Antiproton at rest and in-flight within Intra-Nuclear Cascade Liege model (INCL)

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Abstract. Antiproton-nucleus reaction is a versatile tool. It can be used to study fundamental behavior of antimatter (e.g., at CERN AD facility), neutron halo and skin of atomic nuclei (e.g., PUMA project), hyperon-antihyperon interaction (project at GSI FAIR), to name but a few. Since final state interactions are also important in such reactions and that the intranuclear cascade code INCL is known to do it well, it is naturally that its developers have been asked to add this new projectile to the list. Therefore, recent results of the new INCL version with antiproton as projectile are presented with comparisons to experimental data in wide energy range. The new version will be made available also in GEANT4, allowing to simulate future complex experiments involving $\overline{p}$.

1 Introduction

There are several ongoing and oncoming experiments which utilise antiproton as a probe to study nuclear surface phenomena [1] and nuclear interaction with exotic antimatter particles [2], while some other aim to employ high-altitude balloon detector to search for cosmic antiparticles (e.g. the GAPS experiment [3]). Robust simulation tools are required in all cases either to model the detector behaviour or to compare the results with the outcome of the experiment, and transport codes such as GEANT4 are popular simulation toolkits in this domain. While there are physics packages (Fritiof (FTF), Parton String Model) to model interaction of antiproton and nuclei via the quark-gluon strings production, up to now there was no such option based on the Intra-Nuclear Cascade approach, which is known to work well in the intermediate and low energies. Moreover, antiproton is a special case of projectile, since it has two distinct ways of interaction with the nucleus depending on the incident energy. In high-energy case, which is also called in-flight, antiproton would interact similarly as any other energetic hadron. In low-energy case, the antiproton would typically slow down rapidly in the matter as the stopping power for antiprotons is comparable to that of a proton with similar Bragg-peak effect, then it would be captured into a circular state (high n, l=n-1) of the atomic shell and would approach the nucleus through a series of atomic transitions till the moment, when its wave function would spatially overlap with the outer region of the nucleus, where it will produce a meson star as a final state of annihilation, often causing secondary collisions

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of mesons with nucleons. This case is referred to as at rest annihilation, and no currently available hadronic physics package in GEANT4 simulates such interaction scenario specifically. The purpose of the presented work is to adapt the existing Intra-Nuclear Cascade Liege (INCL) model ([4] and references therein) to model antiproton interactions both at rest and in-flight up to the energies of 10 GeV, after which the string-based model might be optimally applied.

2 In-flight implementation

This scenario is pretty much straightforward, as we just initialize the nucleus by assigning each nucleon its position and momentum and shoot the antiproton with a randomized impact parameter into the nucleus. The subsequent events are defined by the inputs of our model, which are first of all the exclusive momentum-dependent cross-sections. Large part of cross-sections were obtained from Ref. [5] by fitting experimnetal data points with this five-parameter function:

$$y(x) = a + bP_{lab}^{c} + d\ln(P_{lab}) + e\ln^2(P_{lab}) \quad (1)$$

Data for $\bar{p}p$ elementary reactions is numerous, but these is much less for $\bar{p}n$, and very scarce data for $\bar{n}p$ and $\bar{n}n$, while $\bar{n}$ may be also produced in one of binary collisions, so we fulfill these missing cross-section with the help of SU(3) symmetry. The model applicability is believed to be below 10 GeV, due to the reason of limited data for higher energies.

3 At rest annihilation

At rest, the annihilation is believed to be a dominant process at lower energies, because atomic orbitals occupy much more space of the material in comparison to nuclear part. Thus, the antiproton would interact with them much more until its energy is low enough to be captured and annihilated. In INCL we model this process from the moment, when the final state meson star is produced at the periphery of the nucleus. Mesons are assigned random momenta limited by the energy of two baryons which have been destroyed and managed by the embedded INCL phase-space model. Instead of cross-sections, we input relative frequencies of different mesonic final states which include pions, kaons, ω and η mesons, these frequencies are taken from experiments [6, 7]. These final states are different for $\bar{p}n$ and $\bar{p}p$ annihilations, and the relative probability of choosing proton or neutron was taken from deuterium experiments $S_p/S_n \approx 1.331$ and weighted with the numbers of corresponding nucleons in the target. If there were other mesons in the data, these states were populated as their corresponding decay products. One of the issues of at rest annihilation is the normalization constant, which we compute automatically for in-flight through the sum of all cross-sections. At rest we are able to produce yields, but the data are often cross-sections, so a phenomenological formula, which would work for all possible target isotopes, was taken from Ref. [8]:

$$\sigma_{reaction} = \pi R^2 (1 + \frac{Ze^2(m_{\bar{p}} + M_{target})}{4\pi\epsilon_0 E_{kin} R M_{target}}) \quad (2)$$

where $R = 1.840 + 1.120 \cdot A^{1/3}$ is the nuclear radius in fm, ϵ_0 is the vacuum permittivity and e is the elementary charge.

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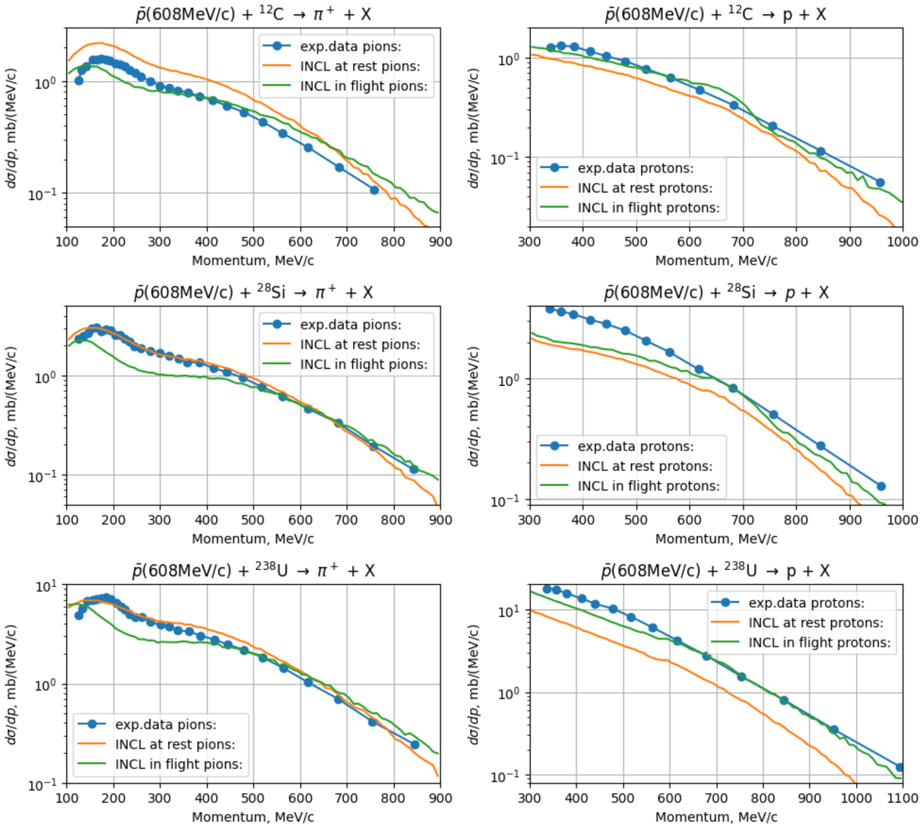

Figure 1. π^+ and proton spectra at P_{lab} = 608MeV/c ≈ 180 MeV $\bar{p}$ incident energy. Data are taken from Ref. [9] and Ref. [10], the ^{28}Si data was manually digitalized.

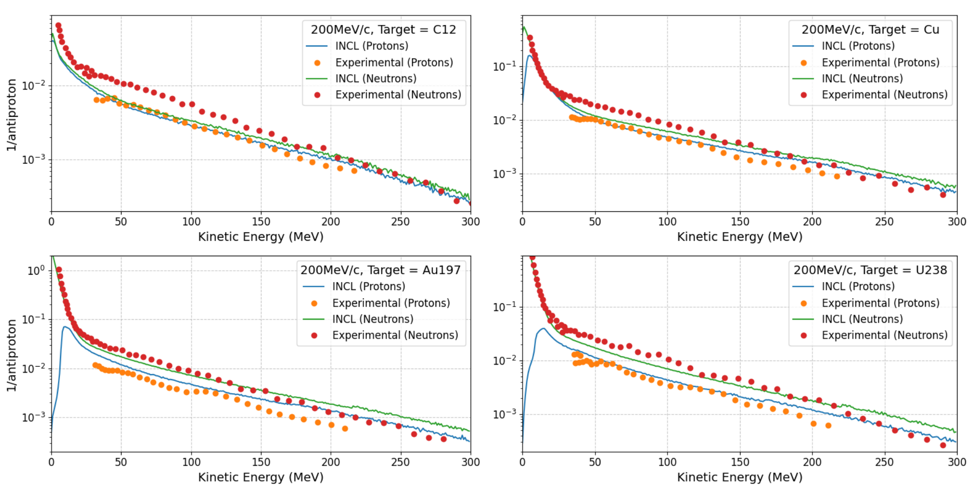

Figure 2. At rest annihilation of stopped antiprotons in INCL vs the experimental data, taken from Ref. [11] for ^{12}C, ^{natural}Cu, ^{197}Au and ^{238}U targets.

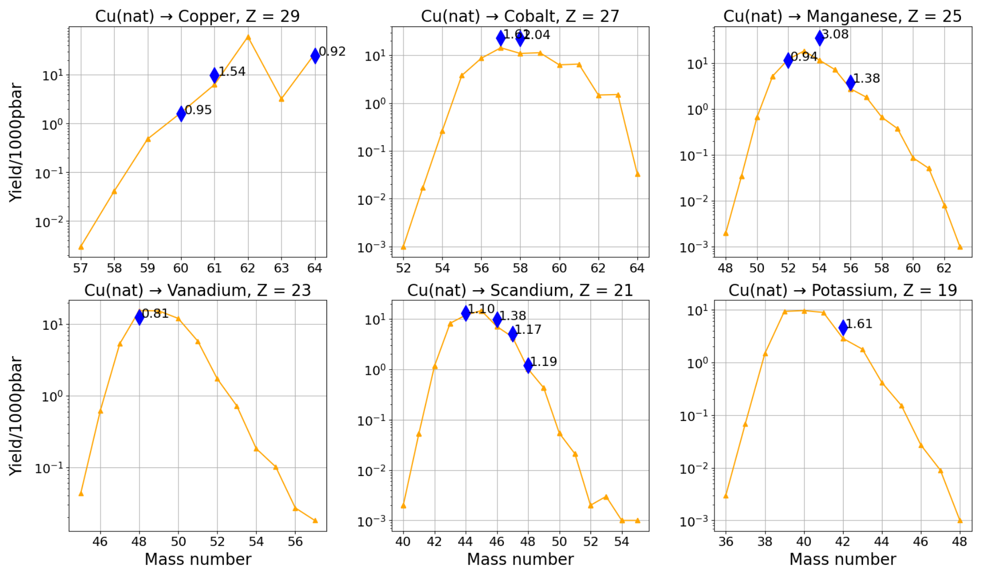

Figure 3. Annihilation of stopped antiprotons with copper, blue diamonds are the data points, they have been chosen to be independent isotopes, i.e. there have no decay chains, in which they participate, this reduces the uncertainty related to parent nuclei detection. The number near each point is the ratio of experimental yield to the INCL result. Data taken from Ref. [12].

4 Results and Discussions

The simulated production of pions seems to agree with the measured data for 608 MeV/c momentum, and from Fig. 1, we can see that the momentum dependence of the INCL at rest annihilation is more in agreement with the measured data than for the INCL in-flight. This suggests that at this energy and below, the antiprotons are more likely to annihilate through the capture process, as we assumed.

INCL results demonstrate underproduction of protons in all three cases, and it becomes more noticeable towards heavier targets. If it might be the normalization which is to blame (again, the curve is in better agreement with the measured data for the at rest scenario, which means that the at rest physics is more appropriate), then there must be an overestimation of pion production, because the normalization coefficient is the same for all spectra.

Underestimation of the distance at which a meson star is created might be another reason due to which mesons interact less with the nucleus and thus kick out fewer protons, while more pions are able to escape absorption. At Fig. 2, we have yields instead of cross sections, thus we can see that proton production is even overestimated at 200 MeV/c of incident momentum. For INCL at rest implementation incident momentum value is only used for normalization, which means that yields of particles would be the same for 200 MeV/c and 608 MeV/c. Neutron production is in quite good agreement with the data, especially towards heavier targets. Still, we generally overproduce fast neutrons on heavier targets.

With Fig. 3, which compares INCL to experimental residue production, we can conclude for the at rest mechanism, that INCL gives pretty good results, and the time has now come to study specific details, specific ingredients of our model.

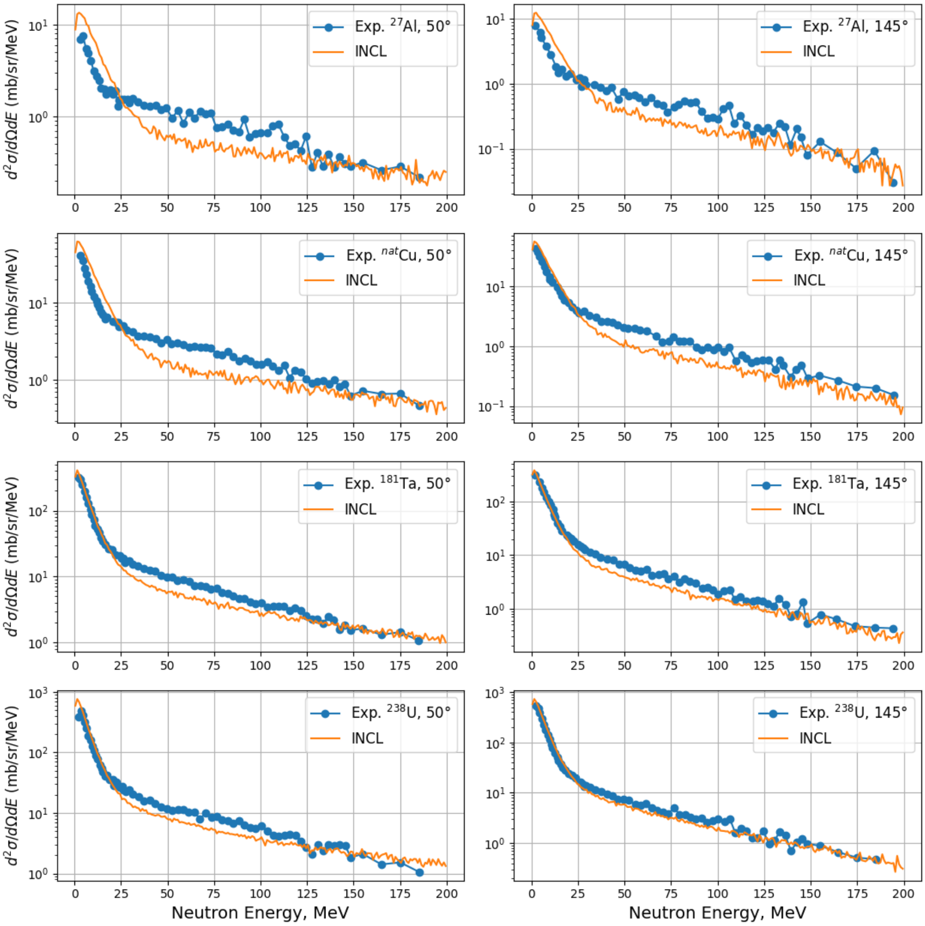

Figure 4. Neutron energy spectra from $\bar{p}$-A collisions at 1.22 GeV. Data taken from Ref. [13].

In Fig. 4, we present a comparison between the results obtained from our model and the data derived from $\bar{p}$-nucleus collisions involving 1.22 GeV protons with ^{27}Al, natural Cu, ^{181}Ta, and ^{238}U targets [13]. These neutron spectra were collected at angles of 50° and 145° relative to the incident antiproton beam direction. Such experimental setup allows us to observe the forward-backward asymmetry created with the momentum of the incident antiproton projectile. Notably, we observe this asymmetry in both the experimental data and our INCL model results, still the underestimation is more pronounced at an angle of 50°. n all cases, INCL shows a smaller deficit of neutrons emitted in the backward hemisphere than in the forward one, implying that the forward-backward asymmetry in INCL is lower than what is observed experimentally.

Another distinct pattern is the trend of decreasing discrepancy with the experimental data as we move towards heavier nuclei. This trend is indicative of an increased number of collisions in heavier nuclei, resulting in a higher fraction of available energy being transferred to neutrons due to more frequent binary collisions. Additionally, as the size of the nucleus increases, we observe a transition in the thermal portion of the spectra, shifting from an INCL overestimation to a closer match with the experimental data.

5 Conclusion

Despite some discrepancies still exist with the data, INCL is able to simulate antiproton-nucleus collisions in a wide energy range, and will be integrated with GEANT4 in the next release, allowing its use to model future experiments. Further improvements might be related to addition of certain exotic cross-sections, which are interesting for oncoming experiments like PANDA at FAIR, and adjustments of the annihilation distance in at rest scenario, as it might reduce the underproduction of nucleons at the energetic part of the spectra.

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