Anti-helium from Dark Matter annihilations

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Abstract

Galactic Dark Matter (DM) annihilations can produce cosmic-ray anti-nuclei via the nuclear coalescence of the anti-protons and anti-neutrons originated directly from the annihilation process. Since anti-deuterons have been shown to offer a distinctive DM signal, with potentially good prospects of detection in large portions of the DM-particle parameter space, we explore here the production of heavier anti-nuclei, specifically anti-helium. Even more than for anti-deuterons, the DM-produced anti-He flux can be mostly prominent over the astrophysical anti-He background at low kinetic energies, typically below 3-5 GeV/n. However, the larger number of anti-nucleons involved in the formation process makes the anti-He flux extremely small. We therefore explore, for a few DM benchmark cases, whether the yield is sufficient to allow for anti-He detection in current-generation experiments, such as AMS-02. We account for the uncertainties due to the propagation in the Galaxy and to the uncertain details of the coalescence process, and we consider the constraints already imposed by anti-proton searches. We find that only for very optimistic configurations it might be possible to achieve detection with current generation detectors. We estimate that, in more realistic configurations, an increase in experimental sensitivity at low-kinetic energies of about a factor of 500-1000 would allow to start probing DM through the rare cosmic anti-He production.

1 Introduction

The particle Dark Matter (DM) which is believed to constitute the halo of our Galaxy (as well as shaping the large scale structures of the Universe) is proving to be more elusive than
ever to direct searches. The search for possible ‘smoking guns’ is therefore as important as it has ever been. One of such smoking guns could be the observation of exotic light anti-nuclei in the cosmic radiation, possibly produced by DM via the rapid coalescence of the anti-nucleons ($\bar{p}$ and $\bar{n}$) emerging among the final products of the annihilation processes in the galactic halo. Indeed, the astrophysical background for these species is predicted to be extremely reduced and to be peaking in a range of energies typically different from the one of the DM-originated one (this is due essentially to the different kinematics in the production processes, as we will recall below). Hence, the claim is often made that the detection of even a single anti-nucleus in the foreseen energy range could constitute a very compelling hint in favor of DM. A well explored scenario is the one of anti-deuterons, which have been proposed more than a decade ago [1] and continue to be of interest [2, 3, 4]. In this paper, instead, we ask whether anti-helium (hereafter anti-He) nuclei could be produced in DM annihilations with a sizable yield to which current experiments such as AMS-02 could be sensitive. Indeed, the AMS-02 experiment lists among its physics goals the search for anti-He and it foresees to push the sensitivity down by several orders of magnitude with respect to the bounds imposed by other recent experiments [5]. It is therefore timely to investigate whether a signal from DM could emerge in such an exotic channel.

The rest of this short paper is organized as follows. In Sec. 2 we review the production mechanism of anti-He, while in Sec. 3 we review its propagation in the Galaxy. In Sec. 4 we present the predicted fluxes for a few relevant benchmark DM cases and in Sec. 5 we put forward our conclusions.

2 Production by coalescence

The production of anti-nuclei in a given reaction is usually described within the framework of the so-called coalescence model [6, 7]. The idea behind this approach is very simple: some of the anti-nucleons produced in the reaction under scrutiny can merge to form an anti-nucleus if their relative momenta is less than an effective parameter, the coalescence momentum $p_{\text{coal}}$, which is usually determined from comparison with experimental data (when available). By following the coalescence approach, the spectrum of an anti-nucleus $\bar{A}$ with mass number $A$ can be written as:

$$
\gamma A \frac{d^3 N_{\bar{A}}}{d^3 k_{\bar{A}}} = \left( \frac{4}{3} \beta_{\text{coal}}^3 \right)^{A-1} \left( \frac{\gamma \beta_{\bar{p}}}{d \beta_{\bar{p}} k_{\bar{p}}} \right)_{k_{\bar{p}}=k_{\bar{A}}/A}^A (1)
$$

As one should expect, the coalescence mechanism predicts that the increase of the mass number $A$ comes with a rapid growth in the suppression factor for the yield of the anti-nucleus $\bar{A}$. As a simple rule of thumb (based on the results of [7, 8]), we can assume that for each additional anti-nucleon involved in the merging process we should expect a decrease of the yield by a factor $O(10^{-4})$. Thus, we decide to focus only on the anti-$^3\text{He}$ and to disregard completely the contribution from anti-$^4\text{He}$.

As shown in [3] for the case of the anti-deuteron production, in order to have a correct computation of the anti-nuclei yields, the details of the angular distribution of the anti-nucleons in the final state, together with possible (anti-)correlations between them, must be taken into account. This can be done by using a MonteCarlo (MC) coalescence model which basically consists in checking on an event-per-event basis if the anti-nucleons that are
produced in a DM annihilation event (which is simulated by using a MC event generator) are sufficiently close in momentum space for the coalescence to occur. In this paper we adopt this approach: for our MC coalescence model we use the MC event generator PYTHIA 6.4.26 [9] and, for each DM candidate that we consider, we simulate $O(10^{10})$ annihilation events (the exact number depending on the condition of reaching a sufficient anti-He statistics). We assume that three anti-nucleons $N_1, N_2, N_3$ merge in a single bound state if all their relative momenta ($||\vec{k}_{N_1} - \vec{k}_{N_2}||, ||\vec{k}_{N_2} - \vec{k}_{N_3}||, ||\vec{k}_{N_3} - \vec{k}_{N_1}||$) are smaller than $p_{coal}$, being $\vec{k}_{N_i}$ the anti-nucleon momenta in the center of mass frame of the $N_1, N_2, N_3$ system (which corresponds to the rest frame of the bound state). In addition, one can easily understand that the anti-He spectrum can be overestimated if the information about the anti-nucleons positions in the physical space is disregarded: in fact, it is highly unlikely to have a coalescence if the three anti-nucleons are formed far from each other (as it is if, for example, one of them comes from the decay of a relatively long-lived particle) [4]. This condition is taken into account by switching off (to the maximal extent allowed by the event generator) the decay of all the long-lived particles (i.e. those with a lifetime $\tau > 10^{-15}$ sec) in our MC event generator.

The anti-nucleons that can take part in the formation process of an anti-He nucleus can be either two $\bar{p}$ and one $\bar{n}$ (and in this case the anti-He is formed directly) or two $\bar{n}$ and one $\bar{p}$ (i.e. in this case the anti-He is the result of the formation of an anti-tritium that subsequently decays into an anti-He in a process that, given the typical propagation scales with which we are dealing, can be considered as occurring instantaneously). However, as stated in [8], we expect the direct formation of the anti-He in the $\bar{p}\bar{n}\bar{n}$ channel to be suppressed by Coulombian repulsion between the two anti-protons. Such repulsion could also induce spectral distortions. Thus, in the following, in order to be as conservative as possible, we will only show the anti-He yields that are produced by the coalescence in the $\bar{p}\bar{n}\bar{n}$ channel. However, we checked that, if the same coalescence momentum is used for the two cases, these two contributions are practically equal for all the benchmark cases that we consider (see Section 4), this being an expected consequence of the fact that the $\bar{p}$ and the $\bar{n}$ production cross sections, in a DM annihilation event, are almost equal. Thus, if one wants to add also the contribution from the coalescence in the $\bar{p}\bar{p}\bar{n}$ channel to the anti-He yields that we show in Section 4, it is sufficient to multiply the fluxes by a factor 2 (if the coulombian repulsion is completely neglected) or smaller (if the coulombian repulsion is taken into account).

Experimental data on the anti-He (or anti-tritium) production are extremely scarce in the literature and they refer uniquely to proton-nucleus [10] or heavy-ions collisions [11] whose dynamics is clearly very different from the one of a DM pair annihilation reaction. Thus, we decide to use as a reference value for the coalescence momentum $p_{coal}$ the one that was found in [4] to reproduce, within the same MC coalescence algorithm, the anti-deuteron production rate in $e^+e^-$ collisions at the $Z$ resonance measured by the ALEPH collaboration at the LEP collider [12], i.e. $p_{coal} = 195$ MeV. However, we must warn the reader that the value of the $p_{coal}$ parameter largely affects our results, as its clear also from Eq. (1) in which for $A = 3$, the dependence from $p_{coal}$ is in the form $p^6_{coal}$. To give an idea of the role played by $p_{coal}$ within our MC coalescence mechanism, in Section 4 we will show how the anti-He flux varies if values of the $p_{coal}$ parameter greater than our reference value are chosen.
3 Propagation in the Galaxy

Once anti-He nuclei are created at any given point in the galactic halo, they have to propagate through the Galaxy all the way to the collection point (the Earth). The suitable formalism to follow this process resembles closely the one adopted for anti-protons or anti-deuterons, reviewed e.g. in [13], to which we refer for further details and references. We here only summarize the main points.

The propagation of charged nuclei is described by a differential equation incorporating the different processes that they undergo:

\[
\frac{\partial f}{\partial t} - K(T) \cdot \nabla^2 f + \frac{\partial}{\partial z} \left( \text{sign}(z) f V_{\text{conv}} \right) = Q - 2h \delta(z) \Gamma f. \tag{2}
\]

Here \( f(t, \vec{x}, T) = dN_{\text{He}}/dT \) is the number density of anti-He nuclei per unit kinetic energy \( T \), in a given location \( \vec{x} \) and at a given time \( t \). \( K(T) = K_0 \beta (p/\text{GeV})^\delta \) is the coefficient of the process of diffusion of the anti-nuclei on the magnetic field inhomogeneities (with \( p = (T^2 + 2m_\text{He}^2 T)^{1/2} \) and \( \beta = v_\text{He} / c = \left( 1 - m_\text{He}^2 / (T + m_\text{He})^2 \right)^{1/2} \) the anti-nucleus momentum and velocity). \( V_{\text{conv}} \) is the velocity of the galactic convective wind. The quantity:

\[
Q = \frac{1}{2} \left( \frac{\rho}{m_{\text{DM}}} \right)^2 \sum_\alpha \langle \sigma v \rangle_\alpha \frac{dN_\alpha}{dT} \tag{3}
\]

represents the source term due to DM annihilations (with thermally averaged cross section \( \langle \sigma v \rangle \)), summed over the different channels \( \alpha \). Several different profiles can be considered for the DM density \( \rho \): Navarro-Frenk-White (denoted ‘NFW’), Moore (‘Moo’), Isothermal (‘Iso’), Einasto (‘Ein’), Burkert (‘Bur’) and contracted Einasto (‘EiB’). We refer to [13] for their precise definitions in terms of functional forms and parameters. The last term describes the interactions of anti-He on the interstellar gas in the galactic plane (with a thickness of \( h = 0.1 \text{kpc} \) with rate \( \Gamma = (n_\text{H} + 4^{2/3} n_\text{He}) \sigma_{\text{p-He}} v_\text{He} \), where \( n_\text{H} \approx 1/\text{cm}^3 \) is the disk hydrogen density and \( n_\text{He} \approx 0.07 n_\text{H} \) is the disk helium density (the factor \( 4^{2/3} \) accounting for the different geometrical cross section in an effective way). For the nuclear cross sections we use the parametrizations in Table 4.5 of [14].

Since one assumes steady state conditions, the equation is solved as \( \partial f/\partial t = 0 \). It is solved inside a cylindrical volume with borders \( z = \pm L \) and \( r = R_{\text{gal}} = 20 \text{kpc} \) (the radius of the Galaxy), on which the particle number density is taken to be vanishing. The propagation parameters entering the formalism are therefore: the normalization of the diffusion coefficient \( K_0 \), its power index \( \delta \), the velocity \( V_{\text{conv}} \) and the thickness of the diffusive region \( L \). As customary, we consider the sets ‘MIN, MED, MAX’ as listed in Table 1. The solution for the anti-He differential flux at the position of the Earth

| Model | \( \delta \) | \( K_0 \text{[kpc}^2/\text{Myr}] \) | \( V_{\text{conv}} \text{[km/s]} \) | \( L \text{[kpc]} \) |
|-------|-------------|----------------|-----------------|----------------|
| MIN   | 0.85        | 0.0016         | 13.5            | 1              |
| MED   | 0.70        | 0.0112         | 12              | 4              |
| MAX   | 0.46        | 0.0765         | 5               | 15             |

Table 1: Propagation parameters in the galactic halo (from [15]).
**Figure 1:** Propagation function for anti-$^{3}$He nuclei from annihilating DM, for the different halo profiles and sets of propagation parameters, and the corresponding fit parameters to be used in eq. (5).

\[
d\Phi/dT (T, \vec{r}_\odot) = v_{\nu_e}/(4\pi)f
d\Phi/dT (T, \vec{r}_\odot) = v_T/(4\pi) \left( \frac{\rho_\odot}{m_{DM}} \right)^2 R(T) \sum_\alpha 1/2 (\sigma v)_\alpha dN/dT
\]

The function $R(T)$ encodes all the astrophysics of production and propagation. There is such a 'propagation function’ for any choice of DM galactic profile and for any choice of set of propagation parameters among those in Table 1. We explicitly provide $R(T)$ for all these cases in terms of an interpolating function:

\[
\log_{10} [R(T)/\text{Myr}] = a_0 + a_1 \kappa + a_2 \kappa^2 + a_3 \kappa^3 + a_4 \kappa^4 + a_5 \kappa^5,
\]

with $\kappa = \log_{10} T/\text{GeV}$ and the coefficients reported in the table in Fig. 1. As could be expected, the functions are very similar in shape to the ones relevant for anti-protons and anti-deuterons, presented e.g. in [13].

The final step consists in applying the effects of the transport of the charged nuclei inside the heliosphere (solar modulation). The details of this process depend on the properties of solar activity (intensity and orientation of the solar magnetic field) at the time of observations, which is of course unknown. We follow the standard formalism (see e.g. [13]) and adopt a Fisk potential of 500 MV as a sensible choice.

## 4 Results and Discussion

By folding the production fluxes presented in Sec. 2 with the propagation functions of Sec. 3 as described in Eq. (4) we obtain the predicted anti-He spectra from DM annihilation. We illustrate the results focussing on three benchmark cases, which span a variety of relevant possibilities:

i) annihilation into light quarks ($u\bar{u}$ for definiteness) of a 20 GeV DM particle, with thermal annihilation cross section $\langle \sigma v \rangle = 3 \times 10^{-26} \text{cm}^3/\text{s}$.

ii) annihilation into $b\bar{b}$ of a 40 GeV DM particle, with thermal annihilation cross section $\langle \sigma v \rangle = 3 \times 10^{-26} \text{cm}^3/\text{s}$.
iii) annihilation into $W^+W^-$ of a 1 TeV DM particle, with a larger annihilation cross section $\langle \sigma v \rangle = 3 \times 10^{-25} \text{ cm}^3/\text{s}$.

In Fig. 2 (left) we show the fluxes (dark red lines) for Min, Med and Max propagation parameters. For what concerns the choice of the DM galactic profile, we choose Einasto for definiteness. Making another choice would have an impact on the prediction that can be easily judged from the span in the propagation functions shown in Fig. 1. Namely, essentially no impact for Min, a factor of $\sim5$ for Max.

An important point to consider is that the same annihilation process that produces anti-He of course also produces anti-protons, which are tightly constrained [16] by the PAMELA measurement [17] of a spectrum very well consistent with the predicted astrophysical background. We take these constraints into account by disfavoring the portion of the predicted region that is excluded by anti-protons (shaded in lighter color in the left panels of Fig. 2). For a concrete example: a model predicting annihilations of a 20 GeV DM particle into light quarks with thermal cross section (the case of the top left panel of Fig. 2) is allowed by anti-proton constraints only if the propagation parameters yield a flux somewhere in between Min and Med [16]; we therefore shade away the upper portion of the area spanned by the spectra. In practice, we determine the maximal annihilation cross section allowed for Med by anti-proton constraints and we then rescale the Med anti-He spectrum by the ratio of such cross section and the thermal one. The rescaled spectrum delimitates from above the allowed region (darker red in Fig. 2).

In the figures we also show the estimate of the astrophysical background (black line), that we take from [7]. As anticipated, and in analogy with the case of anti-deuterons, the astrophysical spectrum peaks in an energy range that is higher than the one of the DM fluxes (except for the case of a large DM mass). This is essentially due to the different kinematics with which an anti-He nucleus is produced in the astrophysical environment (spallation of high energy cosmic rays on interstellar gas at rest) with respect to the case of DM (annihilation at rest of two heavy particles).

We show in grey the areas currently excluded by the experiments which have looked for a flux of anti-He in cosmic rays: AMS-01 [18], BESS [19] and PAMELA [20]. Since all these experimental results are given in terms of $\overline{\text{He}}/\text{He}$ ratios, we convert them into anti-He fluxes using the He flux measured by PAMELA [21] (AMS-02 has also released preliminary data [22], that we do not use). Finally, we show in green the predicted reach of AMS-02, taken from [5]. Although there might be other experiments which might have the capabilities of detecting anti-He, we decide to limit the analysis to AMS-02 as a benchmark case.

The fluxes in the left panels in Fig. 2 are obtained adopting our fiducial value for the coalescence momentum $p_{\text{coal}} = 195$ MeV. However, as emphasized in Sec. 2, the actual value of $p_{\text{coal}}$ is highly uncertain. Moreover, even the effective description of coalescence as based on this single energy-independent parameter can be questioned. We therefore recompute the spectra spanning different values of $p_{\text{coal}}$. The results are shown in the

We correct however the PAMELA spectrum in order to account for the different value of the solar modulation parameter that we are using here.

Most notably the GAPS experiment [23] is aimed at the search of anti-deuterons with a dedicated technique which consists in slowing down the anti-deuteron entering the apparatus and then detect the pion and X ray signatures of its annihilation on the nuclei in the matter of the detector itself. It is not clear whether such an analysis can be adapted to other anti-nuclei for the GAPS set-up currently under development.
Figure 2: Predicted fluxes of anti-He from the annihilation of a 20 GeV DM particle into light quarks (top row), 40 GeV into bb (middle row) and 1 TeV into W+W− (bottom row), compared to the predicted astrophysical background, to the current bounds and to the expected sensitivity of AMS-02. Left column: the three lines from bottom to top correspond to MIN, MED, MAX. Lighter shades individuate fluxes disfavored by p constraints. Right column: varying the coalescence momentum.
right panels of Fig. 2, where we show how the fluxes allowed by anti-proton constraints are modified: the red area in the right plots reproduces the red area in the left plots, while the hashed region refers to $p_{\text{coal}} = 300$ MeV. For case iii) we increase further the value of $p_{\text{coal}}$ to 600 MeV, in order to explore what it would take to skim the AMS-02 sensitivity region.

The inspection of the results in Fig. 2 shows that, for all the cases that we have considered, the anti-He spectrum sits quite below the predicted reach of AMS-02, so that the detection perspectives are rather dim. In terms of the anti-He/He ratio, with $p_{\text{coal}} = 195$ MeV, the DM signal reaches at most $\approx 10^{-13}$ in cases i) and ii) and $\approx 10^{-11}$ in case iii). These values increase by approximately one order of magnitude if $p_{\text{coal}} = 300$ MeV. They can be confronted with the AMS-02 expected sensitivity which is at the level of $10^{-9}$ for anti-He rigidities below 150 GeV [5].

Increasing the DM annihilation cross section to augment the yield is not a viable possibility, given the stringent anti-proton constraints [16]. The one example, among the ones we considered, in which the spectrum skims the AMS-02 sensitivity region (in the highest kinetic energy portion) is for the $W^+W^-$ channel, with a FM mass of 1 TeV and annihilation cross section 10 times larger than the thermal one (case iii, allowed by antiproton bounds), when we assume $p_{\text{coal}} = 600$ MeV and if propagation is close to MAX. For this rather extreme case, however, somewhat unfortunately the shape of the spectrum resembles the one of the astrophysical background, such that, even in case of a positive detection of anti-He nuclei, ascribing the events to a DM origin would be very challenging at best.

5 Conclusions

We have computed the production of anti-He nuclei ($^3\overline{\text{He}}$) for DM annihilations in the galactic halo (performing, with PYTHIA, a MC coalescence that fully takes into account the phase space correlations between the constituent anti-nucleons), computed their transport in the Galaxy (in the MIN, MED, MAX framework) and determined the spectra at the top of the atmosphere at Earth. We focussed on a few specific DM model cases. We incorporated the constraints coming from anti-protons, showing how they restrict the available parameter space severely.

We found that the prospects for detection are currently rather weak, with the fluxes remaining from more than one to several orders of magnitude below the predicted reach of the AMS-02 experiment. It would take a very optimistic configuration of the annihilation, propagation and coalescence parameters to reach the AMS-02 sensitivity region.

While the search for antimatter in general, and exotic anti-nuclei in particular, remains a very interesting avenue for finally exposing a ‘smoking gun’ signature of particle DM in the galactic halo, we find that for anti-He a much larger sensitivity or maybe a dedicated innovative experiment would be needed.

Note Added. While this work was being completed Ref. [24] was posted on the arXiv. The two analyses are similar and reach the same qualitative conclusions. In our approach, we adopt a smaller value for the coalescence momentum and we do not sum the yield of the $\overline{p}p\overline{n}$ coalescence channel, therefore obtaining more conservative estimates for the fluxes. We fully incorporate in the computation the stringent anti-proton constraints and explicitly show their impact. Finally, we compare the predicted fluxes with present antiHe bounds and with the sensitivity of current-generation experiments.
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