Perspectives of dark matter indirect search with ADHD in space

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Abstract. The observation of sub-GeV antideuteron in the cosmic ray flux, could be a very strong signature of dark matter annihilation in our galaxy. Goal of the Anti Deuteron Helium Detector (ADHD) project is to study the signatures offered by an high pressure Helium target for the identification of antideuterons in space.

1. Introduction

Cosmic Rays (CR) are an important tool for the indirect search of dark matter.

Well motivated theories beyond the Standard Model contain viable dark matter (DM) candidates which could lead to a significant enhancement of the antiparticle component in CR due to DM annihilation or decay.

In particular, it was recently suggested that the antiproton spectrum measured by AMS-02 [1] could be interpreted assuming a contribution from dark matter annihilation with a mass between 30 and 100 GeV and with a cross-section close to the WIMP natural scale for a thermal relic. [2–6]. However, analyses of these "excesses" suffer from large systematics coming from the astrophysical background models. Therefore, a pure secondary production of antiprotons ($\bar{p}$) due to collision of primary CR with the Inter Stellar Medium (ISM) turns to be consistent with the measured $\bar{p}$ flux, when accounting for the existing model uncertainties [7].

On the other hand, for other anti-nuclei, the secondary flux resulting from interactions of CR with the ISM is kinematically suppressed with respect to the case of $\bar{p}$. As an example the production energy threshold for antideuterons ($\bar{d}$) in $p-p$ collision is $\sim$ 16 GeV, that is much larger than the $\sim$ 6.5 GeV production energy threshold for antiprotons. Considering the power-law energy distribution of primary CR, this difference is the main reason for the much larger signal to background ratio for DM search expected for the $\bar{d}$ channel with respect to the one of $\bar{p}$ channel. Therefore, despite the very low branching fraction expected for the coalescence production, $\bar{d}$ search in CR can be a very powerful tool for DM indirect search [8].

Regarding the astrophysical background of $\bar{d}$ in CR, the maximum secondary flux due to $p-p$, $p-He$, $He-p$ and $He-He$ collisions, is expected to have a maximum at $\sim$ 4 GeV/n. A sharp cutoff of $\bar{d}$ background below 1 GeV/n is expected, this is due to the fact that the secondary produced $\bar{d}$ are boosted in the direction of the center of mass momentum, thus there is a low probability for the production of low momentum particles in the laboratory system.

Below 1 GeV/n the main $\bar{d}$ background is due to a small "tertiary" component, which is the fraction of secondary produced $\bar{d}$ further inelastically scattering the ISM.

Therefore, despite the large uncertainties in the secondary $\bar{d}$ flux (larger than a decade, considering different propagation models and the coalescence momentum in the 160-248 GeV range) a search for $\bar{d}$ in the sub-GeV energy range has a negligible astrophysical background and can directly test DM models as those suggested by the features in the AMS-02 $\bar{p}$ spectrum [9].

The existing experimental upper limit for $\bar{d}$ flux in CR: 2×10^{-4} ($\mathrm{m^2 s\ sr\ GeV/n})^{-1}$ was published by BESS 97-00 for the 0.2-1 GeV/n energy range [10], however, a preliminary result combining BESS 97-00 with BESS-Polar II can improve the limit to 5.9×10^{-5} ($\mathrm{m^2 s\ sr\ GeV/n})^{-1}$ for the 0.1-1 GeV/n energy range [11]

AMS-02 [12–16] has sensitivity much larger than BESS, but due to higher energy threshold could detect few secondary $\bar{d}$ in the most favorable models, testing the astrophysical background.

Finally new experimental techniques have been developed to test sub-GeV (stopping) $\bar{d}$, i.e. anti-nuclei in the region of interest for dark matter; namely GAPS (General Antiparticle Spectrometer) would profit of the detection of characteristics x-rays to distinguish the heavier $\bar{d}$ from $\bar{p}$ background avoiding the use of a magnet. First science flight of GAPS on a long duration balloon over Antarctica is planned in 2020 [17, 18].

In this paper a new detection technique based on $\bar{d}$ capture in helium target is described.

2. The ADHD concept

Goal of the Anti Deuteron Helium Detector (ADHD) project is to study the signatures offered by an helium target for the identification of $\bar{d}$ in space.

Typical lifetime for stopping $\bar{d}$ (like stopping $\bar{p}$) in the matter is of the order of $\sim$ ps however, since 1991, the existence of long-living ($\sim \mu$s) metastable states for stopping $\bar{p}$ in helium target was measured [19]. These metastable states in helium have also been measured for other heavy negative particles [20, 21], such as π^- and K^-. The theoretical description of the effect [22–24] is predicting that the metastable state lifetimes increase as reduced mass squared, i.e. a slightly larger delay is expected for $\bar{d}$ capture in helium with respect to the measured $\bar{p}$ case.

The antiprotonic-helium metastable states are well understood and their existence is already used for other fundamental physics measurements like the antiproton to electron mass ratio [25].

The phenomenology for the formation of metastable states in helium can be summarized following the scheme of Fig.1. An exotic atom is produced by the capture of the stopping antiproton/antideuteron in helium gas that spontaneously removes one of the two electrons contained in a normal helium atom. The antiparticle begins to orbit the helium nucleus in the electron's place but with large principal and angular momentum quantum numbers. The orbit lies far away from the surface of the nucleus inhibiting the annihilation. This is expected to happen in the case of few percents of the captures. For the He target, the single remaining electron cannot provide (fast) Auger de-excitation channels that is the main de-excitation process for larger Z antiprotonic atoms. On the other hand, the same electron also prevents the Stark collisional de-excitation, that is the main de-excitation process for the electronless $p - \bar{p}$ system. Thus, for antiprotonic-He the (slow) radiative channel is the main remaining de-excitation process. This meta-stability is a unique (and well measured) feature for the He target that is not expected/observed for other target nuclei [26]. The captured antiproton/antideuteron can thus orbit the He nucleus for few microseconds, before finally falling to its surface and annihilating providing a few charged pion tracks.

This characteristic delayed annihilation signal in He is a distinctive signature to identify the antimatter nature of the stopping particle that can be used to detect antideuteron in space.

A possible configuration for an helium-based $\bar{d}$ detector is depicted in Fig.2 and the response of a similar detector to $\bar{d}$, $\bar{p}$ and to the main cosmic ray components (p,He,C,e^-) has been simulated with the Geant4 10.5 package [27]. The inner part is a $\sim$ 20 kg scintillating helium calorimeter (HeCal) where the 400 bar gas is filling a 300L ($\oslash$ = 90 cm) spherical thermoplastic

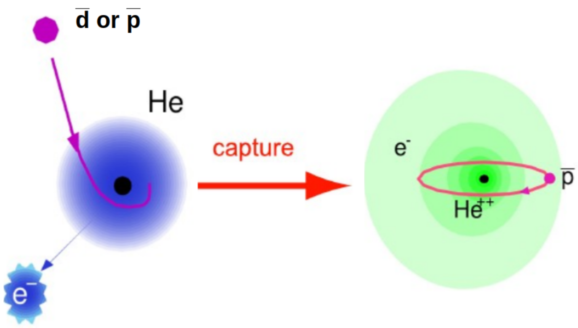

Figure 1. Stopping antiprotons and antideuterons (but also π^- and K^-) can be captured by He and trapped in (μs living) metastable states before annihilation. Metastable states exists only for He target.

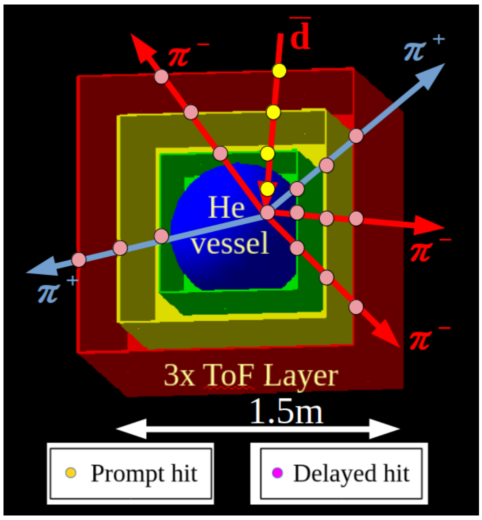

Figure 2. The ADHD detector is made by a 400 bar He gas calorimeter (HeCal) surrounded by three scintillator layers (ToF). $\bar{d}$ are detected as a single in-going prompt track followed by few out-going delayed $\pi^{\pm}$.

vessel. Vessel wall thickness of ∼3 cm (vessel mass ∼ 100kg) ensures a burst pressure larger than 800 bar; a similar vessel is already considered for He transportation in space [28].

Helium gas is a fast UV scintillator, having a light yield similar to other fast plastic/liquid scintillators and capable of providing ∼ ns timing performances [29]. The HeCal is surrounded by three layers, made by 4 mm thick plastic scintillator bars, providing velocity measurement (β) by Time of Flight (ToF) and charge measurement (Z) by ionization energy loss measurement (dE/dX). It is assumed that with current technology such a ToF detector is capable of measuring β with 5% resolution and energy loss with 10% resolution, this would imply time resolution of the order of 100 ps and position resolution of the order of few cm. Considering the energy loss in the ToF and in the vessel, a minimum kinetic energy of ∼ 60 MeV/n is necessary for $\bar{d}$ to reach the He target. On the other hand, $\bar{d}$ with kinetic energy larger than 150 MeV/n would typically cross the 400 bar He active region without stopping inside.

This defines the 60-150 MeV/n energy window explorable by ADHD in this configuration. Fig.2 also shows the typical event topology for a stopping $\bar{d}$ within the He gas. The antiparticle initially produces three prompt hits (yellow) in the ToF and one prompt energy release (S1) in the HeCal; these prompt hits occurs within 10 ns (and are also produced by any other ionizing stopping particle). Then, only for $\bar{p}$ and $\bar{d}$, the antiparticle can be captured in the He metastable states and after a time delay going from several tens of ns to few μs the annihilation occurs.

Typical $\pi^{\pm}$ multiplicity is 3.0 ± 0.2 for each anti-nucleon annihilation at rest [30], therefore for $\bar{d}$ a larger number of delayed out-going tracks is expected in comparison to the case of $\bar{p}$. For the same reason, also the delayed signal (S2) in the HeCal for $\bar{d}$ is expected to be twice the delayed signal for $\bar{p}$.

The typical time structure of S1/S2 signals as measured by HeCal for $\bar{d}$ is shown in Fig.3. The time gap from S1(prompt) to S2(delayed) is related to the metastability of He capture and is statistically distributed with $\tau_c \sim \mu$s. The S1 signal is related to the energy loss in the scintillating He$\bar{d}$, the amplitude measures the residual particle kinetic energy after the energy losses due to ToF and Vessel crossing. The duration of S1 signal is of the order of few ns that

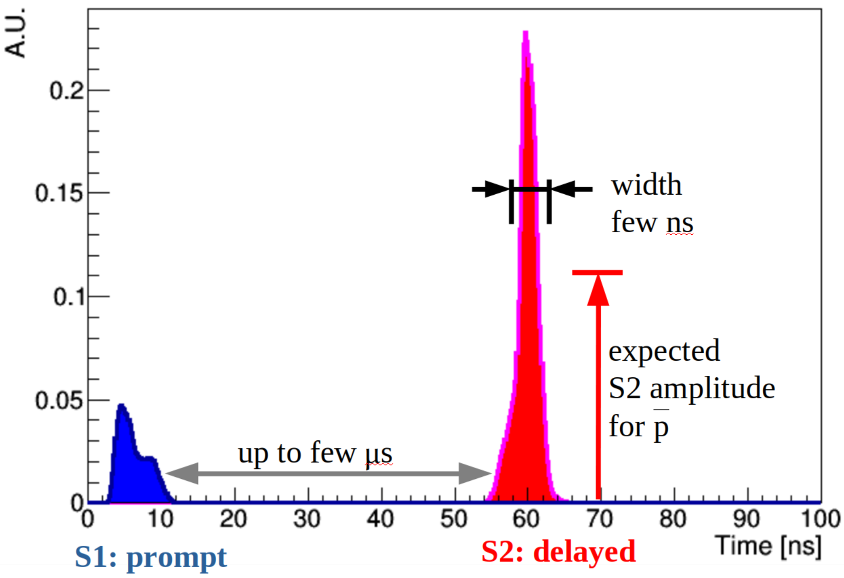

Figure 3. Typical HeCal signature for $\bar{d}$ in ADHD detector.

is the slowdown time for the particle in He.

The S2 signal is related to the number, velocity and trajectory of charged pions produced in the annihilation. The amplitude of S2 is not related to the particle kinetic energy, but measures the number of anti-nucleons. Typical S2 amplitude is larger than S1 and the duration of S2 signal is of the order of $\sim$ ns that is the transit time of pions to move from the helium to the vessel. This peculiar S1/S2 signature, together with the in-going/out-going track topology/timing, is very distinctive for $\bar{d}$ and $\bar{p}$ acting as a powerful rejection for other CR components. The main background for $\bar{d}$ search with ADHD is due to the $\bar{p}$ component whose flux can be extrapolated to be in the range 2-3 $\times$ 10^{-3} (m^{2}s sr GeV/n)$^{-1}$ [11, 31] for the ADHD energy window.

3. The ADHD antiproton rejection and expected antideuteron sensitivity

Existing $\bar{p}$ background can be separated from the $\bar{d}$ signal thanks to velocity vs kinetic energy measurement and to the half pion multiplicity. In the following, results from MonteCarlo simulations of $\bar{p}$ and $\bar{d}$ are shown. For each ADHD $\bar{p}/\bar{d}$ event it is possible to identify a "prompt event", that is the collection of "prompt hits" occurring before the annihilation and a "delayed event", that is the collection of "delayed hits" occurring after the annihilation.

In Fig.4 performances of $\bar{p}$ rejection using the "prompt event" are shown. In particular $\bar{d}$ has lower velocity, β, measured by ToF for a fixed prompt energy, S1, measured by HeCal. Fig.4 also shows that a comparison of the energy loss, dE/dX, measured by ToF with the prompt energy S1, gives an additional tool for $\bar{p}$ rejection, thanks to the β dependence in dE/dX.

In Fig. 5 the $\bar{p}$ rejection obtained by the "delayed event" is shown. Therefore a "ToF delayed activity classifier" is evaluated by combining the information of the number and the energy of delayed hits measured by ToF. On average, $\bar{d}$ annihilations produce twice the number of pions of $\bar{p}$ annihilations, this provides a larger "ToF delayed activity" and twice delayed energy, S2, measured by HeCal. Combining prompt and delayed event information in an overall classifier, ADHD can identify a single $\bar{d}$ over 1000 background $\bar{p}$ in the 60-150 MeV/n range. Considering the expected $\bar{p}$ flux, this technique would be able to test the presence of $\bar{d}$ in cosmic rays down to a flux of 2-3$\times 10^{-6}$ (m^{2}s sr GeV/n)$^{-1}$ with less than 1 $\bar{p}$ as background.

After these selection cuts, the acceptance of ADHD in this configuration is $\sim$ 0.2 m^{2}sr in the

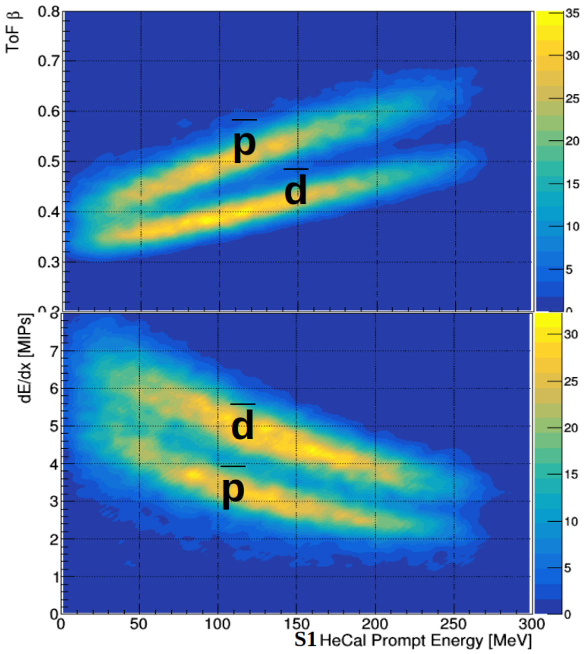

Figure 4. $\bar{p}$ background is rejected thanks to the comparison of prompt track velocity and energy loss as measured by ToF with the total kinetic energy as measured by HeCal (S1).

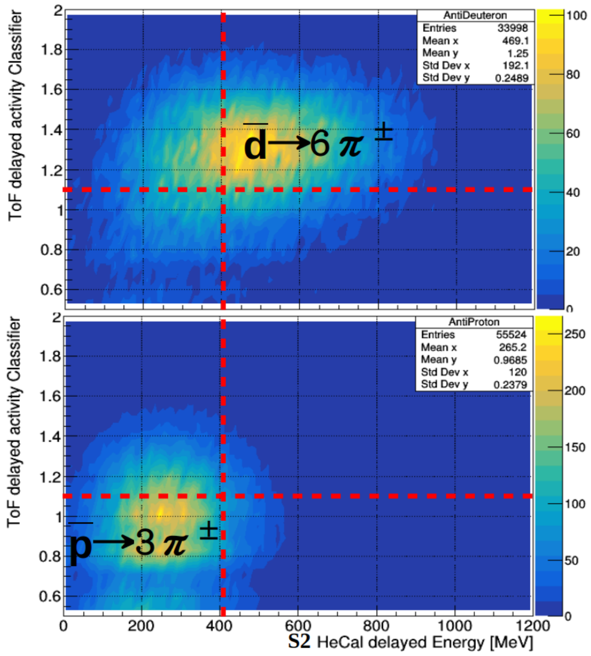

Figure 5. Antideuterons can be separated from antiprotons also thanks to the number/energy of delayed hits in ToF and the delayed energy measured by HeCal (S2).

energy regions 60-150 MeV/n for $\bar{d}$ and 100-300 MeV for $\bar{p}$.

Considering the $\sim 3\%$ probability to form metastable states in helium a sensitivity to $\bar{d}$ flux down to $\sim 10^{-5}$ $(\mathrm{m^2 s\ sr\ GeV/n})^{-1}$ can be achieved by 5 yr of ADHD in space. As by-product also a measurement of $\bar{p}$ flux in the range [100-300] MeV, with few% error, can be achieved.

In Fig. 6 the theoretical dark matter and secondary background models [9] (extrapolated for E<0.1GeV/n) are compared with ADHD sensitivity for $\bar{d}$ flux. The comparison with the expected sensitivity of other experiments, GAPS and AMS-02 and with the current published limit from BESS are also shown.

It is interesting to note that similar sensitivity can be achieved with different techniques in complementary energy windows allowing for a detailed study of $\bar{d}$ flux in the next future.

4. Conclusions

The sensitivity and performances of a possible space mission based on the ADHD concept were shown. The ADHD sensitivity would be similar to the one expected by other experiments, testing the $\bar{d}$ flux in a very low energy window that is interesting for dark matter indirect search. Such a low energy region can be accessed only outside Earth magnetosphere or nearby Earth magnetic poles. Different configurations of the ADHD concept, for a possible balloon are under consideration. Beam tests on a (200bar Arktis Radiation Detectors B670 [32]) helium scintillator prototype are ongoing at INFN-TIFPA to verify expected ADHD performances.

Acknowledgments

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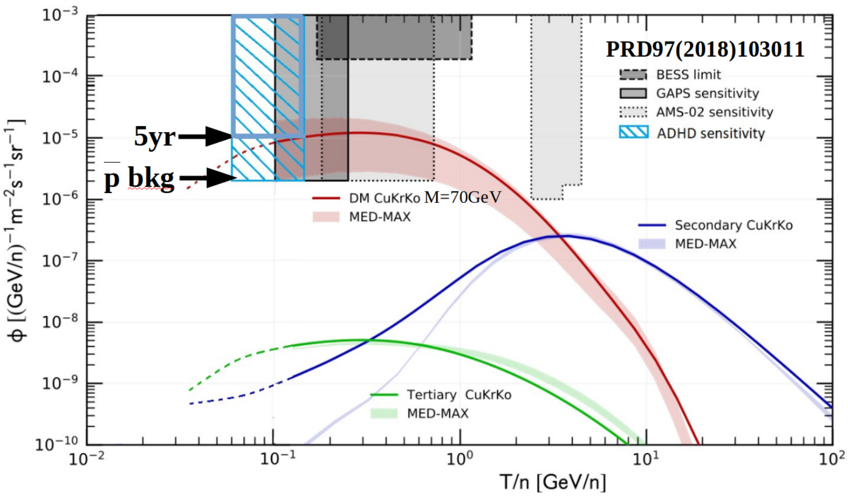

Figure 6. Expected ADHD sensitivity to antideuteron flux compared with theoretical dark matter and secondary background models [9]. ADHD has sensitivity similar to the ones expected from AMS-02 and GAPS in a complementary energy region. ADHD would provide also new antiproton flux measurements in the 100-300 MeV energy region with few % error.

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