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Antimatter-Nucleus reactions with the Liège IntraNuclear Cascade (INCL) code

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The INCL (Intranuclear Cascade Liège) code has been developed and utilized for many years. Its primary goal is to simulate interactions between light projectiles and various types of nuclei within an energy range from a few tens of MeV to 10-20 GeV. To achieve this, it must be combined with a de-excitation code, most commonly the ABLA code. Both INCL and ABLA are also integrated into the Geant4 particle transport code. Additionally, different versions of INCL are available in other codes such as PHITS (Particle and Heavy Ion Transport code System) and GENIE (Generates Events for Neutrino Interaction Experiments).

The latest advancement in INCL is its ability to simulate antiproton-nucleus reactions, from at rest up to approximately 10 GeV. This topic will be presented here, with a focus on the low-energy domain, including details on implementation methods (hypotheses and ingredients) and results obtained (comparisons with experimental data). As the antineutron is currently being implemented, this subject will also be addressed. The next step involves extending this capability to antideuterons, antitritons, etc., and very preliminary results for antideuterons are presented as well.

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1. Introduction

The interaction between an antiparticle and a nucleus is a type of reaction that requires simulation to address fundamental questions. The INCL nuclear reaction code [INC2025], developed at CEA over many years, has therefore been of great interest to those working on these issues. A discussion with the PANDA (antiProton ANnihilation at DArmstadt) collaboration led to the implementation of few-GeV antiprotons in INCL to study the production of (anti)hyperons within the nucleus, one of the primary methods for investigating nucleon-hyperon interactions. The production of hyperons and anti-hyperons could also provide insights into the neutron skin. Another method for studying the neutron skin is by measuring the ratio of π^+ to π^- emitted. This approach is used in the PUMA (antiProton Unstable Matter Annihilation) experiment at CERN (AD) with antiprotons at rest. For this range of reactions, we are collaborating also with A. Gligorova from the ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons) experiment to compare measured and calculated productions of charged particles.

These interests in antiprotons led to a thesis defended at the end of 2023 (D. Zharenov [Zha2023]) on the implementation of antiprotons in the INCL code. This version is available in the Geant4 transport code. We can also highlight the interest in antideuterons and anti-^{3}He, as seen in the GAPS (General AntiParticle Spectrometer) experiment. These particles could be decay products of dark matter, and since their astrophysical production is much lower than that of antiprotons, their detection would provide a more convincing signal of dark matter compared to antiprotons. In this regard, the treatment of antineutrons in INCL has recently been completed, allowing us to begin work on antideuterons.

In Section 2, we explain how these antiparticles have been and are being implemented in the INCL code, after briefly recalling its key features. In Section 3, we present results comparing simulations with experimental measurements.

2. INCL and antiparticles

Before detailing how antiprotons, antineutrons, and antideuterons are implemented in INCL, we first review the main characteristics of the code, from its basic principles to the latest improvements.

2.1 Generalities

INCL is a Monte-Carlo intranuclear cascade code that simulates interactions between a light projectile and a nuclear target within an energy range from tens of MeV to 10-20 GeV. Like all intranuclear cascade models, INCL relies on four fundamental assumptions:

- Scatterings are numerous enough to consider interference effects negligible.
- The positions and momenta of particles are precisely defined, allowing the use of classical trajectories.
- Scattered waves reach their asymptotic values before the next collision, enabling a classical treatment of scattering.
- The interaction time is much shorter than the time between collisions, permitting the neglect of three-body interactions and focusing on binary collisions.

The main ingredients and hypotheses of INCL include:

- A Fermi gas model to construct the nuclear target.
- All particles experience a proper nuclear potential that is energy-dependent for nucleons and constant for other particles.
- Particles move in straight lines.
- The choice of collisions and their reaction products are governed by cross-sections[1].
- At the surface of the nucleus, particles can be emitted or reflected. When a nucleon can be emitted, a phenomenological coalescence model determines whether a light nucleus can leave the nucleus through aggregation.
- Decays are accounted for in Δ, the Σ^0 and the ω meson.
- The cascade stops when it reaches a stopping time defined in a preliminary study[2].

The version of INCL available at the time of writing is capable of handling all nuclei bombarded by nucleons, pions, kaons, η and ω mesons, Λ and Σ hyperons, light ions (A$\leq$18) and $\overline{\mathrm{p}}$. More details about the physics content can be found in several articles: generalities are covered in [Bou2013] and [Man2014], while the latest improvements are detailed in [Rod2017], [Hir2020] and [Zha2023]. Additionally, a series of benchmarks is provided in [Dav2015].

2.2 Implementation

Most of the work presented here focuses on antiprotons. Therefore, the section dedicated to the implementation of antiprotons includes most of the hypotheses and physics ingredients related to antiparticles as projectiles in INCL. The other two sections will highlight only the differences and new features regarding antineutrons and antideuterons.

2.2.1 Antiproton

The treatment of antiproton reactions in INCL is inspired by earlier work by J. Cugnon [Cug1990]. Two mechanisms exist depending on the energy level. Below a certain threshold, an antiproton is captured by the electron cloud and can no longer be treated like other particles that have a defined impact parameter, penetrate the nucleus (accounting for Coulomb deviation), and potentially initiate a cascade by colliding with a nucleon. We focus here on the low-energy mechanism, specifically below approximately 200 MeV.

When an antiproton is captured in a high orbit, three key pieces of information are necessary to describe the interaction: the location where annihilation occurs, the type of nucleon involved in the annihilation, and the characteristics of the annihilation products.

<u>Position of the annihilation</u>

At low energies, antiprotons cascade down towards the nucleus by emitting Auger electrons or X-rays. When they are close enough to the nucleus, their wave function overlaps with the nucleon density, initiating the annihilation process. The position of the annihilation is sampled from the

[1]Those cross sections come principally from experimental measurements, but in some cases models and/or symmetries can compensate the lack of information.

[2]The study of the time needed to reach thermalization of the nucleus has led to formulas depending on the type of projectile (baryon or meson) [Bou2002].

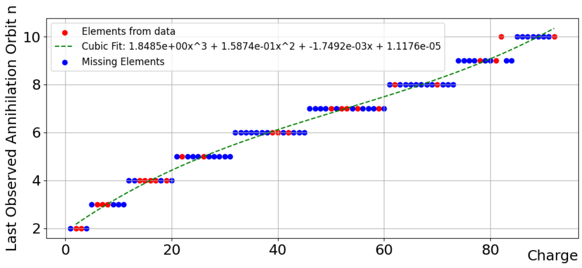

Figure 1: Last principal quantum number n distribution used to compute the annihilation position in INCL. The red points are taken from γ-spectroscopy data [Pot1984, Wyc1993]. These data points are fitted with the dashed curve, and the integer values in blue are those used in INCL.

distributions $P_{neutronic,protonic}(r) = N_{nl} \times \rho_{n,p} \times r^2 \times |R_{n,l}|^2$, where N_{nl} is a normalization constant, $\rho_{n,p}$ are the nuclear densities for neutrons and protons, respectively, r is the distance from the nucleus center and $|R_{n,l}|$ is the radial component of the $\bar{p}$ atomic wave function. The formulas used for $|R_{n,l=n-1}|$ [3] and N_{nl} are:

$$|R_{n,l=n-1}| = ((2n)!)^{\frac{1}{2}} \left(\frac{2}{na}\right)^{\frac{3}{2}} \left(\frac{2r}{na}\right)^{(n-1)} \exp\left(\frac{-r}{na}\right) \quad \text{(a is the Bohr radius)} \tag{1}$$

$$N_{nl} = \frac{2}{n^2}\sqrt{\frac{(n-l-1)!}{((n+l)!)^3}} \tag{2}$$

Determining the position of annihilation involves finding the lowest orbital number reached by the antiproton for a given nucleus. Given the limited experimental data available, this result was obtained pragmatically. Figure 1 shows a fit of the orbital number from the available experimental data. The blue points represent the values used in INCL for each element.

Type of nucleon involved

An antiproton can annihilate with either a proton or a neutron. While the exact probabilities are not well-known, experiments on deuterium [Bar1964, Chi1966, Bet1967] suggest a higher likelihood of annihilation with a proton. Following [Biz1968], we assume that the probability of an antiproton annihilating with a proton is 1.33 times greater than with a neutron.

Additionally, we consider the proportions of neutrons and protons in the nucleus. This leads to a simple formula for the ratio (S_p/S_n) in a nucleus with atomic number Z and mass number A:

$$S_p/S_n(Z,A) = S_p/S_n(D_2)\frac{Z}{A-Z} = 1.331\frac{Z}{A-Z} \tag{3}$$

This formula may be oversimplified, as other factors (e.g., neutron skin) likely play a role. With that in mind, we will defer the study of this factor's influence on our results to a later date.

Annihilation products

The final products of annihilation are primarily mesons, including π, ρ, η, ω, Φ and K. In INCL, we immediately decay ρ mesons into pions and consider the Φ meson as part of the $K\overline{K}$ channels. The probability of each channel is derived from two articles: [Gol1992] for the mesons π, ρ, η, ω, and [Kle2005] for the K mesons.

[3] $l = n-1$: In general, the level where the antiproton is absorbed is a circular orbit [Pot1984].

Typical values for the contribution of strange channels in the annihilation products are around 5% ([Kle2005, Arm1969, Bat1988]). Therefore, we use this value in INCL.

2.2.2 Antineutron

Antineutrons and antiprotons exhibit similar behavior at momenta beyond ~1 GeV/c, sharing the same reaction cross sections and final products (with differences only in electric charge). At low energy, we might expect their interactions with nuclei to differ significantly due to the lack of electric charge of the antineutrons. Surprisingly, both particles behave similarly [Fri2014].

For those reasons, below 165 MeV/c, the interaction mechanism for antineutrons is forced to be similar to that of antiprotons, with a key difference: the position of annihilation is sampled from a Gaussian distribution rather than the specific distributions used for antiprotons. This approach simplifies the modeling process while maintaining accuracy. Between 165 MeV/c and 1000 MeV/c, a specific fit of the cross sections is performed using data from [Iaz2000, Tes1995]. This ensures that the interaction probabilities are accurately represented within this energy range. Beyond 1GeV/c, the behavior of antineutrons is modeled similarly to antiprotons, leveraging the existing work done for antiproton interactions. This approach capitalizes on the similarity in high-energy behaviors between the two particles.

2.2.3 Antideuteron

Given that INCL can simulate both $\overline{\mathrm{p}}$ and $\overline{\mathrm{n}}$ as well as interactions between light nuclei and heavier nuclei, it is feasible to extend this capability to antideuteron-induced reactions with minimal additional effort. The construction of the antideuteron projectile follows the same principles as for a deuteron [Man2014]. The main idea is that once the two antinucleons ($\overline{\mathrm{p}}$ and $\overline{\mathrm{n}}$) enter the target nucleus, they trigger a cascade of interactions. Two challenges arise in this process: Off-shell antinucleons, when an antinucleon enters with energy lower than its mass, specific treatments are required since no cross sections exist for such cases, and, residual antinucleons, although rare, an antinucleon may remain in the nucleus at the end of the cascade and must be annihilated.

Despite these challenges, a preliminary implementation of antideuteron interactions in INCL has been tested for incident energies beyond a few hundred MeV. This implementation leverages the existing capabilities of INCL to handle both $\overline{\mathrm{p}}$ and $\overline{\mathrm{n}}$, as well as light nucleus-nucleus interactions.

3. Results

3.1 Antiproton

The simulation of pion emission from antiprotons at rest using INCL shows good agreement with experimental data.

Charged Pion (Fig. 2): The simulated multiplicity of charged pions fits the experimental data with a very low underestimate (below 5%). This slight discrepancy could be due to the lack of information on high pion multiplicities in annihilations, as INCL only considers channels with fewer than 8 or 9 pions. The momentum spectra from the simulations also compare well with experimental data. It is important to note that INCL provides only the shape of these spectra, while the normalization is determined by a formula for the reaction cross section taken from [Bia2011].

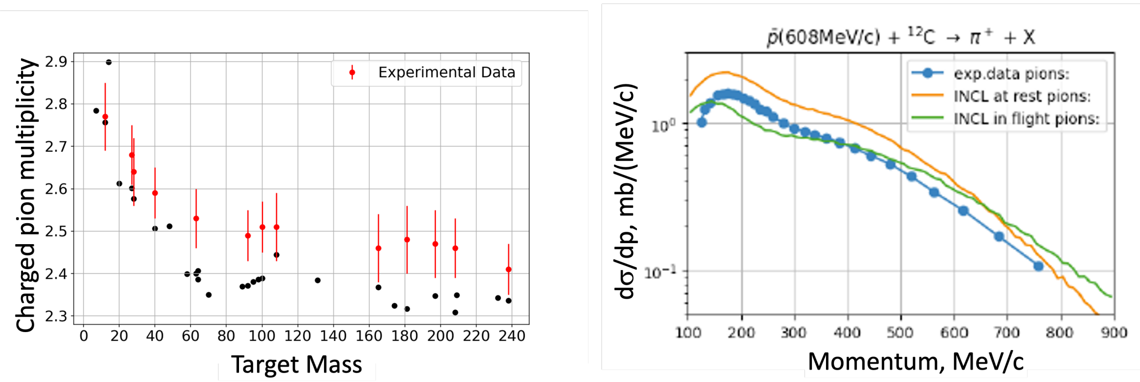

Figure 2: On the left, comparisons of INCL and experimental data [Pol1995] for charged pion multiplicities after interaction of antiprotons at rest on different target masses. On the right, momentum spectrum of π^+ from the reaction $\overline{p}$(608 MeV/c) $+^{12}$ C.

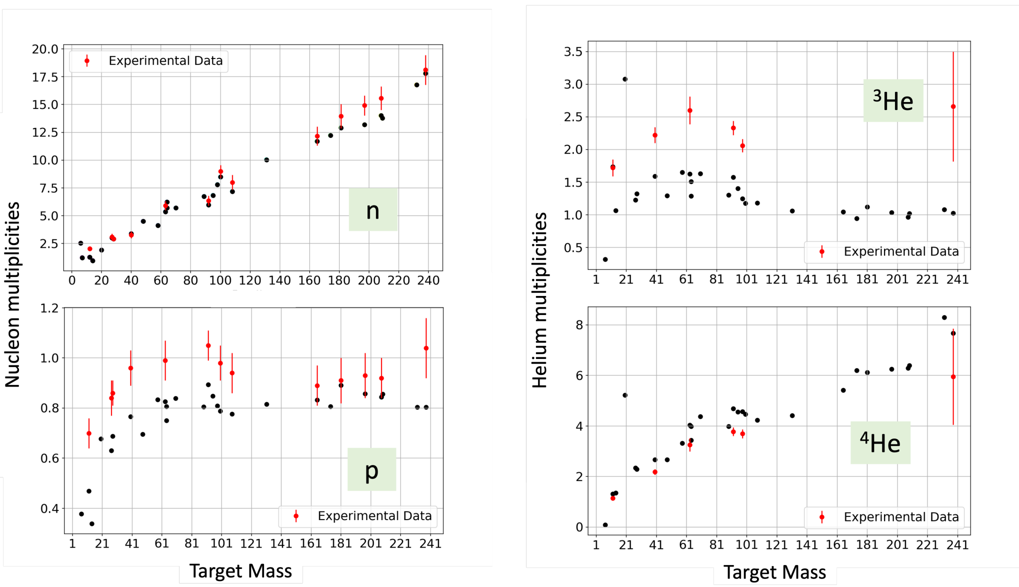

Figure 3: On the left, neutron and proton multiplicity versus the target mass for antiprotons at rest. On the right, the same for ^{3}He and ^{4}He. Experimental data (red points with error bars) taken from [Pol1995] for the nucleons and [Mar1988] for helium nuclei, and simulations done with INCL.

The energy of 200 MeV used in INCL to separate the mechanisms at rest and in-flight is a free parameter. However, Fig. 2 (right side) indicates that using an energy of 180 MeV (608 MeV/c) justifies the mechanism at rest (right shape).

Other particles are given in Fig. 3. Neutrons and Alpha Particles: The multiplicities are well described by INCL; Protons: There is a slight underestimate (~20%) in the proton multiplicity; ^{3}He: A higher underestimate (factor ~1.5) is seen.

These multiplicities were measured over different energy ranges: Neutrons: (2-300 MeV); Protons: (35-200 MeV); Helium nuclei: (30-70 MeV). Therefore, the role of the Intranuclear Cascade (INC) model or the de-excitation process is different according to the case. Moreover, the

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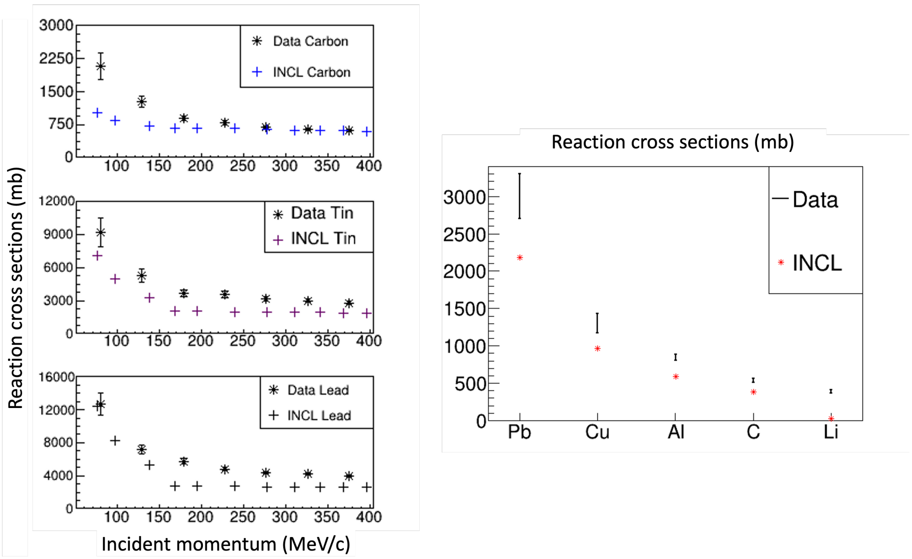

Figure 4: On the left, reaction cross section of $\overline{n}$ impinging three targets (C, Sn and Pb) versus incident momentum. Experimental data (black points) taken from [Ast2002] and simulations done with INCL. On the right, reaction cross section of antideuterons of 13.3 GeV/c on five targets (Li, C, Al, Cu and Pb). Experimental data (black points) taken from [Den1971] and simulations done with INCL.

probabilities to annihilate on a neutron or proton may play a role in the case of emitted protons, but more experimental data are needed for clear conclusions. Finally, we can cite a recent study [Ams2024] where the INCL results are correct, but can still be improved.

3.2 Antineutron

Left part of Fig. 4 compares the reaction cross sections calculated by INCL with experimental data. Below 165 MeV/c the annihilation is forced in INCL, and the cross sections come from literature. For the highest momenta INCL is quite close to the experimental data[4]. Efforts to improve the model focus on the transition region (100-200 MeV/c), where antineutrons seem to be captured similarly to antiprotons.

3.3 Antideuteron

The implementation of light anti-ions as projectiles in INCL is still in its early stages. Preliminary results for antideuterons at high energy (13.3 GeV/c) are presented on the right part of Fig. 4 (reaction cross sections for five target nuclei). The results are encouraging, although they underestimate the measurements by approximately 30% except for Lithium.

References

[INC2025] https://irfu.cea.fr/dphn/Spallation/incl.html

[Zha2023] D. Zharenov - Université Paris-Saclay, 2023. https://theses.hal.science/tel-04511526).

[4] Beyond 400 MeV/c the results are even better. Plot not shown here.

[Bou2002] A. Boudard et al., Phys. Rev. C 66, 044615 (2002).

[Bou2013] A. Boudard et al., Phys. Rev. C 87, 014606 (2013).

[Man2014] D. Mancusi et al., Phys. Rev. C 90, 054602 (2014).

[Rod2017] J.L. Rodríguez-Sánchez et al., Phys. Rev. C 96, (2017).

[Hir2020] J. Hirtz et al., Phys. Rev. C 101, 1 (2020).

[Dav2015] J.-C. David, Eur. Phys. J. A 51 (2015) 68.

[Cug1990] J. Cugnon, P. Deneye, and J. Vandermeulen, Phys. Rev. C 41, 1701 (1990).

[Pot1984] H. Poth. "Physics with Antiprotonic Atoms". In: Physics at LEAR with Low-Energy Cooled Antiprotons. Ed. by Ugo Gastaldi and Robert Klapisch, (1984). pp. 567–588.

[Wyc1993] S. Wycech et al., Nucl. Phys. A 561.4 (1993), pp. 607–627.

[Bar1964] V. Barnes et al. "Proceedings of the XII International Conference on High Energy Physics". In: Dubna, 1964. Vol. 1. 1964, p. 731.

[Chi1966] W. Chinowsky and G. Kojoian, Il Nuovo Cimento A (1965-1970) 43.3 (1966), pp. 684–700.

[Bet1967] A. Bettini et al., Il Nuovo Cimento A (1965-1970) 47.3 (1967), pp. 642–661.

[Biz1968] R. Bizzarri, Il Nuovo Cimento A (1965-1970) 53.4 (1968), pp. 956–968.

[Gol1992] E.S. Golubeva et al., Nuclear Physics A 537.3 (1992), pp. 393–417.

[Kle2005] E. Klempt, C. Batty, and J.-M. Richard, Phys. Rep. 413 (2005), pp. 197-317.

[Arm1969] R. Armenteros and B. French. High Energy Physics. Vol. IV., pp 237-417, Burhop, E. H. S. (ed.). New York, Academic Press, 1969. (Oct. 1969).

[Bat1988] Yu. A. Batusov et al. "PRODUCTION OF NEUTRAL STRANGE PARTICLES IN ANTI-P HE-4 ANNIHILATION AT 600-MEV/C. (IN RUSSIAN)". In: (1988).

[Fri2014] E. Friedman, Nucl. Phys. A 925 (2014) 141-149.

[Iaz2000] F. Iazzi et al., Phys. Lett. B 475.3 (2000), pp. 378–385.

[Tes1995] S. Tessaro - PhD Thesis (Trieste), Private communication.

[Bia2011] A. Bianconi et al., Phys. Lett. B 704 (2011), pp. 461–466.

[Pol1995] D. Polster et al., Phys. Rev. C 51 (1995), pp. 1167–1180.

[Mar1988] W. Markiel et al., Nucl. Phys. A 485.3 (1988), pp. 445–460.

[Ams2024] C. Amsler et al., Eur. Phys. J. A 60, 225 (2024).

[Ast2002] M. Astrua et al., Nucl. Phys. A 697, 209 (2002).

[Den1971] S.P. Denisov et al., Nucl. Phys. B 31.2 (1971), pp. 253–260.

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