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Hyperon production and interaction studies in proton-proton scattering with HADES

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Abstract. Hyperons and their interactions with baryonic matter may play a key role in our understanding of the core of neutron stars. Moreover, the internal structure of hyperons and their excitations are of great interest. Their structure can be probed by exploiting their couplings to radiative probes such as by measuring electromagnetic transition form factors.
HADES (High-Acceptance Di-Electron Spectrometer) at GSI collected high-statistics proton-proton scattering data in 2022 at $\sqrt{s}$ = 3.48 GeV. The Λ - Λ interaction is currently being studied in this data along with production of Σ states where the Dalitz decay of hyperons might be observed for the first time. In addition, the reaction $pp \rightarrow pK^+K^+\Xi^-[\pi^-\Lambda[p\pi^-]]$ has been studied to probe the production mechanism of double strangeness near its production threshold. This proceeding addresses the hyperon physics case and discusses the ongoing Ξ^- analysis. A preliminary upper limit for the cross section at $\sqrt{s}$ = 3.48 GeV is presented taking into account only statistical uncertainties.

1 Introduction

Neutron stars are among the most compact objects we know of in the universe with masses up to two solar masses confined to a sphere of a radius typically less than 15 km. The high-dense interior of neutron stars intimately relates to our understanding of the Equation Of State (EOS), *i.e.* the density-pressure relation.

Hyperons and their interactions with baryons are considered to be key to describing the dynamics of neutron stars. Hyperons are baryons, a system with three valence quarks, that contains strange (s) quarks in addition to up (u) or down quarks (d). They are expected to be created in neutron star cores because the additional strangeness degree-of-freedom lowers the Fermi pressure. This means it would be energetically favorable to have hyperons in the cores. However, if hyperons are present in neutron star cores, the EOS is expected to become softer, *i.e.*, the radius will be less affected by a change in density [1]. This results in a lower maximally allowed neutron star mass than has been observed (two solar masses). This is commonly referred to as the hyperon puzzle in neutron stars. One possibility for solving this puzzle is to introduce strongly repulsive 3-body interaction potentials which can stiffen the EOS when included in the calculations. In order to study the interaction between two or three bodies, the well established femtoscopy method can be used.

Hyperon-hyperon and hyperon-nucleon interaction potentials have been inferred at ALICE for double strange systems (*e.g.* the $\Lambda - \Lambda$ and Ξ^--proton interactions were reported

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in Refs. [2, 3]). HADES has also demonstrated its ability to perform interaction studies for hyperons by measuring the Λ-proton interaction [4].

Not only are the double strange Ξ^- interesting for interaction studies. An excess of Ξ^- yield was observed in Ar+KCl and p+Nb reactions at HADES (see Refs. [5, 6]) where roughly a yield of 10-100 times greater than expected from transport model predictions was observed. This could be explained by the presence of high lying resonances decaying into Ξ^- with significant branching fractions [7]. This still has to be confirmed using elementary reaction studies and therefore it is important to perform a partial wave analysis in order to investigate the contribution of resonant states decaying into $\Xi^- K^+ K^+$. Conceptually, the analysis will be similar to an earlier study by HADES of the channel $N^* \rightarrow \Lambda K^+$ [8, 9] where production amplitudes were determined for the resonances.

This proceeding reports on the analysis of the production of Ξ^- baryons based on proton-proton scattering data taken with a proton beam with a kinetic energy of 4.5 GeV impinging on a liquid-hydrogen target. The experiment took place in 2022. Cross section estimates for the $pp \rightarrow \Xi^- K^+ K^+ p$ reaction range between 0.35 and 3.5 μb [11]. The upper limit is obtained from an extrapolation from proton-nucleus interactions. The lower cross section estimate is obtained by extrapolating data on proton-proton reactions. One of the objectives of the analysis is to determine the production cross section of Ξ^- baryons or to provide an upper limit.

2 HADES

HADES (High Acceptance Di-Electron Spectrometer), see Figure 1, is a fixed target experiment operating at GSI since 2001 [10]. The experiment was originally motivated to investigate the QCD phase diagram by in-medium effects. Electrons and positrons are excellent probes for this since many resonances such as the ρ or ω decay into them and they are largely unaffected by the medium itself, thereby being directly sensitive to the in-medium effects of the resonances. The spectral functions then provide information about phase transitions. SIS18 provides HADES with a beam of protons or heavy ions *e.g.* Ag, Au or Pb that impinges on a liquid hydrogen target or heavy ion target. A unique feature of HADES is its ability to take data with a pion beam in combination with its excellent e^+/e^- detection. Hyperon physics is also a very important topic at HADES as the yields can indicate phase transitions of QCD matter. Production in pp-reactions is very important for understanding the elementary contributions to the production and analyzing them is a big part of the proton beam program [11]. The program includes the production of double strange systems such as Ξ^- and $\Lambda\Lambda$ that have previously been poorly studied at these low excess energies. The measurement of $\Lambda\Lambda$ would enable femtoscopy to measure the interaction. The electromagnetic decay of hyperons provides access to time-like electromagnetic transition form factors, which in turn give information about the structure of baryons. Here, observing the Dalitz decay $\Sigma^0 \rightarrow \Lambda e^+ e^-$ for the first time would be an important milestone. In addition, investigating the structure of $\Lambda(1405)$ via line shape measurements and $\Lambda(1520)$ is important for understanding the internal structure of these hyperons.

For the 2022 beam time, HADES (from here on referred to as the main HADES) was upgraded with a forward detector covering small polar angles ($\theta < 7°$) [11]. The forward detector consists of straw tracking stations for track reconstruction and an RPC detector for time-of-flight measurements. For the analysis presented here, it is assumed that all tracks registered by this detector are from protons originating from the decay of hyperons since hyperons scatter predominantly to small scattering angles and protons are significantly heavier than their partner pions.

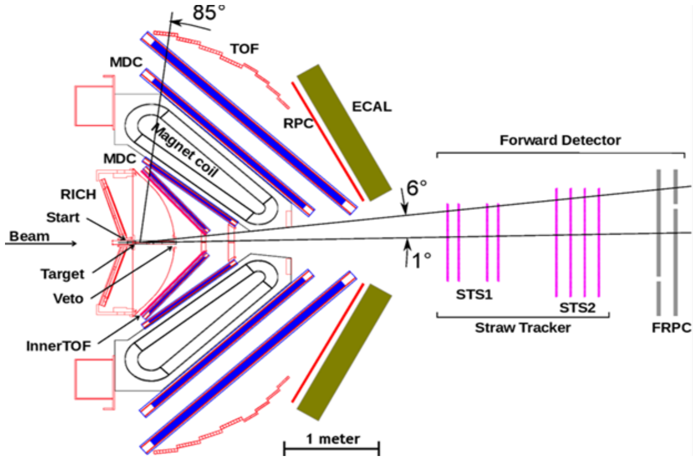

Figure 1. Schematic view of the HADES spectrometer. The main spectrometer includes a toroid magnetic field and covers large scattering angles from 15° to 85°. The forward detector covers scattering angles of less than 7° and does not include a magnetic field. Figure adapted from Ref. [11].

3 Ξ^- Analysis

The channel analyzed is $pp \to \Xi^- + X$ where the Ξ^- decays into a $\Lambda\pi^-$ with a branching fraction of close to 100% and the Λ further decays into $p\pi^-$ with a branching fraction of 64%.

3.1 Selection Criteria

Protons and pions are selected from β vs. momentum relations since the particle species have different values of β for a given momentum. Positive and negative particles are distinguished by the bending direction in the magnetic field. At least two negatively charged pions and one proton are selected for the analysis. The 4-momentum vectors are reconstructed from each selected proton and pion track candidate and combined to form the 4-momenta of the Λ candidate. Events are selected with $\pi^- p$ invariant masses in the vicinity of the Λ mass and accounting for the detector resolution. The data set from the main HADES and the forward detector are treated individually because of the differences in resolution. Either, the proton track candidate can be detected in the main HADES or in the forward detector whereas only pion track candidates registered in the main HADES detector are selected. The 4- momenta of all Λ candidates remaining after the selection are combined with that of an additional pion candidate to form an inclusive Ξ^- candidate. A threshold on the missing mass, MM(pπ^-), for the Λ candidate is applied corresponding to the sum of the masses of the additional particles and a safety margin of 60 MeV/c. In addition, the momenta of pions and reconstructed Λ candidates are constrained by two momentum cuts applied to the main HADES dataset 40 MeV/c < P_{π^-} < 400 MeV/c, 1000 MeV/c < P_Λ < 2250 MeV/c. These cuts are motivated by the outcome of Monte Carlo studies using the signal process as input.

Simulations of the reaction of interest and analysis of 1/15 of the full experimental data set were performed. The simulation is based on a phase space distribution. The efficiency times acceptance to reconstruct this channel was determined from Monte Carlo simulations based upon a phase space distribution of the signal. The results show that the proton from the Λ decay is detected in the main HADES (resp. Forward detector) in 2.4% (resp. 15.2%)

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of the signal events. All inclusive Ξ^- are reconstructed with final state particles only in the main HADES in 0.13% of the events and with particles in the main HADES or the forward detector in 1.5% of the signal events.

For the data set currently analyzed, no statistically significant peak in the vicinity of the Ξ^- mass is yet observed. To estimate the upper limit on the production cross section, the Monte Carlo sample is used to model the expected signal line shape and corresponding signal yield, S. The background yield is taken from the experimental data itself and indicated by B. Figure 2 shows the mass peaks obtained for the various cuts in simulations (left) and experimental data (right). The simulated Monte Carlo sample is then scaled to match the expected number of counts for a given value of the cross section, 1 μb in Figure 2. The histograms with S and B are integrated within a mass window between 1280-1350 MeV/c^2 (as indicated in Figure 2) taking into account the cross section estimate, branching fraction, luminosity acceptance and reconstruction efficiency. It is important to note that no systematic uncertainties are taken into account. The efficiency is estimated from simulations as the fraction of events where at least the pion and proton from Λ decays as well as the pion from Ξ^- decays are measured. The significance,

$$\text{Significance} = \frac{S}{\sqrt{S+B}},$$

is calculated for different cross sections in order to estimate its upper limit.

3.2 Results

The significance as a function of cross section when the proton is detected in the main HADES can be seen in Figure 3. The significance is shown for the case of only the Λ mass peak cut and missing mass cuts for the forward detector dataset (red line) and main HADES dataset (black line).

An upper limit with 5 σ significance is obtained for the forward detector data of 0.5 μb and the main HADES data of 1 μb.

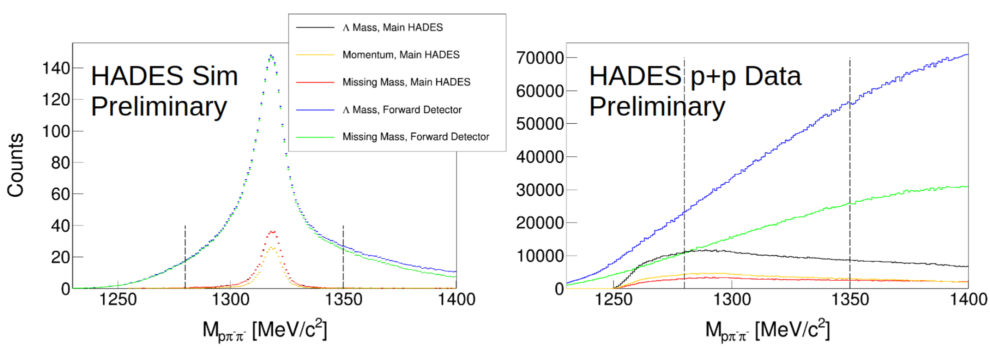

Figure 2. Simulated Monte Carlo data for the $pp \to \Xi^- K^+ K^+ p$ reaction (left) with vertical lines indicating the limits for the mass range, and experimental data (right). The simulated Monte Carlo data is scaled according to the experimental data, in this example it corresponds to a cross section of 1 μb.

4 Discussion and Outlook

We presented preliminary results on the production of Ξ^- hyperons obtained from proton-proton scattering data taken with HADES in 2022. The results from 1/15 of the data sample

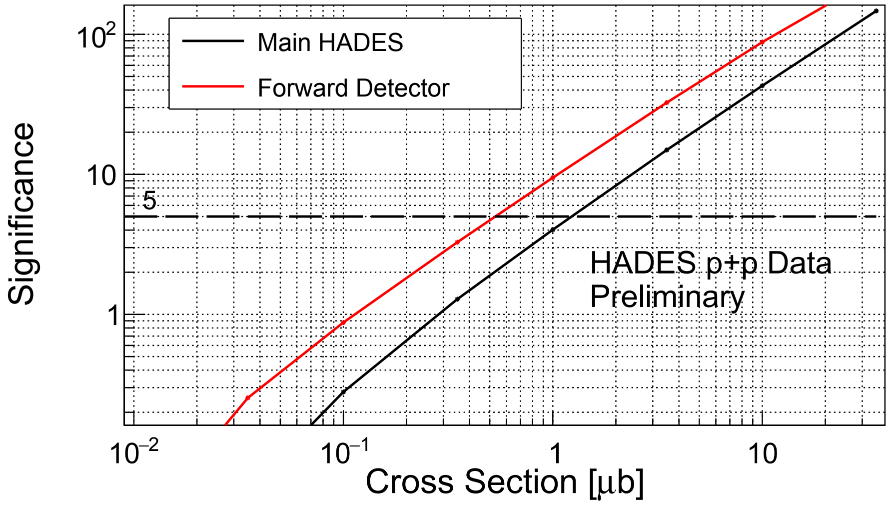

Figure 3. Significance vs cross section, proton measured the forward detector (red curve) or in the main HADES (black curve).

show that we are sensitive to cross sections > 0.5 μb for the main HADES data set for this time period.

The significance estimate can be improved by using a realistic angular distribution in the simulation which affects the acceptance. In addition, systematic effects need to be included. The mass range for calculating the significance will be optimized for the full beam time. There are also further developments currently ongoing for the Ξ^- selection. The PID procedure is being further developed in order to make use of the relative time-of-flight of the particles. In addition, the reconstruction of $\Sigma^*(1385)$ decays will be exploited as a control channel since it has the same final state as the channel of interest. The detection of additional K^+ from the primary reaction is also expected to improve the analysis by reducing background and there are ongoing efforts to identify them.

References

[1] *D. Lonardoni et al.*, Phys. Rev. Lett. **14**, 092301 (2015).
[2] *The ALICE Collaboration*, Phys. Lett. B **797**, 134822 (2019).
[3] *The ALICE Collaboration*, Phys. Rev. Lett. **123**, 112002 (2019).
[4] *The HADES Collaboration*, Phys. Rev. C **94**, 025201 (2016).
[5] *The HADES Collaboration*, Phys. Rev. Lett. **103**, 132301 (2009).
[6] *The HADES Collaboration*, Phys. Rev. Lett. **114**, 212301 (2015).
[7] *J. Steinheimer and M. Bleicher*, J. Phys. G: Nucl. Part. Phys. **43**, 015104 (2016).
[8] *R. Münzer et al.*, Phys. Lett. B **785**, 574-580 (2018).
[9] *The HADES Collaboration*, Eur. Phys. J. A **60**, 18 (2024).
[10] *The HADES Collaboration*, Eur. Phys. J. A **41**, 243–277 (2009).
[11] *The HADES and PANDA @ HADES Collaborations*, Eur. Phys. J. A **57**, 138 (2021).