Studies of hyperon production in HADES at FAIR-Phase0 — the case of an inclusive $\Sigma(1385)^+$ measurement in $pp$ reaction

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Abstract. In this proceedings first results of an inclusive measurement of the $\Sigma(1385)^+$ resonance produced in the proton-proton reaction at the beam kinetic energy of 3.5 GeV are presented. Mass of the $\Sigma(1385)^+$ resonance extracted from a fit with the Breit-Wigner function is found to be $M_0 = 1380.02$ MeV with a fixed width of $\Gamma = 40$ MeV resulting from the previous exclusive measurements done by HADES. The presented analysis is a first trial to obtain the inclusive cross section for the production of the first-excited state of the $\Sigma$ hyperon in elementary collisions at SIS energy range. The inclusive cross section is important for studies of the hyperon electromagnetic decays, which are one of the main fields of interest of the HADES experimental program during the FAIR-Phase0.

1. Introduction

Studies of the strangeness production and interactions are one of the hot topics in the low energy nuclear physics nowadays. The mass spectra of excited strange baryons are only poorly measured, although the theoretical models of hyperon structure have been already introduced in the mid 80s [1]. Although, the masses of the lightest hyperon resonances are known, even with a double pole structure of the famous $\Lambda(1405)$ still not fully understood, there is very scarce data for the hyperon radiative decays, like $\Sigma(1385)$, $\Lambda(1405)$ and $\Lambda(1520)$ via so called Dalitz decays of the type $Y \rightarrow \Lambda(1115)e^+e^-$. The measurement of the electromagnetic transition form-factors accessible in such decays can serve as a good probe of the inner structure of hyperons. Generally, the electromagnetic form-factor, as a function of the squared momentum of the exchanged virtual photon $q^2$, carries information about the baryonic structure, which can be probed in different kind of experiments, depending on the value of the $q^2$: electroproduction in the space-like region with $q^2 < 0$, Dalitz decays for small values of positive $q^2$ and annihilation experiments in the time-like region for higher $q^2 > 0$.

One of the main interests of the studies proposed by the HADES group within the FAIR Phase-0 in the strangeness sector, focuses on the electromagnetic Dalitz decays of the excited hyperons. To estimate count rates for the hyperon Dalitz decays, inclusive cross sections are needed. The cross sections can be extracted based on measurements of the hyperon production in hadronic channels. The presented analysis concerns the inclusive $\Sigma(1385)^+$ production and
Table 1: List of the most significant background sources.

| No. | final state                        | cross-section [µb] |
|-----|-----------------------------------|--------------------|
| 0   | $\Sigma(1385)^+X \rightarrow p\pi^-\pi^+$ | ?          |
| 1   | $pp\pi^+\pi^-$                    | 2950               |
| 2   | $pn\pi^+\pi^+\pi^-$               | 1600               |
| 3   | $pp\pi^+\pi^0\pi^-$               | 1100               |

its immediate hadronic decay: $\Sigma(1385)^+ \rightarrow \Lambda\pi^+$ measured by HADES in the proton-proton collision at the beam kinetic energy of $E = 3.5$ GeV [2].

2. The HADES experiment

The HADES detector (High Acceptance DiElectron Spectrometer) is a magnetic spectrometer, which allows one to measure charged hadrons (like protons, pions, kaons) and leptons (electrons, positrons) in a wide angular range and can serve as a tool for the hyperon studies. The experimental setup is being currently upgraded by adding new detectors: an Electromagnetic Calorimeter (ECAL) for the photon detection and a Forward Detector to cover the very forward scattering angles region. Access to the tracks detected at small polar angles is crucial for the measurement of the hyperon Dalitz decays and also the cascade production in the $pp \rightarrow \Xi^-pK^+K^+$ reaction at the beam kinetic energy of 4.5 GeV. At this energy quite a big fraction of protons from hyperon or cascade decays are emitted mainly in the forward direction. The measurement of the cascade production will provide an important reference for HADES results on its production in pA and AA collisions [3, 4]. The Forward Detector is developed in the cooperation between the HADES and PANDA1 collaborations to increase HADES acceptance for hyperon decays. The PANDA straw tubes technology will be firstly used in the HADES measurement during FAIR-Phase0 before their usage in the PANDA experiment.

3. Particle identification and event selection

In the presented analysis the $\Sigma(1385)^+$ signal is reconstructed from the following reaction chain:

$$p(3.5\text{ GeV}) + p \rightarrow \Sigma(1385)^+ + \Lambda[p + \pi^-]\pi^+] + X.$$  

In the final state $p$, $\pi^-$ and $\pi^+$ are expected. A detection of those three particles is considered as a candidate for a $\Sigma(1385)^+$ signal. Firstly, the particle identification based on the $dE/dx$ measurement in drift chambers is performed. Figure 1 shows the $dE/dx$ vs. momentum spectrum where the areas inside the black lines refer to the applied identification cuts for protons and pions.

3.1. Background identification

As the next step, missing mass of the $p\pi^-\pi^+$ system with respect to the beam-target has been evaluated. Figure 2 shows the corresponding distribution used for the $\Sigma(1385)^+$ reconstruction. The black solid and the red dashed lines in the Fig. 2 refer to the data and to the simulations, respectively. For the latter one following reaction channels of the $\Sigma(1385)^+$ production associated with kaon and nucleon have been simulated: $p + p \rightarrow \Sigma(1385)^+ + p + K^0$ and $p + p \rightarrow \Sigma(1385)^+ + n + K^+$. A minimum missing mass $M_{miss} = M_N + M_K \approx 1440$ MeV must

1 antiProton ANnihilation at DArmstadt
be available for the $\Sigma(1385)$ production. On the other hand in the missing mass distribution reconstructed from the data one can clearly recognise a narrow peak in the nucleon mass and a bump at higher masses. In Table 1 the most significant background reaction channels with at least one nucleon in the final state in addition to $p$, $\pi^-$ and $\pi^+$ are listed. Taking into account the exclusive cross-section for the $\Sigma(1385)^+$ production in $pp$ collisions at the beam kinetic energy of 3.5 GeV, which was found to be $\sigma = 22.27 \mu$b [2], the cross sections for the listed reactions with at least one additional nucleon are significantly higher at a similar proton beam energy. Therefore, those background reactions should be suppressed by the indicated cut on the missing mass distribution.

While the peak at nucleon mass can be explained by the first reaction from Table 1, the second bump is related to the production of three pions proceeding via $\Delta(1232)$ excitation. The decay fraction for: $\Delta(1232)^++ \rightarrow p + \pi^+$ is $BR = 99.4\%$. Since the mean mass of the $\Delta^+$ distribution is $M_\Delta \approx 1232$ MeV and the full width $\Gamma_\Delta \approx 117$ MeV [5], the second, wide structure in the Fig. 2 can be explained by the appearance of the $\Delta$ resonance.

### 3.2. Topological cuts

The $\Sigma(1385)^+$ reconstruction proceeds in two following steps: 1) reconstruction of $\Lambda$ hyperon from proton and $\pi^-$ originating from the $\Lambda$ decay: $\Lambda \rightarrow p + \pi^-$; 2) reconstruction of $\Sigma(1385)^+ \rightarrow \Lambda + \pi^+$. During the analysis a point of the closest approach of the proton and $\pi^-$ tracks (a minimal distance between $p-\pi^-$ tracks ($MTD_L$)) has been calculated to define the $\Lambda$ decay vertex. Because of the fact that the mean decay length of $\Lambda$ is $c\tau = 7.89$ cm, while $\Sigma(1385)^+$ decays immediately (approx. at the reaction point), the primary ($\Sigma(1385)^+$ decay) and the secondary ($\Lambda$ decay) vertices can be efficiently separated. The distributions obtained for the two topological variables: $MTD_L$ and a distance between the vertices ($dVert$) are presented on the Figs. 3a and 3b, respectively, where the vertical lines indicate the cuts values chosen after the following optimisation procedure. A scan over $MTD_L$ has been performed from 2 to 30 mm with a step of 2 mm. Next, for every $MTD_L$ value a scan over $dVert$ from 5 to 75 mm with a step of 5 mm has been done. For each $MTD_L$-$dVert$ pair a $p-\pi^-$ invariant mass
Figure 3: Distributions of the variables used for the optimization of the topological cuts. Black solid lines — data, red dashed lines — simulations.

Figure 4: A significance map calculated for the $p - \pi^-$ invariant mass spectra using a scan of the $MTD_L$-$dVert$ values. The bin with the highest significance is marked with a star and the topological cuts values for this point are given.

was constructed, a Voigt function for the $\Lambda$ together with the background function (polynomial of the 6th order) was fitted to the $p - \pi$ invariant mass and the significance $\alpha$ was calculated for the $\Lambda$:

$$\alpha = \frac{S}{\sqrt{S + B}},$$

where $S$ — number of signal events, $B$ — number of background events under the signal peak (see Fig. 4).

As the best topological cuts the pair of values which gives the highest significance have been chosen ($MTD_L < 14 \text{ mm}$, $dVert > 30 \text{ mm}$) and applied to the analysis. The invariant mass spectrum of the $p - \pi^-$ pairs selected with the use of the topological cuts is presented in Fig. 5.

4. $\Sigma(1385)^+$ reconstruction

The final step of the presented analysis in this contribution was the reconstruction of the $\Sigma(1385)^+$ signal from the $\Lambda$, selected as described above, and a $\pi^+$ track. The $\Lambda$ events with
Figure 5: The invariant mass distribution of the $p - \pi^-$ pairs selected after the topological cuts. The red line — a Voigt+polynomial function fitted to the distribution, black line — the signal peak after the background (blue line) subtraction.

Figure 6: The invariant mass distribution of $\Lambda - \pi^+$. The red line — a sum of a Breit-Wigner function and a polynomial of the 6th order fitted to the $\Sigma(1385)^+$ spectrum, black line — the signal distribution after the background (blue line) subtraction.

the mass in the range of 1105–1125 MeV were used. The relativistic, mass dependent Breit-Wigner function was fitted to the $\Lambda - \pi^+$ distribution, with the peak position as a free parameter and a fixed value of the width of the distribution of $\Gamma_{\Sigma^*} = 40$ MeV adopted from the exclusive $\Sigma(1385)^+$ analysis [2]. The result together with the obtained values for the resonance mass and width is presented in Fig. 6. The analysis is ongoing to clarify the origin of the shape of the final $\Sigma(1385)^+$ spectrum, to enhance the signal-to-background ratio and to extract inclusive cross section for the $\Sigma(1385)^+$ production.

5. Summary and outlook
The first results of the inclusive analysis of the $\Sigma(1385)^+$ production in $pp$ collisions have been presented. The background estimation as well as the optimisation procedure for selecting the best topological cuts for the $\Sigma(1385)^+$ reconstruction have been described. The resulting $\Sigma(1385)^+$ distribution has been well described by the Breit-Wigner function with the mean mass value of $M_{\Sigma^*} = 1380.02$ MeV and $\Gamma_{\Sigma^*} = 40$ MeV. The very next step of the analysis will be determination of the inclusive cross section for the $\Sigma(1385)^+$ production. This information is an essential input for the investigation of the electromagnetic decays of the excited hyperons, which is part of the current HADES physics program during the FAIR-Phase0.

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