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Antinuclei with the DRAGON2 code and AMS-02 preliminary observations

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The creation of anti-nuclei in the Galaxy has been has been discussed as a possible signal of exotic production mechanisms such as primordial black hole evaporation or dark matter decay/annihilation, in addition to the conventional production from cosmic-ray (CR) interactions. Tentative observations of CR antihelium by the AMS-02 collaboration have re-energized the quest to use antinuclei to search for physics beyond the standard model.

In this talk, we show state-of-art predictions of the antinuclei spectrum from both astrophysical and standard dark matter annihilation models obtained from a new version of the DRAGON2 code that is already publicly available. We find that the secondary production of antinuclei from CR interactions is capable of producing $\mathcal{O}(1)$ antideuteron event and $\mathcal{O}(0.1)$ antihelium events over 15 years of AMS-02 observations. Standard dark matter models could potentially produce $\mathcal{O}(1)$ antihelium-3 event, while the production of a detectable amount of antihelium-4 would require more exotic mechanism of productions than the standard WIMP scenario. We also discuss that annihilation/decay of a QCD-like dark sector could potentially explain the AMS-02 preliminary observations of antihelium-3 and antihelium-4.

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1. Introduction

The detection of CR antiparticles has long been used as a window for indirect searches of dark matter, in particular for WIMPs. However, no clear signature from decay or annihilation of a dark matter particle has been detected so far [1]. What is more, the measurements on the spectra of antiparticles have revealed our lack of precision on modelling their astrophysical production (either produced by sources, like pulsars [2] or primordial black holes [3], or produced from the interactions of CRs with gas [4]) and their transport throughout the Galaxy. It turns out, in fact, that the indirect WIMP searches carried out in the last years are also allowing us to improve substantially our models of propagation and production of these CRs.

Interestingly, observations by the Alpha Magnetic Spectrometer (AMS-02) on board the international space station has recently reported the tentative detection of a few antideuteron ($\overline{d}$) events and up to ten events that have charges and masses consistent with antihelium nuclei ($\overline{He}$), opening up again the game to analyse the compatibility of these signals with exotic and standard mechanisms of astrophysical production, though it is difficult to eliminate the possibility that these events are also consistent with the misreconstructed events [5, 6]. Indeed, the antihelium events detected seem to be evenly distributed in $^{3}\overline{He}$ and $^{4}\overline{He}$ (i.e. similar amounts of both isotopes of antihelium are detected). The roughly similar (within an order of magnitude) detected number of events of antihelium-4, antihelium-3 and antideuterium nuclei would be extremely unexpected. Kinematic considerations make the addition of each additional antinucleon improbable, with models predicting that each successive antinucleon species should have a flux that is suppressed by $\sim \mathcal{O}(10^4)$ compared to the previous generation [6].

Indeed, the production of $\overline{He}$ from interactions of CRs with interstellar gas is expected to be well below the AMS-02 sensitivity and completely unable to explain the detection of similar number of events of $\overline{He}$ and $\overline{d}$ nuclei. On top of this, the production of these antiparticles from a generic WIMP annihilating or decaying into Standard Model (SM) particles predict a $\overline{He}$ flux at Earth that is still far to explain the number of observed events [7]. Therefore, different exotic sources of antihelium and mechanisms to boost its production have been explored, although yet none of these models seem to be consistent with the recent observation from AMS-02.

New experiments devoted to the detection of these antinuclei are expected to be launched in the next years and many others have been proposed too. In addition, the experimental analyses methods of these preliminary measurements are also expected to be improved. Therefore, new and more refined predictions are also needed. In this contribution we present updated state-of-the-art predictions of the spectra of these light antinuclei produced from both, CR interactions and WIMP annihilation in the Galaxy using a new version of the DRAGON2 code devoted for the study of CR antiparticles.

2. Secondary production of antideuteron and antihelium

The computation of the spectra of these particles has been implemented in a new customised version of the `DRAGON2` code [8, 9], that has been publicly released at `https://github.com/tospines/Customised-DRAGON-versions/tree/main/Custom_DRAGON2_v2-Antinuclei`. The full propagation chain and production from CR interactions and WIMPs annihilation/decay is implemented taking as input tables of multiplicity or injection that have been derived from the most recent accelerator data. The code allows the possibility of using other input tables as well. More information and details can be found in the GitHub repository mentioned above.

In this section, we show the estimated flux of $\overline{d}$ and $^3\overline{He}$ from CR interactions with the gas in the interstellar medium. These calculations include the production of these antinuclei from p-p, p-He, He-p and He-He collisions as well as their tertiary contribution. To calculate this, we use the cross sections of antiproton production described in Ref. [10] and take into account the isospin asymmetry for the production of antineutrons and antiprotons. Then, we compute the cross sections of antinuclei production using the averaged momentum distribution of each antinucleon as [11, 12]:

$$E_{\bar{A}}\frac{d^3N_{\bar{A}}}{dp^3_{\bar{A}}} = B_A\left(E_{\bar{n}}\frac{d^3N_{\bar{n}}}{dp^3_{\bar{n}}}\right)^Z \times \left(E_{\bar{p}}\frac{d^3N_{\bar{p}}}{dp^3_{\bar{p}}}\right)^N . \tag{1}$$

This model simply states that that an antinucleus with A constituents will form whenever A antinucleons are found within a small enough region of momentum space given by B_A. The coalescence parameter, B_A is different for each antinuclei species, and it contains the crucial information about the probability of coalescence, often approximated as a function of the, so-called, coalescence momentum, p_0:

$$B_A \simeq \left(\frac{1}{8}\frac{4\pi p_0^3}{3}\right)^{A-1} \frac{m_A}{m_p^Z m_n^N} \tag{2}$$

We set $p_c = 219 \pm 4$ MeV and $p_c = 243^{+12}_{-15}$ MeV for $\overline{d}$ and $^3\overline{He}$, respectively, derived from a fit to recent ALICE data [13]. More details will be provided in an upcoming publication.

Here, we use a diffusion-reacceleration setup, where the spatial diffusion coefficient is parameterised as:

$$D(R) = D_0\beta^\eta \frac{(R/R_0)^\delta}{\left[1 + (R/R_b)^{\Delta\delta/s}\right]^s}, \tag{3}$$

with $R_0 = 4$ GV.

The parameters of the diffusion coefficient, as well as the other propagation parameters (namely the halo height, H, and Alfvèn speed, V_A), are set to those obtained from a Markov chain Monte Carlo (MCMC) analysis [14–16] that combines a fit to AMS-02 data of the spectra of the main secondary CR nuclei (B, Be and Li) along with the $\bar{p}$ spectra. Concretely, the parameters that we use are those obtained in the main analysis (called "Canonical") of Ref. [17]. For the rest of ingredients involved in the computation of the fluxes of CRs, we employ identical setup as in Ref. [14], where we refer the reader for more details.

Figure 1 shows the predicted $\overline{d}$ (left panel) and $^3\overline{He}$ (right panel) spectra produced from CR collisions with the interstellar gas and its tertiary component, evaluated from the propagation parameters mentioned above. The uncertainty bands correspond to the uncertainty in the determination of the coalescence momentum, as indicated above. We notice that the uncertainty related to the determination of the propagation parameters is not a relevant source of systematic uncertainty, as already was shown by Ref. [18], since what mainly matters is the flux of protons, which is known with a $2-3\%$ accuracy thanks to the AMS-02 measurements. Inelastic cross sections uncertainties were also found to have a very minor impact here [19].

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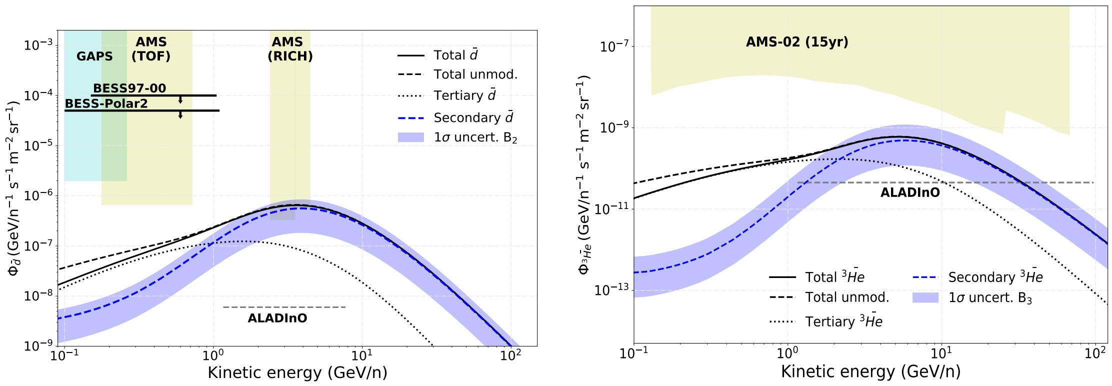

Figure 1: Left panel: Predicted $\overline{d}$ spectrum produced from CR collisions on the interstellar gas (secondary $\overline{d}$), from annihilation from a generic WIMP and the tertiary component compared to the upper-limits obtained by the BESS experiment, the sensitivity region of GAPS (three flights of 35 days) and AMS-02 (15 years) and the ALADInO forecasted sensitivity. **Right panel:** Similar to what is shown in the left panel but for the $^3\bar{He}$ spectrum compared to AMS-02 (15 years) and the future the ALADInO experiment.

In the left panel of Fig. 1, the predicted $\overline{d}$ spectrum is compared to the upper-limits from the Balloon-borne Experiment with a Superconducting Spectrometer (BESS) [20], the sensitivity regions for the RICH and TOF instruments in the AMS-02 detector (taken from Ref. [21]), for 15 yrs of operation, and the sensitivity region for the General Antiparticle Spectrometer (GAPS) [21, 22] (for the expected three flights of 35 days). Moreover, we include the forecasted sensitivity for the future Antimatter Large Acceptance Detector In Orbit (ALADInO) [23] (expected for 5 years of operation). From our predictions, we see that the secondary production of $\overline{d}$ from CR interactions can explain the detection of a few $\overline{d}$ events – only if they are detected by the RICH instrument on the AMS-02 experiment. However, we do not foresee any detection of this antinucleus by the GAPS detector or the TOF instrument. In turn, as we see in the right panel the secondary production of $^3\overline{He}$ is, at least, a factor of ~ 5 below the sensitivity of AMS-02 after 15 yr of operation, motivating the search for more exotic mechanisms of production of this antinucleus, as WIMP annihilation.

3. Antinuclei from WIMP annihilation

In this section, we report updated expectations for the fluxes of $\overline{d}$ and $^3\overline{He}$ at Earth, produced from the annihilation of WIMPs into b$\bar{b}$ pairs. The DRAGON2 code takes tables with the production spectrum (i.e. differential distribution, dN/dE) of each particle for the requested WIMP mass as an input and they are interpolated to the energies requested in the input file. This interpolation also helps for smoothing the distribution when the data given in the table is very disperse (as it is the case when there are uncertainties present in the spectrum calculation). The annihilation injection spectrum is computed using the Pythia (v.8.2) package [25], assuming a colorless neutral resonance decaying into b$\bar{b}$ final states. For these computations, we fix the coalescence momentum to $p_c = 215$ MeV. The uncertainty in this parameter may lead to a factor not larger than 2 in the fluxes that we show. Finally, we include in our calculations the correction on the transition of ratio $f(b \to \overline{\Lambda}_b) = 0.101^{+0.039}_{-0.0031}$ that was reported first in Ref. [26] and that is motivated to reproduce the measurement by LEP [27, 28].

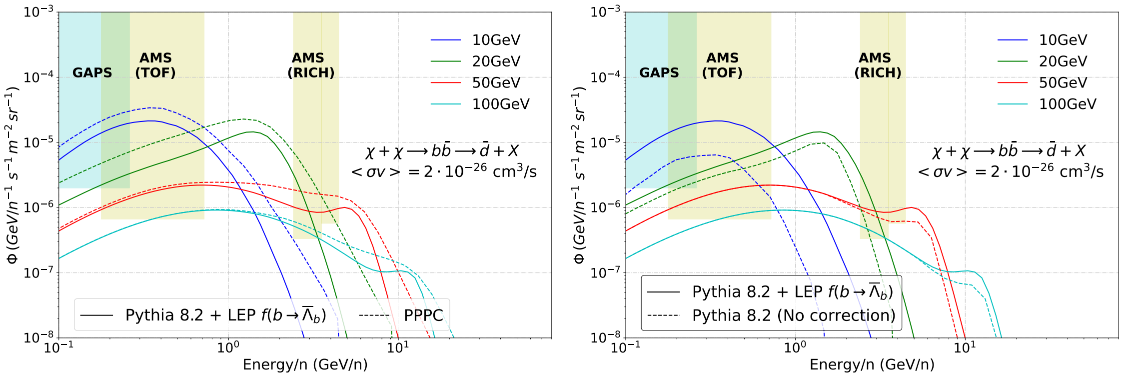

Figure 2: Predicted antideuteron flux produced from WIMP annihilation into $b\bar{b}$ pairs at an annihilation rate of $\langle\sigma v\rangle = 2\cdot10^{-26}$ cm^3/s, assuming a standard NFW profile with local DM density of 0.43 GeV/cm^3. In the left panel we compare our predictions with those derived with the annihilation spectra from the PPPC table [24]. In the right panel we show the impact of including the correction for the branching ratio of production of $\overline{\Lambda}_b$.

We show in Figure 2 the predicted $\overline{d}$ spectra produced from annihilation of WIMPs of different mass (10, 20, 50 and 100 GeV) with annihilation rate around the thermal relic value for a NFW dark matter distribution and a dark matter density at Earth position of 0.43 GeV/cm^3. We remark that this value for the annihilation rate constitutes a conservative value, since the recent limits derived in Ref. [29], from the analysis of the AMS-02 antiproton spectrum, excluded this value with 95% C.L. below ∼ 200 GeV. We compare our main predictions (appearing in both panels as solid lines) with those derived using the PPPC table [24], in the left panel, and those derived without including the LEP correction commented above, in the right panel. These comparisons allow us to see the impact of the uncertainties in the determination of the production spectra of these particles, which are the main source of uncertainty for these estimations, along with the determination of the height of the Galactic halo. In every case, we observe that WIMP production of $\overline{d}$ should be simultaneously detected by the TOF and RICH instruments for WIMP masses above 10 GeV. In addition, we observe that the GAPS experiment could detect these signals if they are produced by a WIMP with masses below ∼ 50 GeV.

Then, we show in the left panel of Figure 3 we show a comparison of our main predictions with those derived without including the LEP correction. Also here, we show the spectra of $^3\overline{He}$ produced from annihilation of WIMPs of different masses (from 20 GeV tp 500 GeV) with an annihilation rate around the thermal relic value for a NFW dark matter distribution and a dark matter density at Earth position of 0.43 GeV/cm^3. As we see, for masses below ∼ 50 GeV, this mechanism is able to produce the observation of a few $^3\overline{He}$ events. However, since the production of $^4\overline{He}$ is suppressed by at least 3 orders of magnitude, it is completely unable to explain the preliminary observations of AMS-02. We show in the right panel of this figure the $^3\overline{He}$ spectra obtained for the same WIMP masses for a contracted NFW profile as a way to boost the signals. However, this can yield to a ∼ 50% increase in the $^3\overline{He}$ flux. The explanation of the AMS-02 detection of $^4\overline{He}$, thus, requires much more exotic mechanisms of production at play, if this detection is confirmed to be robust.

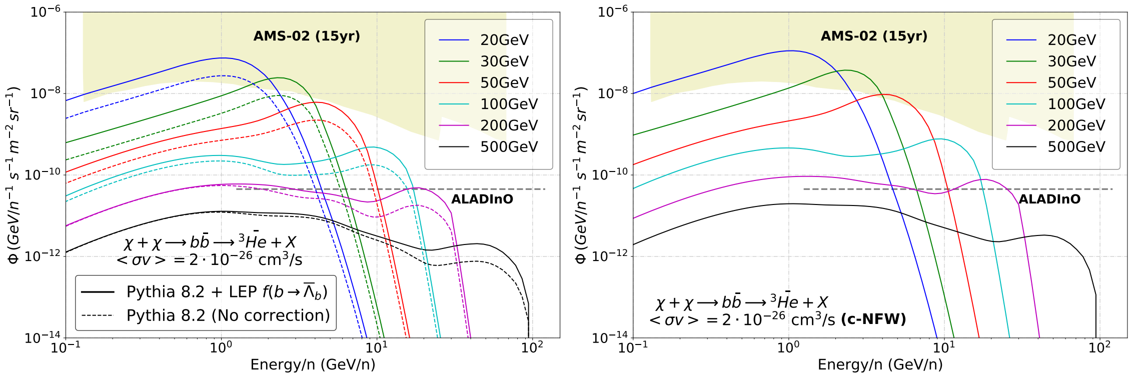

Figure 3: Predicted ^{3}He flux produced from WIMP annihilation into $b\bar{b}$ pairs at an annihilation rate of $\langle \sigma v \rangle = 2 \cdot 10^{-26}$ cm^3/s. In the left panel we show the impact of including the correction for the branching ratio of production of $\overline{\Lambda}_b$, assuming a standard NFW profile and a local DM density of 0.43 GeV/cm^3. In the right panel we show our predictions for a contracted NFW assuming the same local DM density.

At the moment, there are only a couple of theories proposed able to explain the observation of $O(1)$ $^4\overline{He}$ events:

- One of them explore the possibility of Galactic anticlouds or antistars [30], or even anti-novae and anti-supernovae [31]. However, although it is true that it is not ruled out this as a mechanism able to produce such a boost of the $^4\overline{He}$ signal, it can not explain the detection of similar amounts of $^3\overline{He}$ (since this antinucleus would not be produce on such systems in appreciable amounts).
- Another possibility invokes the presence of a QCD-like dark sector[32], which could produce a very high-density final state of antinucleos that could boost the signals of $^3\overline{He}$ and $^4\overline{He}$ in roughly the needed amounts, without exceeding the observations of antiprotons or $\overline{d}$. We remark that, although this hypothesis offers an explanation of all these preliminary observations of anitnuclei, the modelling of such signals is really uncertain to extract firm decisions.

4. Conclusions

We present updated calculations of the expected flux of $\overline{d}$ and $\overline{He}$ obtained with a new version of the DRAGON2 code.

We find that the production of $\overline{d}$ produced from CR interactions is compatible with the preliminary observations of AMS-02, and a robust detection seems to be achievable in a mid-to-short term. In addition, we notice that the detection of these antinuclei by the TOF detector, or the GAPS experiment, would be a very strong indication of new physics, given that the standard mechanism of secondary production of $\overline{d}$ is unable to produce enough events at the energies covered by this detector. Still, our predictions are uncertain by a factor of a few, mainly because of our limited knowledge on the coalescence process. Furthermore, we show that the secondary production of $\overline{He}$ is far below the sensitivity of AMS-02, being totally unable to explain the preliminary events observed by AMS-02.

Then, we have explored the production of $\overline{d}$ and $\overline{He}$ from the annihilation of WIMPs into $b\bar{b}$ final states, showing different uncertainties in the estimation of these signals at Earth. From our evaluations, we find that the expected $\overline{d}$ flux produced from WIMP annihilation could be detectable by AMS-02 and even GAPS in the region from $\sim 0.2 - 10$ GeV. On the contrary, we discuss that the production of $\overline{He}$ from WIMPs is unable to explain the preliminary observations of AMS-02. We remark here that the unique feature produced in the $\overline{He}$ spectrum by the decay of the $\bar{\Lambda}_b$ particle could be fundamental for future dark matter searches. If the preliminary signal of a few $\overline{He}$ events detected is confirmed and the analysis techniques of AMS-02 demonstrates to be robust enough, we could really be witnessing the first signal of physics beyond the standard model, although other astrophysical production mechanisms could also be at play.

From these calculations and discussions, we conclude that, unless very exotic mechanisms of production of antinuclei are present in the Galaxy, the most probable explanation for the AMS-02 preliminary observations of $\overline{He}$ is misreconstruction of events.

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