and secondaries, respectively. However, we stress that this process, as well as convection and diffusive reacceleration, have important impact on the low-energy part of the computed fluxes and should not be neglected. Note also that in the case of antideuterons the secondaries coming from the spallation of primary antiprotons, i.e. antiprotons of DM origin, on the ISM are to be considered as signal and not background. This component is much lower than the primary component and the background when the gravitino mass is low, but for masses higher than 10 TeV, it is of the same order of magnitude as the primary component and hence should not be neglected. Figure 1 displays these different components for a gravitino mass of 100 GeV.

In figure 2, we present the interstellar antideuteron spectrum from gravitino DM decays and compare it to the expected astrophysical background and the flux limit obtained by the BESS experiment [14]. In addition, we present the projected sensitivity regions of the BESS-Polar II [15], AMS-02 [16] and GAPS [17] experiments. In the left panel, we show the uncertainty

1 The GAPS sensitivity assumed in this work corresponds to three Antarctic long duration balloon flights with
Figure 1: Various components of the antiproton and antideuteron fluxes at Earth. The astrophysical background (secondaries) comes from the interaction of cosmic-ray protons and α-particles with the ISM. For the case of antideuterons also interactions of secondary antiprotons with the ISM contribute. The primary antiproton and antideuteron components come from gravitino decay; for the case of antideuterons also from the interaction of primary antiprotons with the ISM. The tertiary component corresponds to a redistribution of high-energy cosmic rays to lower energies due to non-annihilating inelastic scattering off the ISM. Since every component creates teriaries, they have been incorporated directly and are not displayed as separate components.

band due to the lack of precise knowledge of the propagation parameters as constrained by measurements of the boron-to-carbon ratio in cosmic rays [19]. The coloured bands correspond to a full scan over the allowed parameter space. As an illustration we also display the fluxes obtained with three benchmark models often used in the literature. We use a common decay lifetime of $\tau_{3/2} = 10^{28}\text{s}$ for illustration. Note that, as for the case of antiprotons, the MIN/MED/MAX benchmark models do not size the full extent of the uncertainty band. This shows again the importance of performing scans over the full propagation parameter space allowed by other data rather than checking only a few cases.

In the right panel of figure 2, we display the same fluxes but setting the decay lifetime to the minimum values allowed by the constraints obtained using the antiproton measurements (see [12]). Note that the coloured bands correspond to the extreme cases obtained for antiprotons and are not the full uncertainty band. Indeed, the limiting cases correspond to situations where the antiproton flux is maximised at a given energy bin. This does not mean that the antideuteron flux is maximal over the whole energy range.

3. Discussion of the Detection Prospects
A striking feature of figure 2 is that for masses as low as 100 GeV the gravitino decay signal can be of the same order as the astrophysical background below a few GeV, even for lifetimes as large as $10^{28}\text{s}$, a value not yet excluded by gamma-ray and antiproton observations (see for instance [20]). In this respect, it would also be interesting to see what antideuteron flux could a total duration of 105 days [18].
Figure 2: Left: Cosmic-ray antideuteron flux expected from the decay of gravitino DM compared to the expectation from astrophysical secondary production and the sensitivities of forthcoming experiments. The flux from gravitino decay is shown for a lifetime of $10^{28}$ s and masses of 100 GeV, 1 TeV and 10 TeV. The coloured bands correspond to propagation uncertainties within constraints from boron-to-carbon ratio measurements. Right: Same as left panel but fixing the gravitino lifetime to the lowest value allowed by antiproton constraints. No solar modulation has been implemented here since the time of data taking is unknown.

be expected for even lower gravitino masses. It could thus be worthwhile to study this region in a future work using the spectra obtained from gravitino three-body decays [21].

But also for larger gravitino masses the antideuteron signal could be at the same order as the background. This was not observed in earlier studies as the signal for large DM masses is artificially suppressed in the factorised coalescence prescription. Therefore, for decaying DM candidates there is in principle also the possibility of observing an exotic component in the higher-energetic part of the spectrum, where currently no experiments are planned. Note, however, that both background and signal are extremely low and quite challenging for experimentalists as this would mean improving sensitivity by at least four orders of magnitude in flux, but also to reach much higher energies.

When taking into account the constraints derived from antiproton observations [12], we find that the remaining parameter space for having a gravitino decay signal significantly higher than the astrophysical background becomes quite small but does not vanish completely. Since the coalescence process still suffers large theoretical uncertainties, one cannot exclude that all the fluxes are in fact larger (or smaller) than what we assume here.

Still, it seems clear that the current generation of experiments will not be able to observe any antideuteron events. Only an improvement of the flux sensitivity by two orders of magnitude aiming for a detection of astrophysical antideuterons should be the target of the next generation of experiments. Concerning Dark Matter search, the main hopes seem to reside either in the highest energy range (above $\sim 50$ GeV) or in the lowest one (below $\sim 1$ GeV). Note, however, that the latter is affected by solar modulation, a phenomenon that to date is not fully under modelling control.

This clearly challenges antideuterons as the golden channel it has long thought to be. Indeed the antiproton channel has become extremely constraining thanks to the PAMELA data [22]. A forthcoming release of AMS-02 antiproton data could make these constraints a bit more stringent, especially at higher energies.
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