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First measurement of antiproton production cross section in p-He collisions at the AMBER experiment at CERN

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One of the indirect detection methods of dark matter (DM) is based on the search of the products of DM annihilation or decay. They should appear as distortions in the gamma-ray spectra and in the rare Cosmic Ray (CR) components, like antiprotons, positrons and antideuterons, on top of the standard astrophysical production. In particular, the antiprotons in the Galaxy are mainly of secondary origin, produced by the scattering of cosmic proton and helium nuclei off the hydrogen and helium in the interstellar medium (ISM). In order to obtain a significant sensitivity to DM signals, accurate measurements of the antiproton production cross section in p-p and p-He collisions are crucial. The AMBER experiment at CERN collected in 2023 the first data ever in p-He collision at a center-of-mass energy from 10 to 21 GeV. The 2024 AMBER program with proton beam on liquid hydrogen and deuterium targets is also described.

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1. Cosmic-ray fluxes and dark matter

Multiple and concurring evidence indicates that the vast majority of the matter content of the universe is non baryonic and electrically neutral. This constituent of the universe is usually referred to as Dark Matter (DM), for its lack of electromagnetic interactions. One of the most promising candidate for DM is the so-called Weakly Interacting Massive Particle (WIMP) which is foreseen to decay or annihilate into standard model particles, on top of the standard astrophysical component. One method to search for DM signals involves analysing particles arriving at the top of Earth's atmosphere, known as cosmic rays (CRs). For several cosmological models, the antimatter fluxes are the most sensitive to DM annihilation, as they have fewer natural sources. Among the particles analysed for DM signals, antiprotons, anti-deuterons, and heavier anti-nuclei fluxes are the most promising. However, anti-nuclei detection in CR fluxes has not yet yielded results, making antiprotons the key channel for investigating DM in CR. Disentangling any potential DM signal from standard astrophysical processes requires a deep understanding of the antiprotons propagation and production mechanisms. AMS-02 has provided the most precise data on the antiproton flux [1], which has triggered many theoretical studies. However, the current knowledge of the production and propagation mechanisms of antiprotons is limiting the significance of such results [2].

1.1 Antiproton source term

In the cosmic rays paradigm, the source term represents the injection spectra and takes into account the spatial distribution of the sources of that particular CR species in the Galaxy and their energy spectrum. In a more general form, for secondary produced CRs, the source term also depends on the progenitor species. For a secondary species like the antiprotons, assuming completely secondary production, the source term can be expressed as:

$$q_{ij}\left(T_{\bar{p}}\right) = \int_{T_{\rm th}}^{\infty} dT_i \; 4\pi \; n_{{\rm ISM},j} \; \phi_i\left(T_i\right) \frac{d\sigma_{ij}}{dT_{\bar{p}}}\left(T_i, T_{\bar{p}}\right) \tag{1}$$

where $T_{\bar{p}}$ is the antiproton kinetic energy; $n_{ISM,j}$ the density of the ISM j-component; $\phi_i(T_i)$ the energy differential flux of the progenitor primary CR component i at kinetic energy T_i; σ_{ij} is the nuclear cross section for i+j $\rightarrow$ $\bar{\text{p}}$ + X process and T_{th} is the threshold energy to produce the secondary. In the realm of collision energies conducive to antiproton production, nucleus-nucleus collisions are predominantly characterized by singular nucleon-nucleon interactions. In the galactic frame, with the target particle nearly stationary, these collisions follow fixed-target kinematics. The inclusive production rate of antiprotons in reactions such as A + B $\rightarrow$ $\bar{\text{p}}$ + X, where A and B represent the projectile and target nuclei, respectively, is determined by the inclusive, differential antiproton-production cross section. The majority (> 90%) of cosmic-ray antiprotons stem from collision processes within our Galaxy, predominantly involving p+p, p+He, He+p, and He+He interactions [3].

1.2 Cross section for cosmic rays

Given that the source term serves as the starting point for all subsequent calculations of the antiproton flux, its uncertainty directly impacts the accuracy of predictions for the antiproton flux observed at Earth. These uncertainties are currently driven by limited knowledge of the relevant cross-sections, particularly in the low-energy regime where most antiprotons are produced. While the initial parton-parton interactions in these collisions can be described by perturbative Quantum Chromodynamics (QCD), which governs the behaviour of quarks and gluons at high energies (the "hard scattering" regime), the subsequent hadronization process — where quarks combine to form hadrons, including antiprotons — is dominated by low-energy, non-perturbative QCD effects (the "soft" regime). Experimental data are then essential to measure measure the rates of antiproton production. Compared to p+p interactions, data on p+He collisions — the second most relevant reaction for antiproton production in the ISM — is extremely limited. Historically, cross sections for p+He interactions have been estimated using Monte Carlo simulations and parametric models based on atomic number scaling from p+p data. However, these approaches introduce significant uncertainties, especially in the low-energy regime where most cosmic ray antiprotons are produced. The only results for p+He $\rightarrow \bar{\text{p}}$ +X has been obtained by the LHCb experiment at CERN, which collected data in 2016 at a center-of-mass energy of $\sqrt{s} = 110$ GeV [4]. Although this dataset has been instrumental in refining parametric models, it does not cover the full phase space relevant to cosmic ray antiproton production, particularly at lower collision energies [3]. The lack of comprehensive data across the entire energy range means that current models for antiproton production in $p + He$ collisions rely heavily on extrapolations from p+p data, leading to large uncertainties and model-dependence. The AMBER experiment at CERN is going to give a critical contribution to this field. The first data on antiproton production cross-sections in p+He interactions at energies ($\sqrt{s} = 10.7 - 21.7$ GeV) were taken by AMBER in 2023. In 2024, the data set was expanded to include p+H and p+D collisions, which will help to further constrain the antiprotons production mechanisms.

2. Preliminary results from 2023 AMBER data

The secondary hadron beam delivered to the AMBER experiment by the M2 beam line of the SPS at CERN is a mixture of protons, pions and kaons. In order to measure a proton induced reaction in the helium target, it is mandatory to identify the beam particle. For this purpose two Cherenkov Detector with Achromatic Ring focus (CEDAR) type-N [5] were placed ~ 40 m upstream the target. A beam particle crossing the detector radiator gas with momentum above a certain threshold emits light that is collected into the 8 Photomultiplier Tubes (PMTs) of each CEDAR. A pressure scan of the radiator gas inside the vessel is performed in order to set the pressure working point (which determines the refractive index value) on the proton signal. With the correct pressure and diaphragm opening only the photons produced by the protons are focused on the PMTs and produce a signal with large multiplicity. The beam PID relies on the combined PMTs hit multiplicity. With the beam momenta used, spanning from 60 to 250 GeV/c, the proton signal is very well separated from the pions and kaons signals, allowing us to select an almost pure sample of protons. The proton tagging efficiency with a 6-fold (over 8-fold) hit multiplicity on both CEDARs has been evaluated to be ~96% from the data sample with beam momentum of 190 GeV/c. The misidentification probability has been extracted from dedicated runs with one CEDAR set on pion tagging and the other on proton tagging. The resulting misidentification probability is $\sim 10^{-4}$. Considering that the pion fraction in the beam at this energy is ~ 25%, a dual CEDARs proton tagging provides a high-purity proton sample.

After the proton in the beam has correctly been identified, only events with primary vertices inside the target volume are selected for the analysis. To minimize the systematic error induced by interactions with other target materials (e.g. the general support structure of the target), the exact dimension of the helium-target volume has been determined. Furthermore, the correct target position has to be extracted for the precise estimation of the incoming proton flux to derive the luminosity. A tomography of the target material has been performed by using the reconstructed primary vertices in the expected target region, allowing a very precise determination of the target geometry and position.

The final state hadrons are identified thanks to a ring-imagining Cherenkov detector, the RICH-1. The identification and misidentification probabilities have been estimated from the data using a track sample extracted from the decays of the so-called V0 secondary vertices, i.e. the decays of the neutral Λ, $\bar{\Lambda}$, K_S^0 and ϕ. The measured number of hadrons is computed after a selection of inelastic events in the target induced by beam protons. From these events, the track selection follows minimum criteria to ensure a good reconstruction of the hadron candidates. The bin size of the phase space was tuned based on the momentum resolution of the spectrometer, estimated with a dedicated study on a reconstructed MC sample.

The number of the antiprotons collected is divided in bins of laboratory momentum and transverse momentum of the antiprotons. The statistical uncertainty in each bin is shown in Fig. 1, after a preliminary analysis of the data at $\sqrt{s} = 18.9$ GeV (proton beam momentum of 190 GeV/c). This result shows the excellent coverage of the phase space in terms of collected statistics by AMBER. We expect that the systematic uncertainty on the RICH-1 PID matrix extraction and the luminosity determination will be the dominant contributors to the total error. The complete collection of 2023 datasets includes reactions of $p + He$ at $\sqrt{s}$ = 10.7, 12.3, 13.8, 17.3, 18.9, 21.7 GeV, analysis of which is ongoing.

2.1 Physics motivation and expected impact of 2024 AMBER data

In general, the prompt antiproton production accounts only for $\sim 40\%$ of the total antiprotons in cosmic rays. Another 40% comes from antineutron decay and the remaining 20 % from antihyperon decays [6]. While antiprotons generated through direct hadronization or the decay of antihyperons in collisions can be directly probed experimentally via accelerator-based experiments, the contribution from antineutrons remains entirely unexplored. Typically, the assessment of antineutron generation in collisions relies solely on theoretical principles founded upon isospin symmetry. However, NA49 data at $\sqrt{s} = 17.3$ GeV indicates an enhanced production of antineutrons compared to antiprotons, leading to the non solved question regarding the production asymmetry of isospin pair $p\bar{n}$ and $\bar{p}n$ in pp collisions. In [7], the author suggested that this asymmetry originates from isospin effects and until now this remains one of the biggest source of uncertainties on the low-energy parametrization of the antiproton production cross section for CRs interpretation, given that almost half of the CR antiprotons arrive from antineutrons decays. The antiproton multiplicity was found higher in neutron proton scattering compared to proton proton, which only differs in the third component of isospin of the initial state. The asymmetry has its maximum at $x_F \sim 0$ of roughly $\sim 50\%$, consequently resulting in an enhanced production of antiprotons with respect to isospin symmetry consideration. The production asymmetry seems to disappear when dealing with higher center of mass energy. The determination of the isospin factor, defined as $\Delta_{IS} = f^0_{\bar{n}}/f^0_{\bar{p}} - 1$ (with $f^0_{\bar{n}}$ and

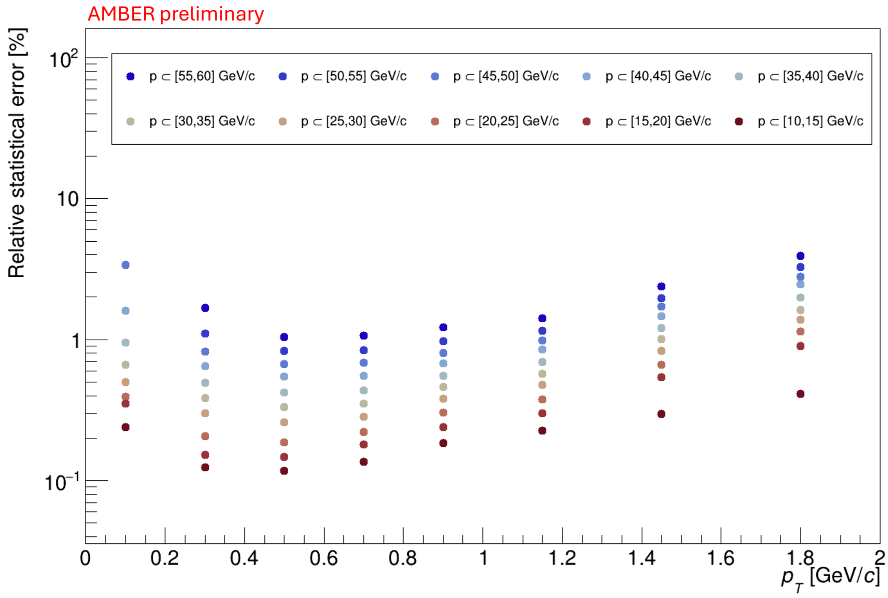

Figure 1: Statistical error on the RICH-unfolded number of antiprotons from interaction in $p + He$ at $\sqrt{s} = 18.9$ GeV. On the x-axis the p_T of the antiprotons and on the y-axis the statistical uncertainty in the bin. The different colors indicate the bins in laboratory momentum of the collected antiprotons. The error is calculated as the square root of the number of entries. The markers indicate the center of the bins.

$f^0_{\bar{p}}$ being the prompt-production cross section of antineutrons and antiprotons) [8], was extracted from data by modeling the x_F-multiplicity dependence of the antiprotons into a projectile and target component, weighted with the number of interacting nucleons and the neutron-to-nucleon numbers of the colliding particles. From this parametrization, it is clear that the errors associated to the low energy regime, due to the scarcity of data, becomes huge below ∼ 50 GeV, directly afflicting the final source term predictions. To verify or exclude such an isospin-asymmetric production of antiprotons and antineutrons, AMBER collected data in p+p and p+D collisions, with a nearly identical setup. By replacing the liquid hydrogen in the target with liquid deuterium, AMBER can indirectly measure the antiproton-production cross section in p+n collisions by subtracting the measured p+p→ p̄+X cross section from the measured p+D→ p̄+X cross section with minimal systematic uncertainty due to the identical experimental setup. The measurements performed at several different collision energies allow to constrain a possible isospin-asymmetric production of antiprotons and antineutrons and its dependence on the collision energy. By providing three measurements of the isospin asymmetry at different beam energies, 80 GeV$/c$, 160 GeV$/c$, and 250 GeV$/c$, with measurement uncertainties of the individual antiproton production cross section of around 5%, AMBER will constrain the level of the isospin asymmetric production of antiprotons around 10% and constrain its collision-energy dependence. In Fig. 2, the impact of the additional measurements by AMBER on the uncertainty of the isospin factor is projected.

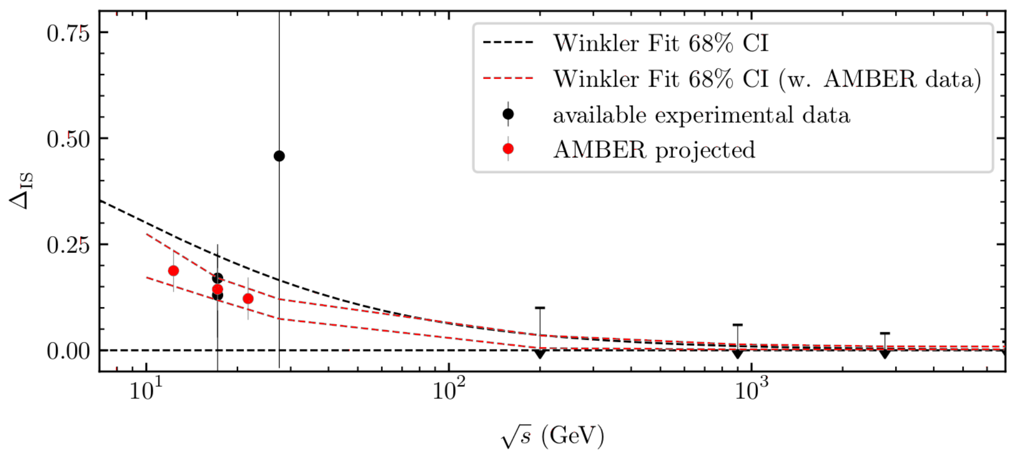

Figure 2: Isospin factor dependence on collision energy in different experiments. Black lines are the error bands from the fit performed in [8]. The isospin factor $\Delta_{IS} = f^0_{\bar{n}}/f^0_{\bar{p}} - 1$ is calculated from the projectile and target proton-neutron composition. The extrapolation of the energy dependence is used in the cross section parametrization and induces relevant errors in the low energy regime, where only NA49 data points are available with reasonable uncertainty. In red, an estimation of the impact of the AMBER measurement of the isospin factor using experimental data at 3 different collision energies. Figure adapted by the author from [9].

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