EPJ Web of Conferences **171**, 19006 (2018) https://doi.org/10.1051/epjconf/201817119006
SQM 2017

Subthreshold Ξ^- production in proton-nucleus collisions in a BUU model

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Abstract. We study the production of the doubly strange Ξ baryon in subthreshold $p + A$ collisions using a BUU type transport model. We propose a new mechanism for Ξ creation in a two-step process via hyperon-nucleon collisions. We study the influence of the anisotropy of hyperon production in $N + N$ collisions on the Ξ multiplicity. Applying reasonable assumptions on the unknown elementary cross sections, we are able to reconstruct the Ξ yield observed by the HADES collaboration (GSI, Darmstadt) in subthreshold p+Nb collisions.

1 Introduction

Particle production in nuclear collisions near or below the kinematical threshold of elementary $N + N$ reactions is sensitive to the details of the reaction dynamics, e.g. Fermi motion, collision of secondaries or in-medium modification of particle properties. Due to strangeness conservation in the strong interaction, strange particles are created in pairs, which leads to higher production thresholds. Thus subthreshold strangeness production is a suitable tool to study the reaction dynamics at higher energies where higher baryon densities are reached.

Proton-nucleus ($p + A$) collisions are an intermediate step between $N + N$ and $A + A$ collisions. Here properties of hadrons at normal nuclear matter density are studied. In $p + A$ collisions fewer elementary production channels of a specific hadron species are possible, since e.g. the collision of two secondaries is rather unlikely.

The HADES collaboration has studied the production of the doubly strange Ξ^- baryon in both p+Nb reactions at the subthreshold energy of $\sqrt{s_{NN}} = 3.2$ GeV [1], and in Ar+KCl collisions at the deeply subthreshold energy of $\sqrt{s_{NN}} = 2.61$ GeV [2]. In both reactions a surprisingly high Ξ^- multiplicity has been found. The THERMUS statistical model gives a good description of most strange and non-strange hadron yields in both reactions. The only exception is the Ξ^- yield which the model underestimates by a factor 15 in the case of the reaction Ar+KCl and by a factor 8 in the case of the reaction p+Nb [3].

In earlier transport model calculations, Ξ production in strangeness exchange reactions has been considered, in particular in antikaon-hyperon collisions, $\bar{K}+Y \to \pi+\Xi$ ($Y = \Lambda$ or Σ), hyperon-hyperon collisions, $Y + Y \to \Xi + N$ and the reaction $\eta + \Lambda \to \Xi + K$. All these reaction channels involve the

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collision of two secondaries, therefore they cannot account for the high Ξ multiplicity in subthreshold $p + A$ collisions.

At present only the UrQMD transport model is able to reproduce the Ξ multiplicities found by HADES in subthreshold p+Nb and Ar+KCl reactions [4]. In that study it was assumed that the high mass tail of some higher nucleon resonances decays to the $\Xi + K + K$ final state with a branching ratio of 10 %.

In the present contribution we propose a new production mechanism of the Ξ baryon in nuclear collisions via the collision of a secondary hyperon and a target nucleon. In Sec. 2 we discuss this new production mechanism, give some estimates of the elementary cross sections, and discuss the relevance of the angular distribution of hyperon production to the Ξ multiplicity. BUU transport calculations are presented in Sec. 3, where our results are compared to the HADES data.

2 Ξ production via hyperon-nucleon collisions

We propose the following production mechanism for Ξ production in p+A collisions: first, the projectile proton collides with a nucleon in the target and they create a hyperon via the reaction $p + N \to N + K + Y$, ($Y = \Lambda$ or Σ). This hyperon then collides with a second target nucleon and they create a Ξ baryon via $Y + N \to N + K + \Xi$.

The threshold energy for $\Lambda(\Sigma)$ production in a $p + N$ collision is $\sqrt{s_{NN,\text{thr}}} = 2.55$ GeV (2.62 GeV), which is lower than the CM energy $\sqrt{s_{NN}} = 3.2$ GeV available in the first collision of the projectile proton and a target nucleon in the p+Nb collision studied by HADES. Furthermore, in the ideal case of a hyperon emitted in the forward direction, the maximum available CM energy in the collision of the Λ hyperon with a second target nucleon is $\sqrt{s_{\Lambda N,\text{max}}} = 3.05$ GeV, which is above the threshold of $\sqrt{s_{\Lambda N,\text{thr}}} = 2.75$ GeV for Ξ production. The energetical situation with a Σ hyperon instead of a Λ is very similar. This means that both steps of the above production mechanism are kinematically allowed in the p+Nb experiment of HADES. We note that, according to the proposed mechanism, not only the energy but also the two units of strangeness are accumulated in two steps.

Estimate of the elementary cross section

We assume that Ξ production in $Y + N$ collisions proceeds via an intermediate Λ^* or Σ^* resonance, as shown in Fig. 1. In order to obtain a rough estimate of the cross section of this process, we first assume

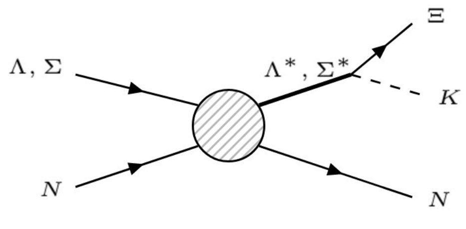

Figure 1. Schematic diagram for Ξ production in a hyperon-nucleon collision.

that the total $Y + N$ cross section is of the same order of magnitude as the proton-proton cross section at the same excess energy $\sqrt{s} - \sqrt{s_{\text{thr}}} \approx 0.3$ GeV, that is, a few times 10 mb. If resonance dominance is assumed, i.e. all final states in $Y + N$ reactions are reached via intermediate (strange or non-strange) resonances, then the total $Y + N$ cross section equals the total resonance production cross section in the same reaction. The cross section for Λ^* and Σ^* creation, which is a considerable part of the above, should be of the order of 10 mb at the maximum energy available in the HADES experiment. The Ξ production cross section is obtained via multiplication by the $\Lambda^*(\Sigma^*) \rightarrow \Xi + K$ branching ratio. The only available information on this branching ratio is for the $\Lambda(2100)$ resonance, for which an upper limit of 3 % is given by the Particle Data Group [5]. Using 10 mb for the $\Lambda^*(\Sigma^*)$ creation cross section and 3 % for the ΞK branching ratio, we get an estimate of 0.3 mb for the $Y + N \rightarrow N + \Xi + K$ cross section, which should be valid at an excess energy of about 0.3 GeV.

In order to model the energy dependence of the elementary cross section of Ξ production, we study the phase space effects of the process depicted on Fig. 1. We calculate the production cross section of Λ^* and Σ^* resonances assuming a constant matrix element of the processes $\Lambda(\Sigma) + N \rightarrow \Lambda^*(\Sigma^*) + N$ and we consider the mass dependence of their decay widths. We include the 3 and 4 star Λ^* and Σ^* states in the relevant mass range and choose the constant matrix element in such a way that the Ξ production cross section of 0.3 mb at 0.3 GeV excess energy, the estimate obtained in the previous paragraph, is roughly reproduced. The resulting energy dependence of the $\Lambda + N \rightarrow N + \Xi + K$ cross section is shown in Fig. 2. For the corresponding cross section with the Σ hyperon in the initial state we obtained a very similar energy dependence.

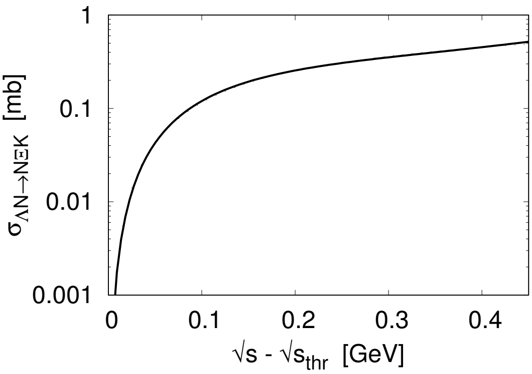

Figure 2. Cross section of the process $\Lambda + N \rightarrow N + \Xi + K$ as a function of the excess energy.

Relevance of the angular distribution of hyperon production

Λ and Σ hyperons emitted in the forward direction in the first $p + N$ collision have more energy available in their collision with a second target nucleon than those emitted in a different direction. Thus, the angular distribution of Λ and Σ creation in $N + N$ collisions is expected to influence the Ξ multiplicity in subthreshold $p + A$ collisions. This angular distribution has been studied by the COSY-TOF collaboration and they have found an increased emission probability of hyperons in the forward direction [6], which can result in an enhancement of Ξ production in $p + A$ collisions.

3 BUU calculations

We use the BUU code developed in a Budapest-Rossendorf collaboration, that has been successfully applied to strangeness production near and below the production threshold [7]. The elementary cross sections of Λ and Σ production in $N+N$ collisions are implemented in the code based on an effective Lagrangian model study, which assumes the dominance of resonance contributions [8]. For the $Y + N \rightarrow N + \Xi + K$ cross section we use our estimate shown in Fig. 2.

Assuming an isotropic distribution of the produced Λ and Σ hyperons in the elementary $N+N$ reaction in the center of momentum frame of the colliding nucleons, we obtained a Ξ^- multiplicity of $P_{\Xi^-} = 1.4 \times 10^{-4}$ and a Ξ to hyperon ratio of $P_{\Xi^-}/P_{\Lambda+\Sigma^0} = 0.68 \times 10^{-2}$. Implementing the anisotropy of hyperon production found in [6], we get the increased values of $P_{\Xi^-} = 2.16 \times 10^{-4}$ and $P_{\Xi^-}/P_{\Lambda+\Sigma^0} = 1.14 \times 10^{-2}$. These have to be compared to the experimental values by the HADES collaboration, $(P_{\Xi^-})_{\text{exp}} = (2.0 \pm 0.4 \pm 0.3) \times 10^{-4}$ and $(P_{\Xi^-}/P_{\Lambda+\Sigma^0})_{\text{exp}} = (1.2 \pm 0.3 \pm 0.4) \times 10^{-2}$.

4 Conclusions

We have proposed a new mechanism for the production of the doubly strange Ξ baryon in subthreshold proton-nucleus collisions via a reaction of a secondary Λ or Σ hyperon with a target nucleon. We implemented this mechanism in our BUU transport code and studied the reaction p+Nb at $\sqrt{s_{NN}} =$ 3.2 GeV energy, which has been measured by the HADES collaboration. In the new mechanism, both the energy needed to create the Ξ and the associated kaons, as well as the two units of strangeness are accumulated in two steps. The angular distribution of the first step process (hyperon creation) has an influence on the energy available in the second step process (Ξ creation in hyperon-nucleon collision). We have found that the anisotropy of hyperon production in $N+N$ collisions enhances the Ξ^- multiplicity by about 50 % in p+Nb collisions at the studied subthreshold energy.

Applying reasonable assumptions on the cross section of the experimentally unknown process of Ξ production in hyperon-nucleon collisions, we were able to reproduce the high Ξ^- multiplicity found in p+Nb collisions in the HADES experiment. The new mechanism utilizes the first two energetic elementary collisions in the $p + A$ reaction. It is clear that in a thermalised medium formed in the same reaction, the energy needed for Ξ creation would not be available in a hyperon-nucleon collision. This is consistent with the finding that a thermal model calculation strongly underestimates the experimentally observed Ξ^- multiplicity.

Acknowledgements

This research was supported by the Hungarian OTKA Fund No. K109462 and by the ExtreMe Matter Institute EMMI at the GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany.

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