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Advancing Antideuteron Detection in Cosmic Rays: Innovations in Methods and Technologies

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Low-energy antideuterons in cosmic rays (CRs) provide a unique probe of the matter–antimatter asymmetry and of dark matter annihilation in the Galactic halo. The PHeSCAMI project (Pressurized Helium Scintillating Calorimeter for AntiMatter Identification) demonstrated the use of delayed annihilation events in helium targets, but with limited scalability for balloon missions. We propose PLASTICAMI, a segmented plastic tracker optimized for the detection of the "two-step annihilation" signature of antideuterons. The detector consists of segmented plastic scintillator layers and an external Cherenkov veto for triggering and background rejection. Trigger logic, acceptance, and preliminary sensitivity have been evaluated with Geant4 simulations. Results indicate that PLASTICAMI could achieve competitive sensitivity to low-energy antideuteron flux in cosmic rays, allowing investigation of the predicted dark matter annihilation models.

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1. Introduction

The search for low-energy antideuterons ($\bar{d}$) in cosmic rays (CRs) provides one of the most sensitive channels to probe dark matter annihilation and to test the possible presence of primordial antimatter in our Galaxy. Because the secondary production of $\bar{d}$ in conventional astrophysical processes is expected to be extremely rare, the corresponding background is essentially negligible; thus, even a few detected events would be highly significant.

The most up-to-date limit on the flux of antideuterons in cosmic rays has been published by the *BESS Polar-II* balloon spectrometer: $\Phi_{\bar{d}} < 6.7 \times 10^{-5}$ $(\mathrm{m^2 sr\, s\, GeV/n})^{-1}$ in the kinetic-energy interval 163–1100 MeV/n [1]. Current and forthcoming experiments, such as the *Alpha Magnetic Spectrometer* (AMS-02) [2] on the International Space Station and the balloon-borne *General AntiParticle Spectrometer* (GAPS) [3], continue to search for antideuterons in cosmic rays with improved sensitivities. However, these measurements remain exceptionally challenging due to the extremely low expected fluxes and the need for unambiguous particle identification. This motivates the investigation of alternative detection techniques and novel signatures that could enhance the sensitivity to $\bar{d}$ and complement existing approaches.

The PHeSCAMI project (Pressurized Helium Scintillating Calorimeter for AntiMatter Identification) explores a novel detection technique based on delayed annihilation signatures in a helium target. Negatively charged antinuclei can form metastable exotic atoms in helium (about 3% of the cases), which annihilate after characteristic delays of a few microseconds, producing a distinctive experimental signature [4]. A PHeSCAMI-type detector combines a segmented Time-of-Flight (TOF) system with a pressurized helium calorimeter. Nevertheless, the large volumes of pressurized helium required pose major scalability challenges for balloon-borne missions, motivating the exploration of alternative detector concepts.

Within this framework, a novel signature of complex antinuclei can be exploited in plastic scintillators, leading to the development of the PLASTICAMI concept.

In particular, in a hydrogen-rich target, the annihilation of an antideuteron ($\bar{d}$) can proceed in two steps: one antinucleon annihilates promptly on a proton, while the surviving antinucleon retains kinetic energy, travels a finite distance, and subsequently annihilates on another proton. If the first annihilation involves the $\bar{p}$, the emitted $\bar{n}$ can propagate several centimeters before interacting. The resulting spatial displacement and nanosecond-scale delay between the two annihilation vertices produce a distinctive double “pion-star” topology, which constitutes a unique signature of complex antinuclei, as illustrated in figure 1.

Plastic scintillators provide an attractive medium for this approach: they are fast, lightweight, inexpensive, and rich in hydrogen. In a detector geometry based on stacked and segmented layers, the displaced vertices can be identified through their spatial separation and precise timing.

Preliminary Geant4 simulations [5] indicate that a stopped $\bar{d}$ in plastic scintillator produces a single full annihilation in about 30% of events, while in the remaining ~70% a partial annihilation occurs and a recoiling antinucleon is emitted. The antinucleon emission after the first, partial, annihilation is roughly evenly split between $\bar{n}$ and $\bar{p}$, both subsequently annihilate, producing a nearby "pion-star". For $\bar{d}$ annihilating at rest in a plastic medium, the median separation between the two annihilation vertices is ~3.5 cm for $\bar{n}$ emission and ~1.5 mm for $\bar{p}$ emission, values consistent with antinucleon recoil energies of order 10 MeV. Comparable kinetic energies have

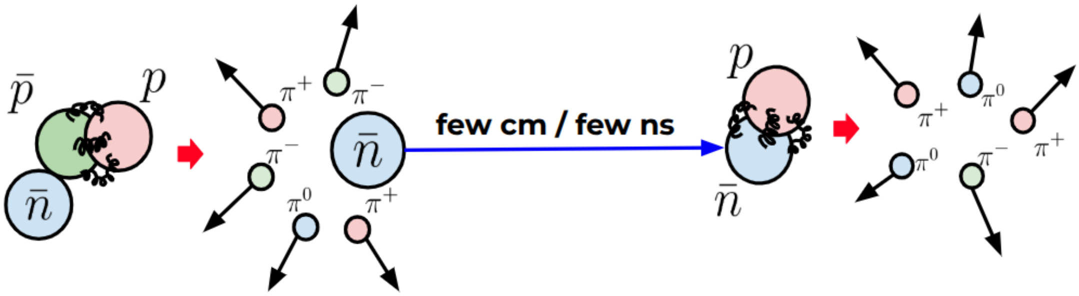

Figure 1: Illustration of the *two-step annihilation* signature of an antideuteron in a hydrogen-rich target. The antiproton first annihilates with a proton, while the surviving antineutron travels a finite distance before annihilating with another proton. The resulting spatially separated double vertices form a distinctive signature of complex antinuclei.

been experimentally observed in the "mirror process," where the spectrum of protons recoiling from $\bar{p}$ annihilations on deuterium has been measured [6]. Results from $\bar{p}$ annihilation on C_3H_8 (propane) [7], as well as on heavier nuclei such as C, Mo, and Au [8], further support the modeling of nucleon emission and pion multiplicities. For higher $\bar{d}$ kinetic energies (hundreds of MeV), fragmentation in the detector becomes more significant, increasing the fraction of events exhibiting a double-annihilation topology. Moreover, at such energies the antinucleon surviving the in-flight $\bar{d}$ annihilation is expected to carry a relatively large momentum, further increasing the vertex separation and making the two-step topology even more recognizable. Interestingly, the PLASTICAMI signature also applies to antihelium and other complex antinuclei.

2. A possible PLASTICAMI detector design

A possible implementation of PLASTICAMI is presented here: a segmented plastic tracker specifically conceived to detect the two-step annihilation signature of antideuterons. The detector integrates segmented scintillator pads for tracking with energy-deposition and timing measurements, complemented by an external Cherenkov veto made of FB118 wavelength–shifting plastic [9, 10].

The PLASTICAMI tracking system consists of 30 layers of plastic scintillator plates, each measuring $3 \times 3\ \text{m}^2 \times 0.5$ cm. Twenty layers form the detection planes, while ten layers constitute the lateral walls (Fig. 2, left). Each layer is segmented into pads of $75 \times 15 \times 0.5\ \text{cm}^3$ to provide coarse tracking and hit multiplicity information suited to reconstructing double-vertex topologies.

Each pad is read out by two SiPM units mounted on the short (15 cm) edges. This configuration provides both deposited-energy and hit-time measurements; by exploiting the arrival-time difference between the two ends, the longitudinal position along the 75 cm axis can be reconstructed. Combined over multiple pads, the system provides time-of-flight (ToF) and tracking capability with a resolution that improves with pad multiplicity. The typical spatial resolution of a single hit on the scintillator bars is $\simeq 10$ cm $\times$ 5 cm $\times$ 0.15 cm, depending on the direction. Layers of pads are stacked with alternating tiling directions, forming crossed planes. The time resolution of each scintillator pad is expected to be about 0.3 ns.

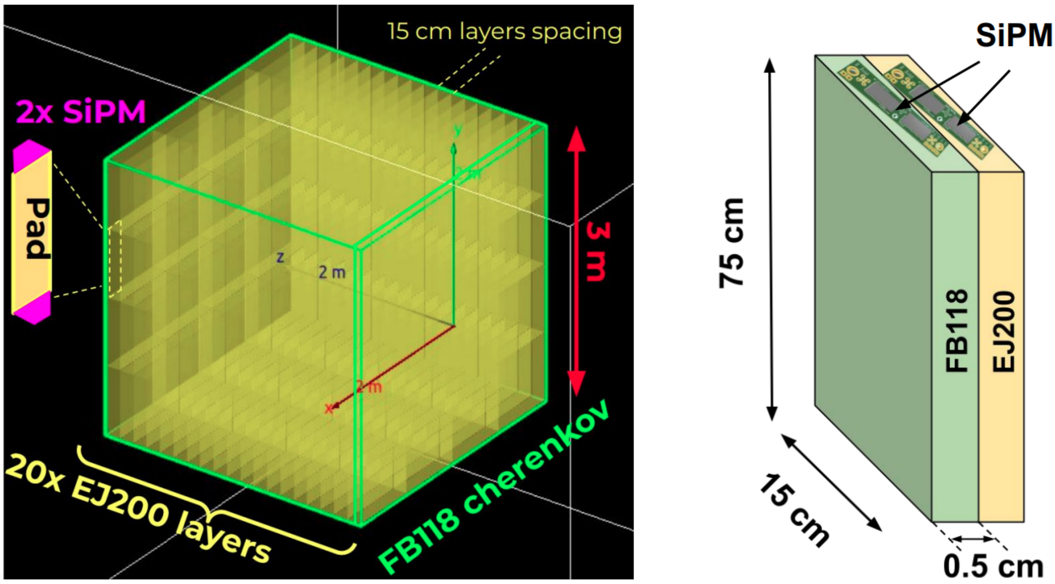

Figure 2: Left: Layout of the proposed PLASTICAMI detector consisting of 20 detection planes and 10 lateral walls built from segmented plastic-scintillator layers (EJ200), with inter-plane spacing to resolve displaced vertices. Right: detail of the external veto pads composed of a plastic-scintillator layer coupled to an FB118 (η = 1.5) Cherenkov radiator layer.

Pads with the same geometry realized in FB118 (a BBT doped PMMA acting as a η = 1.5 Cherenkov radiator) are placed externally to the outermost scintillator layers and operated as a compact Cherenkov veto (Fig. 2, right). Recent characterization indicates negligible residual scintillation (< 30 ph/MeV) and an intense Cherenkov yield ($\sim$ 200 ph/mm), enabled by efficient UV-to-visible conversion [9, 10]. This veto layer efficiently rejects fast ($\beta \gtrsim 0.8$) particles while preserving high efficiency for the low-velocity $\bar{d}$ candidates.

The considered PLASTICAMI design has an estimated mass of $\sim$ 1.6 ton for the scintillator and Cherenkov layers. Including supporting structures and electronics, the total payload weight is expected to be $\sim$ 2.5 ton.

With the adopted segmentation and per-pad readout, the detector features $\sim$ 5760 SiPM channels. Considering the available low-power ToF front-end solutions, the expected overall power consumption is within $\sim$ 1.5 kW, compatible with long-duration balloon mission constraints.

3. Trigger logic and acquisition rate

The trigger logic of PLASTICAMI is organized in two levels. The first level exploits unvetoed hits on the outermost layer, combining the energy deposited in the first scintillator pad with the Cherenkov veto signal from the FB118 (η = 1.5) layer.

Only "slow" particles ($\beta \lesssim 0.8$) can trigger the plastic scintillator without releasing a Cherenkov signal in the superimposed FB118 layer. Nuclei with $Z \geq 2$ are further rejected by imposing an upper threshold of about 10 MIP-equivalent in the signal of the first scintillator pad. Considering both conditions, the first-level trigger remains highly efficient for $\bar{d}$ in the energy region [80, 1200] MeV.

Figure 3 (left) shows the efficiency of the first-level trigger for antideuterons, protons, and α-particles. Relativistic protons and electrons, as well as nuclei with $Z \geq 2$, are efficiently rejected at this stage.

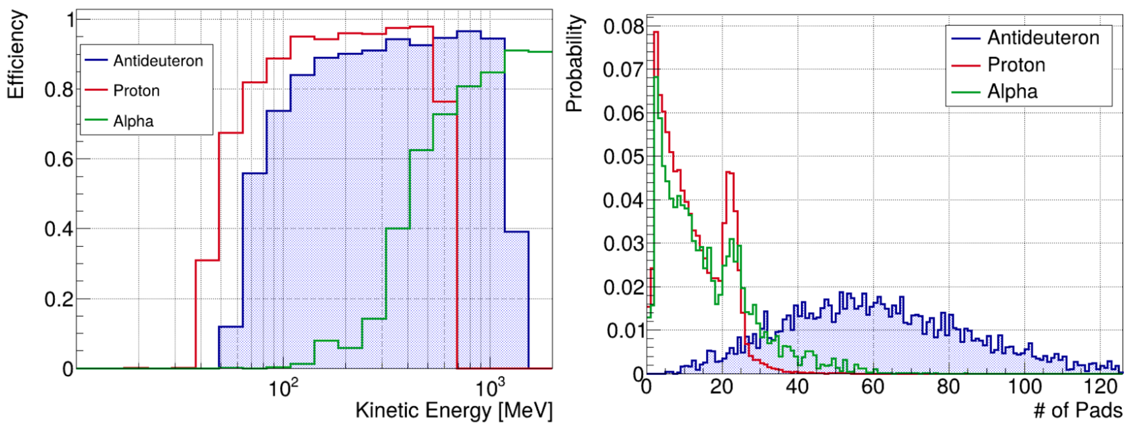

Figure 3: Left: efficiency of the first-level trigger (dE/dx and Cherenkov veto) for protons, antideuterons, and α-particles (red, blue, and green, respectively). Right: distribution of the number of scintillator pads hits after the first trigger selection.

If the first-level conditions are satisfied, a 50 ns gate is opened to validate the second-level trigger. This time window is sufficient to encompass the full two-step annihilation process of the antideuteron and to collect the resulting charged pions, as verified by Geant4 simulations.

The second-level trigger is based on the total number of pads hit within the gate. Two-step annihilations are expected to produce an almost isotropic emission of about five charged pions [11], resulting in a large number of pads being hit across different planes. In contrast, spallation or fragmentation products from ($\beta \lesssim 0.8$) background hadrons rarely mimic this multiplicity. By requiring at least 30 pads to be hit, the second-level trigger rejects ~99% of protons and ~90% of α particles, while keeping about 90% efficiency for two-step antideuteron annihilations events.

Figure 3 (right) shows the expected distribution of pad multiplicity for different species that pass the first-level trigger. Considering the natural flux of protons and helium [12], the expected first-level trigger rate is about ~50kHz, dominated by protons. This ensures that within the 50 ns gate the dead time and event pile-up remain negligible. Taking into account the second-level trigger, the expected PLASTICAMI acquisition rate is ~1kHz.

4. Acceptance and expected sensitivity

The PLASTICAMI detector can identify stopping antideuterons by recognizing a two-step annihilation signature with offline vertex reconstruction based on the timing and energy deposition of the 5760 readout channels. A simulated candidate event is shown in Fig. 4.

For the evaluation of the preliminary performance of the offline analysis, a fiducial volume is applied to exclude annihilation candidates in the external scintillator layers. In addition, quality cuts are applied, requiring a minimum spatial separation of > 15 cm and a time delay of > 2 ns between the two reconstructed annihilations. Finally, the energy depositions of the incoming primary track

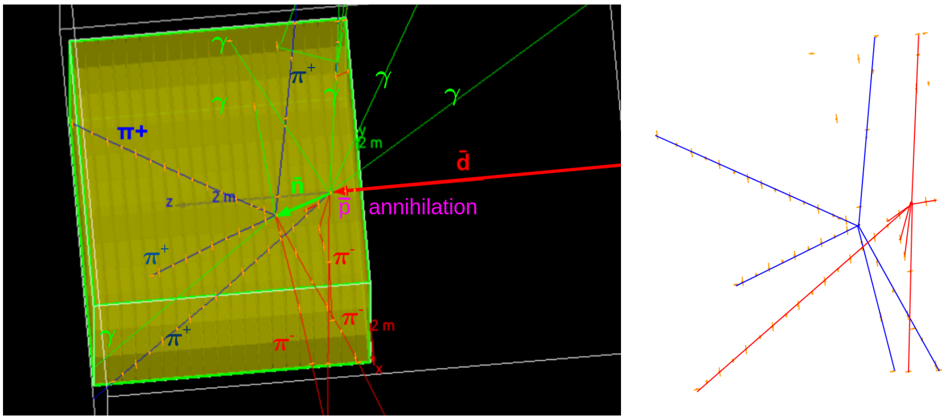

Figure 4: Left: simulated antideuteron event undergoing a two-step annihilation. Right: offline reconstruction of the two annihilation vertices based on the spatial and timing distribution of hits.

are matched with the time-of-flight information to verify whether the mass of the primary particle is compatible with that of an antideuteron.

The preliminary acceptance of PLASTICAMI detector for the identification of two-step antideuteron annihilations is shown in left panel of Fig. 5. This has been evaluated using a dedicated Monte Carlo simulation considering an offline event reconstruction efficiency of ~ 50% in addition to the mentioned fiducial volume cuts and quality cuts. To account for energy loss and in-flight annihilation or fragmentation before reaching the instrument, a compressed atmosphere is inserted in front of the detector, modeled as a flat slab with column density ~ 4 g/cm^2 [3]. Moreover, the efficiency loss due to the shielding effect of the geomagnetic field is included ($\epsilon_{\bar{d}} \sim 0.75$ at 0.2GeV/n) taking into account the rigidity cutoff typical of Antarctic long-duration balloon flights [3].

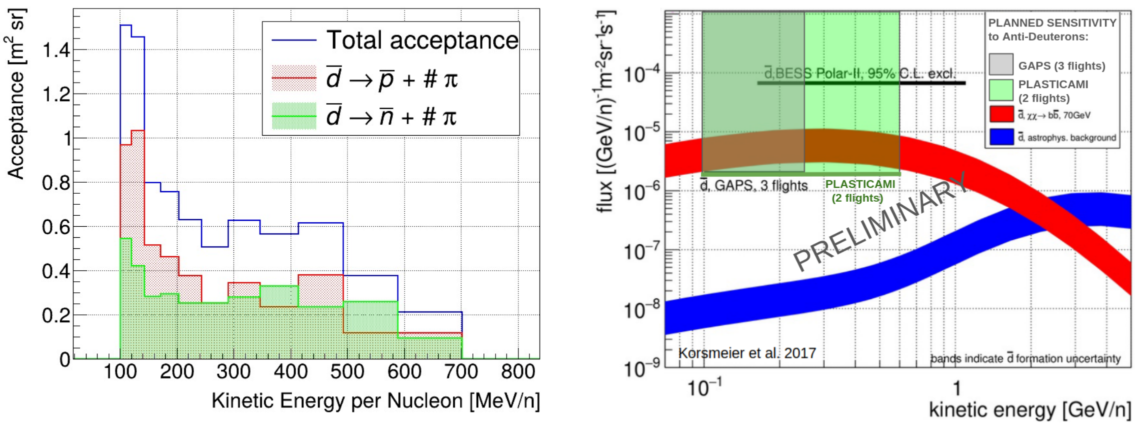

Figure 5: Left: preliminary acceptance for two-step antideuteron annihilations of a PLASTICAMI detector after trigger efficiency and analysis selections. Red filled area depicts the contribution from a $\bar{p}$ recoiling from the first annihilation, while green filled area depicts the contribution from a $\bar{n}$ recoiling. Right: projected 99% C.L. sensitivity for two PLASTICAMI balloon flights as compared with: BESS Polar-II limit [1], GAPS (three LDB flights) sensitivity [3], expected astrophysical $\bar{d}$ background (blue filled) and *CuKrKo* dark-matter benchmark model (red filled) [13].

Considering two Antarctic balloon flights, totaling 70 days exposure, and assuming zero observed events, PLASTICAMI can explore the presence of Antideuterons in cosmic rays with a sensitivity of $\simeq 2 \times 10^{-6}$ $(\mathrm{m^2 sr\, s\, GeV/n})^{-1}$ in the kinetic-energy interval 100–600 MeV/n.

The right panel of Fig. 5 compares the projected sensitivity for two PLASTICAMI flights with: BESS Polar-II limit [1], GAPS planned sensitivity [3], expected astrophysical $\bar{d}$ background and the potential dark-matter signal corresponding to the *CuKrKo* benchmark model derived from the AMS-02 antiproton spectrum [13].

5. Conclusions

PLASTICAMI leverages the distinctive two-step annihilation signature of antideuterons in plastic scintillators, reconstructed through segmented layers and supported by an external Cherenkov veto. The design is simple while providing effective tracking, timing, and background rejection. Considering two long-duration balloon flights, PLASTICAMI achieves competitive sensitivity in the low-energy window, complementing current and planned experiments and providing direct relevance for probing possible dark matter scenarios.

Acknowledgements

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