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Antihyperon potentials in nuclei via exclusive antiproton–nucleus reactions

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ABSTRACT

The exclusive production of hyperon–antihyperon pairs close to their production threshold in $\bar{\mathrm{p}}$-nucleus collisions offers a unique and hitherto unexplored opportunity to elucidate the behavior of antihyperons in nuclei. For the first time we analyze these reactions in a microscopic transport model using the Gießen Boltzmann–Uehling–Uhlenbeck transport model. The calculation takes the delicate interplay between the strong absorption of antihyperons, their rescattering and mean field deflection as well as the Fermi motion of the struck nucleon into account. We find a substantial sensitivity of transverse momentum correlations of coincident $\overline{\Lambda}\Lambda$-pairs to the assumed depth of the $\overline{\Lambda}$-potential. Because of the high cross section for this process and the simplicity of the experimental method our results are highly relevant for future activities at the international Facility for Antiproton and Ion Research (FAIR).

1. Introduction

The interaction of individual baryons or antibaryons in nuclei provides a unique opportunity to elucidate strong in-medium effects in baryonic systems. While for neutrons and protons as well as some strange baryons experimental information on their binding in nuclei exists, information on antibaryons in nuclei are rather scarce. Only for the antiproton the nuclear potential could be constrained by experimental studies. The (Schrödinger equivalent) antiproton potential at normal nuclear density turns out to be in the range of $U_{\bar{p}} \simeq -150$ MeV, i.e. a factor of approximately 4 weaker than expected from naive G-parity relations [1]. Gaitanos et al. [2] suggested that this discrepancy can be traced back to the missing energy dependence of the proton–nucleus optical potential in conventional relativistic mean-field models. The required energy and momentum dependence could be recovered by extending the relativistic hadrodynamics Lagrangian by non-linear derivative interactions [3,2,4] thus also mimicking many-body forces [5]. Considering the important role played e.g. by strange baryons and antibaryons for a quantitative interpretation of high-energy heavy-ion collisions and dense hadronic systems it is clearly mandatory to test these concepts also in the strangeness sector. Of course, the question if and to what extend G-parity is violated by antihyperons in nuclei is also a challenging problem by itself.

Antihyperons annihilate quickly in nuclei and conventional spectroscopic studies of bound systems comparable to hypernuclei are not feasible. As a consequence, no experimental information on the nuclear potential of antihyperons exists so far. As suggested recently [6], quantitative information on the antihyperon potentials may be obtained via exclusive antihyperon–hyperon pair production close to threshold in antiproton–nucleus interactions. Once these hyperons and antihyperons leave the nuclear environment they can be detected and their asymptotic momentum distributions will reflect the depth of the respective potentials. In Ref. [6] it was demonstrated that momentum correlations of emitted hyperon–antihyperon pairs can be used to extract information on the relative potential of hyperons and antihyperons in nuclei. Since in the $\bar{\mathrm{p}}\mathrm{p}$ center-of-mass the distribution of the free baryon–antibaryon pairs is non-isotropic, the analysis relied mainly on the *transverse* momenta of the coincident baryons and antibaryons. The calculations of Ref. [6] revealed significant sensitivities of the transverse momentum asymmetry α_T which is defined in terms of the transverse momenta of the coincident particles

$$\alpha_T = \frac{p_T(\Lambda) - p_T(\overline{\Lambda})}{p_T(\Lambda) + p_T(\overline{\Lambda})}, \tag{1}$$

to the depth of the antihyperon potential. The asymmetry α_T turned out to be rather robust in case of model parameter

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variations and remained substantial also if the momentum dependence of the potential was considered [7]. However, these schematic simulations ignored rescattering processes and mean field deflections. (In the following we subsume these effects under *secondary deflection*.) These effects are expected to erode the two-body character of the $\overline{\Lambda}\Lambda$ production and may thus diminish or even destroy the sensitivity. In order to go beyond the schematic calculations presented in Refs. [6,7] and to include simultaneously secondary deflection and absorption effects, we present here first realistic calculations of this new observable with a microscopic transport model.

2. Transport calculations

The Giessen Boltzmann–Uehling–Uhlenbeck transport model (GiBUU, Release 1.5) [8] describes many features of $\bar{p}$-nucleus interactions in the FAIR energy range [1,8,9]. Particularly the presently available data on strangeness production are well reproduced. In this code non-linear derivative interactions [2] are not yet included and a simple scaling factor $\xi_{\bar{p}} = 0.22$ was applied to ensure a Schrödinger equivalent antiproton potential of -150 MeV at saturation density [9]. (Note that this value differs slightly from the scaling factor $\xi_{\bar{p}} = 0.25$ given in Ref. [1].) The hyperon potentials were fixed by hypernuclear and hyperatom data [9]. No experimental information exists for antihyperons in nuclei and G-parity symmetry is therefore used to specify their default potentials. This leads to a $\overline{\Lambda}$-potential $U(\overline{\Lambda}) = -449$ MeV. As already stressed in Ref. [9], the attractive Σ-potential and the weak attraction for kaons adopted in the GiBUU model is not compatible with experimental data. In the present work we focus on exclusive $\overline{\Lambda}\Lambda$-pair production in the threshold region. Therefore, we do not expect that a more realistic treatment of the Σ and kaon potentials will modify the conclusions of the present study.

We have studied the exclusive reaction $\bar{p} + {}^{20}\mathrm{Ne} \rightarrow \overline{\Lambda}\Lambda$ at beam energies of 0.85 GeV and 1 GeV. These energies correspond to antiproton momenta of 1.522 GeV/c and 1.696 GeV/c, respectively. At 0.85 GeV the excess energy with respect to the elementary reaction $\bar{p} + p \rightarrow \overline{\Lambda}\Lambda$ amounts to only 30.6 MeV. Therefore, the $\overline{\Sigma}\Lambda$ and $\Sigma\overline{\Lambda}$ channels are not accessible and also the production of a pion in addition to a $\Lambda\overline{\Lambda}$-pair can be neglected. The higher energy of 1 GeV lies above the $\overline{\Sigma}\Lambda$-threshold and makes also the $\bar{p}n \rightarrow \overline{\Lambda}\Sigma^-$ and $\bar{p}p \rightarrow \overline{\Lambda}\Sigma^0$ as well as their charge conjugate channels accessible. Those channels will be discussed in a forthcoming paper.

In order to explore the sensitivity of the transverse momentum asymmetry on the depth of the $\overline{\Lambda}$-potential we have performed a series of calculations where only the antihyperon potentials were modified by a single scaling factor, leaving all other input parameters of the model unchanged. The calculations were performed at the High Power Computing Cluster HIMSTER located at the Helmholtz-Institute Mainz. Each GiBUU-Job comprised 1000 parallel events. In order to keep the necessary computing time low, all cross sections for antihyperon–hyperon pair production were artificially enhanced by a factor of 10. Since within the 1000 parallel events of an individual job the probability of a multiple production of hyperon pairs is low, the mean field dynamics is insignificantly distorted. For each parameter set a total of 26460 Jobs were generated. Using the maximum number of parallel jobs allowed at the HIMSTER, it took typically 3 weeks to produce one of the 8 data sets. Each parameter set shown in the following contains approximately 8000 $\overline{\Lambda}\Lambda$-pairs where both, the $\overline{\Lambda}$ and the Λ escaped the nucleus.

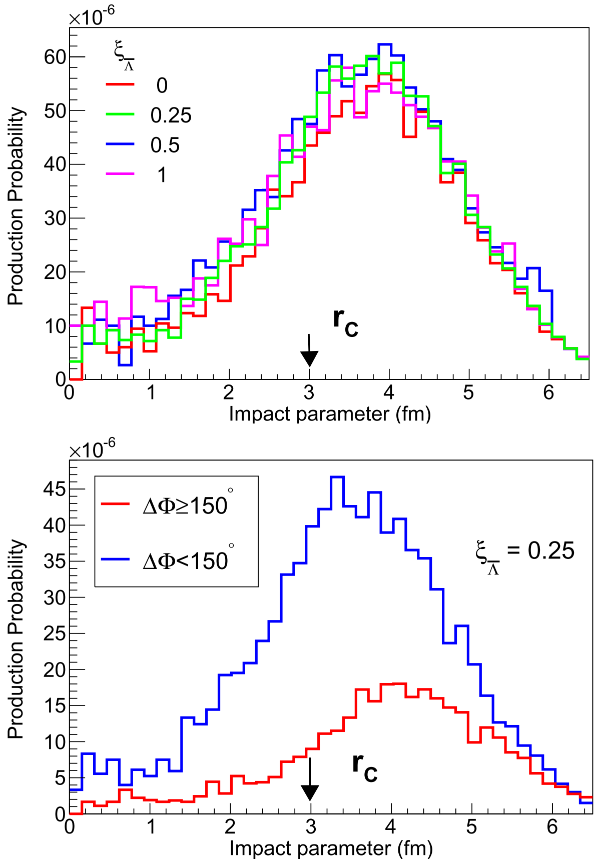

Fig. 1. Top: Probability distribution for free $\Lambda\overline{\Lambda}$-pair production in 0.85 GeV $\bar{p} + {}^{20}\mathrm{Ne}$ collisions as a function of the impact parameter. The different lines show the GiBUU predictions for different scaling factor $\xi_{\overline{\Lambda}}$ of the $\overline{\Lambda}$-potentials. Bottom: Impact parameter distributions for planar ($\Delta\Phi \geq 150°$) and non-planar ($\Delta\Phi < 150°$) $\Lambda\overline{\Lambda}$ pairs (cf. Fig. 2) using a fixed $\overline{\Lambda}$-potential scaling factor $\xi_{\overline{\Lambda}} = 0.25$.

3. Results

Unlike in inclusive reactions [10,11], the strong absorption of the antihyperons in nuclei favors the production of free hyperon–antihyperon pairs in the corona of the target nucleus. The top part of Fig. 1 shows the probability for free $\overline{\Lambda}\Lambda$-pair production ($\sim b^{-1} dN_{\overline{\Lambda}\Lambda}/db$) as a function of the impact parameter b for different $\overline{\Lambda}$-potentials. (The artificial increase for $\overline{Y}Y$ production by a factor of 10 is taken into account.) The distributions peak around 3.8 fm which is significantly larger than the ^{20}Ne rms-charge radius of $r_C = 3.0$ fm [12] marked by the arrow in Fig. 1. Consequently, free antihyperon–hyperon pairs are mainly produced at low nuclear densities corresponding to 20 to 25% of the central density.

For scaling factors $\xi_{\overline{\Lambda}}$ between 1 and 0.25 the average impact parameter persists at 3.8 fm. Only for $\xi_{\overline{\Lambda}} = 0$ a slight increase to 3.9 fm is observed. At the same time the number of produced $\overline{\Lambda}\Lambda$-pairs remains fairly constant on a level of about 8700 events over the range $1 \leq \xi_{\overline{\Lambda}} \leq 0.5$ and decreases for $\xi_{\overline{\Lambda}} = 0$ by about 15% to $\approx$ 7500 events. This moderate decrease indicates that absorption does not change dramatically with the depth of the $\overline{\Lambda}$-potential. In Fig. 1 (top) the main variations are seen at impact parameters below about 4 fm. This suggests that the smaller number of events in case of a shallow antihyperon potential is caused by an increased absorption. For a quantitative interpretation one has to keep in mind, however, that also a potential-dependent rescattering can enhance the escape probability from the nucleus by decreasing the