$\Sigma^0$ production in proton nucleus collisions near threshold

HADES Collaboration


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1. Introduction

The study of hyperon production in proton-induced collisions at beam energies of a few GeV is important for many open questions in the field of hadron physics. While several experimental results exist for Λ hyperons in p+p and p+A reactions [1-6], measurements of Σ0 production are scarce [4-6]. The dominant electromagnetic decay Σ0 → Λ + γ (BR ≈ 100%) requires the identification of photons with Ep ≈ 80 MeV coincident to the detection of π0 decays from Λ decays. Our measurement is the first step towards gaining access to the hyperon electromagnetic form factors [7]. Once the measurement of virtual photons in the Dalitz decay Σ0 → Λe+e− (BR < 1%) is performed it can be separated from the decays involving a real photon and therefore provide complementary information on the nucleon and Λ baryon form factors [8].

Hadron collisions at energies of a few GeV with hyperons in the final state are also suited to study the role played by intermediate hadronic resonances in the strangeness production process. Indeed, non-strange resonances like N* and Λ have been found to contribute significantly [9-13] via the channels N* → Λ + K+ and Λ++ → Σ(1385)+ + K+. In case of N*, up to seven resonances with similar masses and widths have been identified including the occurrence of interference effects among them [2,14]. In this context, the simultaneous measurement of Λ and Σ hyperons becomes important to understand the interplay between the spin 1/2 and 3/2 states occurring in the strong conversion process Σ + N → Λ + N. This process manifests itself as a peak structure on top of the smooth Λ + p invariant-mass distribution close to the Σ-N threshold and is known to be responsible for cusp effects [15]. Hyperon production in nuclear reactions gives also access to details of the hyperon–nucleon interaction. The existence of Λ hypernuclei is argued as evidence for an attractive potential at rather large inter-baryon distances [16,17]. Theoretical models [18] trying to describe scattering data [19,20] with hyperon beams postulate the presence of a repulsive core for the Λ–N interaction. Σ0 hypernuclei, on the other hand, have not been observed so far due to difficulties implied by the electromagnetic Σ0 decays and the requirement of large acceptance and high resolution electromagnetic calorimeters. Since also scattering data for Σ hyperon beams are scarce, constraints on the Σ–N interaction are missing so far and new measurements of Σ0 production in nuclear targets are essential.

Medium-energy heavy-ion collisions producing hyperons allow to study their properties within a dense baryonic environment (up to ρ ≈ 2–3ρ0) [21-24]. One question of interest is whether the attractive Λ–N interaction in vacuum or at nuclear saturation might change due to the postulated appearance of a more dominant repulsive core at increased densities and short distances [25]. The quest for detailed information on such aspects requires the knowledge of Λ feed down effects from Σ0 production and its corresponding behaviour in baryonic or even cold nuclear matter.

Experimental data for simultaneous Σ0 and Λ production are available for proton–proton collisions either close to the free NN production threshold (Ecm = 2.518 GeV for Λ and Ecm = 2.623 GeV for Σ0) [4,5] or at excess energies of ≈ 5 GeV and above [26]. So far, no data are available for Σ0 hyperons emerging from proton + nucleus collision systems at few GeV incident beam energy. In this work we present the first measurement of Σ0 production in p + Nb collisions at an incident kinetic beam energy of Ecm = 3.5 GeV. Our paper is organised as follows. In section 2, we describe the experimental set-up. Section 3 is devoted to Σ0 identification and background subtraction. In section 4 the method for efficiency correction and differential analysis is shown. In section 6 the extracted cross sections and yields are compared to different models. In sections 6 we give a summary and short outlook.

2. The HADES experiment

The High-Accuracy Di-Electron Spectrometer (HADES) [27] located at the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt (Germany) is an experimental facility for fixed target nuclear reaction studies in the few GeV energy region. The spectrometer is dedicated to measure low-mass dielectrons originating from the decay of vector mesons in the invariant-mass range up to the φ mass and offers excellent identification by means of charged hadrons such as pions, kaons and protons. The detector setup covers polar angles between 18° to 85° over almost the full azimuthal range designed to match the mid-rapidity region of symmetric heavy-ion collisions at E = 1–2 AGeV. A set of multiwire drift chamber (MDC) planes arranged in a sixfold segmented trapezoidal type structure, two layers in front and two behind a toroidal magnetic field, is used for charged-particle tracking and momentum reconstruction with a typical resolution of Δp/p ≈ 3%. An electromagnetic shower detector (Pre-Shower) and a Time-Of-Flight scintillator wall (TOF and TOFINO) build the Multiplicty and Electron Trigger Array (META) detector system used for event trigger purposes. The energy loss (dE/dx) signals measured in the TOF and MDC detectors are used for charged particle identification. In addition, electrons and positrons are identified over a large range of momenta with a Ring Imaging Cherenkov (RICH) detector surrounding the target in a nearly field-free region.

In the present experiment, a proton beam accelerated by the SIS18 synchrotron to a kinetic energy of Ep = 3.5 GeV has been
3. \( \Sigma^0 \) identification and background subtraction

The identification of \( \Sigma^0 \) hyperons was achieved via the decay channel \( \Sigma^0 \rightarrow \Lambda \gamma \) (BR \( \approx 100\% \)) by reconstructing \( \Lambda \rightarrow p\pi^- \) decays correlated with the emission of a dielectron from external pair conversion \( \gamma \rightarrow e^+e^- \) or from the Dalitz decay \( \Sigma^0 \rightarrow \Lambda e^+e^- \) (BR \( \approx 5 \times 10^{-2} \)) [28]. Fig. 1 depicts the \( p\pi^- \) invariant-mass distribution of such events with a clear signature of a \( \Lambda \) content in the data sample. Due to the low mass difference \( m_{\gamma^0} - m_{\Lambda} \approx 77 \text{ MeV/c}^2 \) a considerable fraction of coincident \( e^\pm \) candidates have momenta below the spectrometer acceptance threshold \( p_{\text{thr}} \approx 50 \text{ MeV/c} \) needed for full track and momentum reconstruction.

For this reason, dielectrons have been identified by requiring two RICH rings, at least one fully reconstructed \( e^\pm \) track and one neighbouring incomplete tracklet detected in front of the magnetic field in the first two MDCs. The missing momentum of the incomplete tracklet has been estimated by applying a most probable hypothesis as described in detail in [29] which partly exploits results and constraints from kinematically similar \( \pi^0 \) Dalitz decays. In this way, the observed incomplete dielectron tracks are combined into most probable photon signals with a resolution of \( \Delta E_{\gamma} \) (FWHM) = 57 \( \pm \) 2 MeV [29].

The combinatorial background has been determined with two approaches. First, background yield and shape have been estimated from polynomial fits of the \( p\pi^- \) invariant mass in the sideband regions below and above the \( \Lambda \) peak, 1090 MeV/c^2 < \( m_{\pi^-} \text{inv} \) < 1105 MeV/c^2 and 1125 MeV/c^2 < \( m_{\pi^-} \text{inv} \) < 1140 MeV/c^2 (see Fig. 1). The second approach aimed at the suppression of a random peak structure. The measured background was scaled to the sideband of the smeared distribution shown in Fig. 1 to evaluate the background in the signal region. After weighting and normalisation, both methods lead to the same background yield within 10%. The side band samples used to construct the \( p\pi^- \) background are combined with the reconstructed \( e^\pm \) pairs to obtain the background to the \( \Sigma^0 \) candidates (for details see [29]).

The inclusive four-particle \( p\pi^- e^\pm \) invariant mass distribution is shown in the inset of Fig. 1. A peak structure becomes apparent at the \( \Sigma^0 \) pole mass with a width (FWHM) of 52 \( \pm \) 22 MeV/c^2. The observed FWHM is mainly attributed to the resolution of the \( \gamma \) reconstruction. The estimated background is shown by the red histogram.

Full scale UrQMD [30,31] simulations have been carried out and processed through Geant and a digitisation procedure to emulate the detector response. Subsequently the events have then been analysed in the same manner as the experimental data. Then the simulation has been normalised to the \( \Sigma^0 \) yield. The inset in Fig. 1 shows that the simulated \( \Sigma^0 \) mass distribution is in agreement with the measured distribution. A total of \( N_{\Sigma^0} = 224 \pm 24 \text{ Stat} \pm 65 \text{ Syst} \) \( \Sigma^0 \) candidates has been extracted.

4. Efficiency correction and differential analysis

After background subtraction, a differential analysis has been performed for the kinematic variables transverse momentum \( p_t \) and rapidity \( y \) of the \( \Sigma^0 \) candidates. Due to the limited event statistics, the experimental yields are computed for three equally spaced momentum bins between 240 MeV/c \( \leq p_t \leq 960 \text{ MeV/c} \) split in two rapidity bins 0.5 \( < \) \( y \) \( < \) 0.8 and 0.8 \( < \) \( y \) \( < \) 1.1. The acceptance and efficiency correction matrix for this phase space region has been obtained from simulations utilizing the UrQMD/Geant3 data set (see above) and after \( \Sigma^0 \) reconstruction. The systematic errors of these corrections stem from various sources. The uncertainty on particle identification of protons and pions of \( \approx 5\% \) is adopted from the high statistics analysis of inclusive \( \Lambda \) production [3]. The overall uncertainty for identification of low momentum \( e^+e^- \) partners and pair reconstruction with two complete tracks is \( \approx 25\% \) as deduced in a previous search for dark photons with hypothetical masses in the interval \( \approx 50 \text{–} 100 \text{ MeV} \) [32]. The error in the background subtraction is estimated from a comparison of the two methods described above and contributes with \( \approx 8\% \). Other sources are of order \( 10^{-2} \) and less. The quadratic sum results in a total systematic error of \( \approx 30\% \). The statistical errors did not exceed values of \( \lesssim 10\% \). The corrected reduced transverse-mass spectra (with \( m_T = \sqrt{p_T^2 + m_{\gamma^0}^2} \)) for the \( \Sigma^0 \) candidates are shown in Fig. 2 separately for both rapidity intervals. Towards smaller transverse momenta, the geometrical spectrometer acceptance does not cover the full region for at least one of the decay partners \( \Lambda \) or \( \gamma \). To extrapolate to uncovered phase space regions we have assumed a thermal \( \Sigma^0 \) phase space production. Hence, the differential distributions have been fitted with a Maxwell–Boltzmann distribution (1/m^2) (d^2N/dm^2dy) = A(y) \cdot \exp(-(m_{\gamma^0})^2)/T_B(y), \text{ where } A(y) \text{ is a rapidly dependent scaling factor and } m_{\gamma^0} = 1192.642 \pm 0.024 \text{ MeV/c}^2 \text{ [28]. The inverse-slope parameters } T_B = 82 \pm 23 \text{ MeV for the rapidity bin } 0.5 < y < 0.8 \text{ and } T_B = 78 \pm 22 \text{ MeV for the more forward region } 0.8 < y < 1.1 \text{ can be compared with the average value of } 84 \text{ MeV extracted for } \Lambda \text{ hyperons in the same reaction [3].}

The experimental rapidity–density distributions dN/dy obtained for both hyperons from integration of the corresponding Maxwell–Boltzmann distributions with the given parameters are depicted in the upper panel of Fig. 3. The calculation of minimum-bias multiplicities requires normalisation of the observed yields to the
total number of reactions which we obtained by multiplying the number of M3 triggers (charged particle multiplicity ≥ 3) with a correction factor C. The latter has been extracted from a UrQMD simulation of the p+ Nb reaction with impact parameters in the range 0–8 fm and full Geant3 propagation of the events yielding C = 1/RM3−M1 with RM3−M1 = 0.58 ± 0.06. Summation over both rapidity bins in Fig. 3 gives the multiplicity inside the acceptance NΣ0 = (2.7 ± (0.2)stat ± (0.7)sys ± (0.2)norm × 10−3)/evt. and NΛall = (6.1 ± (0.3)sys ± (0.8)norm × 10−3)/evt. Note that the NΛall signal includes the feed down from heavier resonances, mainly from Σ0 decays. The production ratio inside the acceptance 0.5 < y < 1.1 is found to be Λall/Σ0 = 2.3 ± (0.2)stat ± (0.6)sys.

5. Cross sections and comparison to models

The production cross section has then been obtained by multiplying the multiplicity with the total interaction cross section σp+ Nb = 848 ± 126 mb for the p + Nb reaction [33,34] and correcting it for the trigger bias. The acceptance integrated cross section ΔσΣ0 which can be obtained from the experimental count rates by multiplication with the luminosity is found to be equal to ΔσΣ0 = 2.3 ± (0.2)stat ± (0.6)sys ± (0.2)norm × 10−3 mb within the rapidity interval 0.5 < y < 1.1.

Extrapolation to the uncovered rapidity region and extraction of an estimate for the total production cross section have been deduced with the help of transport model calculations. We have extracted Σ0 rapidity distributions from UrQMD [30] and GiBUU [35,36] event generators and normalised them to match the experimental data points. The distributions are plotted in Fig. 3 and exhibit considerable differences. Those possibly indicate different weights in the models for the implementation of the slowing down of the Σ0 which are initially produced at the rapidity of the NN centre-of-mass system. While the data are well reproduced by UrQMD in the region above y > 0.4, the extrapolation to target rapidities seems to be ambiguous. Under the assumption that both hyperons experience comparable emission kinematics due to their very similar masses we can profit from the larger rapidity coverage and smaller bin sizes of the reconstructed Λ. Hence, as an alternative guidance we have used the measured Λ rapidity density distribution (Λ-like) as published in [3] and normalised it to the Σ0 distribution. For comparison, the resulting total Σ0 yields and extrapolated production cross sections of the scaled distributions are listed in Table 1.

The Σ0 production cross section has finally been calculated from a mean of the Λ-like and UrQMD rapidity distributions resulting in σΣ0p+ Nb = 5.8 ± (0.5)stat ± (1.4)sys ± (0.6)norm ± (1.7)extrapol mb. A Σ0 yield of NΣ0 = (7 ± 3) × 10−3/evt for the full phase space has been extracted in the same way. The ratio Λall/Σ0 = 2.3 ± (0.2)stat ± (0.7)sys ± (0.7)extrapol has been obtained by using the ratio within the acceptance and an additional extrapolation uncertainty stemming from the difference between UrQMD and Λ-like extrapolation methods. This can be justified by the rather flat distribution of experimental data as well as for the UrQMD and GiBUU simulations. The error on the extrapolation procedure introduces the largest uncertainty. The statistical and systematic errors have been added quadratically.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Σ0 yield per event</th>
<th>σΣ0p+ Nb [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Λ-like</td>
<td>5.2 × 10−3</td>
<td>4.4 ± 0.2 stat ± 1.1 sys ± 0.5 norm</td>
</tr>
<tr>
<td>GiBUU</td>
<td>7.3 × 10−3</td>
<td>6.2 ± 0.5 stat ± 1.5 sys ± 0.6 norm</td>
</tr>
<tr>
<td>UrQMD</td>
<td>8.6 × 10−3</td>
<td>7.3 ± 0.6 stat ± 1.1 sys ± 0.8 norm</td>
</tr>
</tbody>
</table>

All data points but two stem from proton–proton collisions. Our result for the production in a heavy nucleus (heavy bullet in Fig. 4) fits well to the systematics and model predictions. In this comparison, the multi-step interaction of the Σ0 with one, two or even more nucleons has been neglected as well as the Fermi motion.
6. Summary and outlook

We have demonstrated the capability of HADES to reconstruct the low energy $\gamma \rightarrow e^+e^-$ conversion processes in the detector material via the identification of electrons and positrons. With this technique we were able to measure for the first time $\Sigma^0$ hyperon production in proton-induced reactions off a heavy nucleus near threshold. We provide transverse mass distributions in two rapidity bins. Based on them, a $\Sigma^0$ production cross section of $\sigma_{p+p\rightarrow p+\Sigma^0} = 5.8 \pm 2.3$ mb has been determined. The inclusive light hyperon production ratio is $\Lambda_{\text{all}}/\Sigma^0 = 2.3 \pm 1.1$. All uncertainties have been summed up quadratically. These experimental values compare reasonably well with transport model calculations and results from a statistical hadronisation scheme. In spite of the limited spectrometer acceptance the obtained relative production cross sections may hint to a slightly larger production probability in nuclei as compared to expectations from proton-proton collisions, $\frac{\sigma_{pA}}{\sigma_{pp}} > \frac{\sigma_{p\Lambda}}{\sigma_{pp}}$. A possible measurement with a low magnetic field will allow full reconstruction of the dieelectrons and thereby offer the possibility to determine electromagnetic transition formfactors. The currently ongoing upgrade includes an electromagnetic calorimeter which will significantly enhance the $\gamma$ detection capabilities of HADES. Measurements able to separate the contribution of $p-p$ and $p-n$ reactions are planned, which should go beyond the average values extracted now from proton-nucleus collisions. This opens up the investigation of reaction channels involving photon decays of hyperons and other baryonic resonances produced in proton/pion-proton, proton/pion-nucleus and heavy-ion collisions and might even give access to measurements of electromagnetic transition form factors for these resonances.

Acknowledgements

The HADES collaboration gratefully acknowledges the support by the grants VH-NG–823, TU Darmstadt (Germany); BMBF05P15WOFCA, DFG EcList 153, MLL, TU München (Germany); BMBF05P12RGHM, JLU Giessen (Germany); CNRS/IN2P3, IPN Orsay (France); GACR13–06759S, MSMT LM2015049, Rez (Czech Republic); BMBF05P15PXFC, GSI WKAMPE1416, BU Wuppertal (Germany); NCN 2013/10/M/ST2/00042 (Poland); NSC 2016/23/P/ST2/04066 POLEONE (Poland).

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