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Investigation of the Σ^0 hyperon production in p(3.5GeV)+p collisions

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Abstract. The production mechanism of the Σ^0 was investigated via the exclusive reaction pp → p$K^+\Sigma^0$ at a beam energy 3.5 GeV with the HADES detector. The preliminary value of the extracted total production cross section is found to be $\sigma(pK^+\Sigma^0)[\mu b] = 17.7 \pm 1.7(stat) \pm 1.6(syst)$. The dynamics of the reaction pp → p$K^+\Sigma^0$ was investigated by studying the angular distributions in the center-of-mass, Gottfried-Jackson and helicity frames. The angular distributions in the center-of-mass frame supports the pion exchange mechanism. Furthermore, the helicity angular distributions are highly non-isotropic, which is a clear indication of resonant production component.

1 Introduction

Hyperons are of particular interest to the field of hadron physics. A good understanding of hyperon production in proton-proton (p+p) or proton-nucleus (p+A) reactions provides a way to study the strong interaction at the non-perturbative energy regime. Furthermore, it serves as a tool to understand hot and dense nuclear matter in heavy ion collisions, since strangeness enhancement is one of the key signatures proposed for the formation of the quark-gluon plasma [5, 8].

Although there are numerous experimental results and countless dedicated theoretical studies, hyperon production near threshold is not yet well understood. Within the framework of the one-boson exchange models [1], the initial p+p system exchanges a virtual meson, which results in the production of the final state particles. This process can proceed directly or via an intermediate resonance. Hyperon production can be put into one of two categories depending on the mediator properties. The first category, a pion exchange, represents a scenario where the initial p+p system exchange a non-strange meson. In the second category, a kaon exchange mechanism, the p+p system exchange a strange meson [7]. This formalism simplify the exclusive reaction pp → p$K^+\Sigma^0$ to pion or kaon induced reactions πp →K^+ Σ^0 or K^+ p →K^+ p, respectively. Since no resonances in the K^+ p system are known, the pion exchange mechanism is more likely to involve resonances, such that the hyperon is produced via an intermediate resonance πp →N^*/Δ^* →K^+ Σ^0 [2].

2 Experimental details

The High Acceptance Di-Electron Spectrometer (HADES) located at the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt is a fixed target experiment designed to

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measure low-mass di-electrons originating from the decay of vector mesons. However, it has excellent hadron detection capabilities as well, which allows various measurements including hyperon physics. HADES acceptance covers almost the full azimuthal range and polar angles from ϑ= 18° to ϑ= 85°. The detector setup consists of a hadron-blind Ring Imaging CHerenkov (RICH), two sets of Mult-Wire Drift (MDC) chambers and Time-Of-Flight (TOF) system. Effective particle identification (PID) across a wide momentum range is possible by combining the information from the sub-detectors. In addition, a Forward Wall (FW) is placed 7 meters downstream of the target, which consists of a scintillating hodoscope that covers the very forward polar angles ϑ= 0.33° to ϑ= 7°. More details on the experimental setup can be found in [3].

The Σ^0 decays electromagnetically to the less massive Λ hyperon with BR($\Sigma^0 \rightarrow \Lambda\gamma$) ~ 100%. The Λ decays weakly and reconstructed with the decay mode $\Lambda \rightarrow p_{decay}\ \pi^-$ (BR = 63.9%). Therefore, the final state contains 2 protons, 1 pion, 1 kaon and 1 photon. The Σ^0 is reconstructed via the missing mass technique since the photon is not detected directly [9]. Deep learning techniques was applied to perform the PID as explained in [9].

The strategy to select the Σ^0 signal is two fold, where two exclusive data-sets have been identified. The first, referred to as the *spectrometer data-set*, where exactly 2 p, 1 π^- and 1 K^+ are required to be within the main HADES acceptance. Since the Λ decays via the weak interaction, it travels some distance before it decays ($c\tau$ = 7.89 cm). Therefore, it was possible to apply a set of topological cuts to enhance the signal [9]. Furthermore, the signal was further purified by exploiting the kinematics of reaction pp $\rightarrow$ $pK^+\Sigma^0$. In this context, the squared missing mass of the proton and the Λ hyperon ($MM^2(p\ p_{decay}\ \pi^-)$) are required to be > 0.2 GeV^2/c^4. This cut was introduced primarily to reject the multi-pion production $p\ p \rightarrow p\ p\ \pi^-\ \pi^+$.

The second data-set, referred to as the *wall data-set*, where exactly 1 p, 1 π^- and 1 K^+ are required to be within the main HADES acceptance. In addition to a hit registered in the FW, which is assumed to be due to the Λ decay proton. Because there is no track information since only one hit is registered, the background in this case was reduced based only the reaction kinematics. Once again, events in the range $MM^2(p\ p_{decay}\ \pi^-) > 0.2$ GeV^2/c^4 were selected (here p_{decay} is registered in the FW). In addition, the missing mass squared of all charged particles is required to be in the range $-0.02 < MM^2(p\ K^+\ p_{decay}\ \pi^-) < 0.01$ GeV^2/c^4 since there is a photon in the final state.

To suppress the remaining background and obtain a better mass resolution, a kinematic refit has been applied. The track parameters (1/p, ϑ, φ) of final state particles were fit under two kinematical constraints [9]. The first constraint: the daughter proton and the pion were constrained to the nominal Λ mass. In addition, all final state charged particles were constrained to the photon mass. In total 2613 candidate Σ^0 events were collected within the pK^+ missing mass range of 1.170-1.220 GeV/c^2.

3 Results

The dynamics of the reaction pp $\rightarrow$ $pK^+\Sigma^0$ were investigated by analyzing the angular distributions in the Center of mass (CMS), Gottfreid-Jackson (G-J) and helicity frames. The distributions were corrected for the detector acceptance and efficiency using the inverse of the detector response matrix calculated by the singular value decomposition method and then fit with Legendre polynomials $d\sigma/d\Omega = \sum_\ell A_\ell \cdot P_\ell$, where ℓ = 0,1,2 represent the contributing partial waves [9]. In this way the total cross section is $\sigma = 2A_0$ and the coefficients A_1 and A_2 are used to judge the asymmetries and anisotropies of the experimental distributions.

The angular distributions of the three final state particles in the CMS are shown in the top row of figure 1 alongside with the Legendre fit coefficients. Because p+p is a symmetric system, the CMS angular distributions must be symmetric with respect to $\cos\theta = 0$. The angular distributions of the hyperon 1(a) and the proton 1(b) show anisotropies, which is more pronounced in the case of the proton as quantified by the A_2 parameter. This is in contrast of to the case of the kaon 1(c), where the distribution is almost isotropic. These anisotropies indicate that there is a non-zero relative angular momentum in both the $(p - K^+\Sigma^0)$ and $(\Sigma^0 - pK^+)$ systems. In the case of a pure pion exchange mechanism, the proton is the leading particle, the small mass of the exchange pion results in a small 4-momentum transfer such that the produced proton is preferably emitted in the direction of the initial protons, which could explain the anisotropy in the proton CMS distribution.

The Gottfried-Jackson (G-J) frame [6] is defined as the rest frame of two out of the three produced particles. In the G-J frame, the G-J angle is defined as the angle between one of the rest frame particles (e.g. the kaon) and the initial proton $\theta^{\mathrm{RF}\,K^+\Sigma^0}_{p_{p,t},\Sigma^0}$, the superscript indicates which rest frame (RF) is used and the subscript stands for the two particles, between which the angle is measured. Because the initial protons are indistinguishable, it is not known which of those protons contributes to the reaction. Therefore, the angle is calculated with respect to both protons ($p_{p,t}$ stands for the beam and target protons). The G-J angular distributions provide information about resonant production, since the internal angular momentum of the resonance is reflected in these observables.

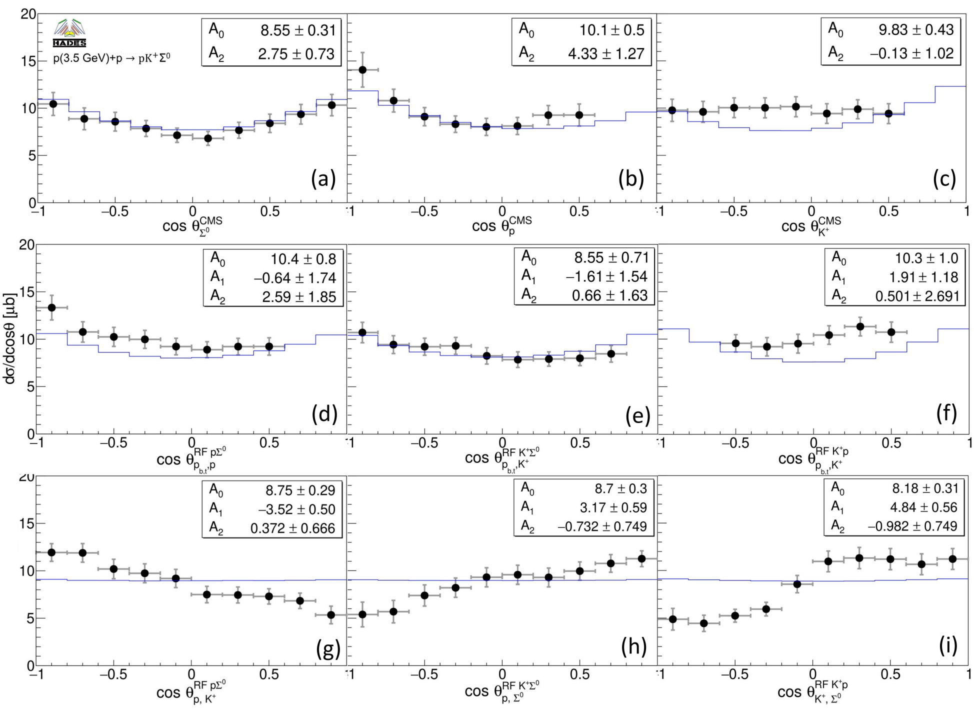

Figure 1: The angular distributions in the CMS frame (top row), G-J frames (middle row) helicity frames (bottom row). The experimental data are shown by the black points, where the error bars are the square root of the quadratic sum of the statistical and systematic uncertainties. The insets lists the Legendre fit parameters and the blue histogram represent the $pp \to pK^+\Sigma^0$ phase space simulation [1].

A pronounced anisotropy is observed in the $p\Sigma^0$ G-J frame (shown in figure 1 (d)), which could be explained as a relative angular momentum in the $p\Sigma^0$ system. This behavior is also observed in the CMS distributions of proton and the hyperon since they are related by kinematics. The angular distribution in the in $K^+\Sigma^0$ G-J frame 1(e) tends to be asymmetric, which could be caused by the excitation of nucleon resonances decaying into the $K^+\Sigma^0$ channel [7]. Because the final state proton and kaon do not originate from the same vertex, the angular distribution in the K^+p G-J frame 1(f) is expected to be isotropic if the reaction proceeds via an intermediate resonance (N^* or Δ^*). Therefore, a deviation from isotropy could be explained by a kaon exchange component.

The helicity angle is defined in the same way as the G-J angle, but instead of calculating the angle with respect to the initial proton, the angle is calculated between one of the rest frame particle and the third produced particle. In this sense, the helicity angle interrelates only the kinematics of the three output particles of the reaction. The helicity angular distribution is a special projection of the Dalitz plot, and is thus a proper observable to identify the kinematics behind the particle production. The helicity angular distributions are shown in bottom row of figure 1, all distributions are far from isotropic, which is a clear indication that the reaction proceeds in two steps via an intermediate resonance(s).

The effect of nucleon resonances on the helicity angular distributions can be tested by fitting the incoherent sum of phase space and a list of possible N^* or Δ^* resonances that might contribute at this energy to match the experimental data. The fitting was performed by means of a χ^2 minimization. A fit of phase space ($pp \rightarrow pK^+\Sigma^0$) has resulted in $\chi^2/\mathrm{ndf} \approx 4.1$, while the incoherent sum of phase space and $N^*(1710)$ ($J^P= 1/2^+$), $N^*(1880)$ ($1/2^+$), $N^*(1895)$ ($1/2^-$), $\Delta^*(1900)$ ($1/2^-$) has resulted in $\chi^2/\mathrm{ndf} \approx 1.46$.

A preliminary value of the total production cross section that corresponds to an excess energy ϵ = 556 MeV has been calculated by averaging the integrated yield of the different angular distributions and found to be $\sigma(pK^+\Sigma^0)[\mu b] = 17.7 \pm 1.7\,(\mathrm{stat}) \pm 1.6\,(\mathrm{syst})$. The systematic uncertainty is mainly due to the PID (5%), the signal selection cuts (2%) and the normalization to the p+p elastic cross section (7%), which is used as reference measurement at the same beam energy [4].

4 Conclusion

The exclusive reconstruction of the reaction $pp \rightarrow pK^+\Sigma^0$ at a beam kinetic energy of 3.5 GeV has been presented and the $pp \rightarrow pK^+\Sigma^0$ total production cross section was determined with competitive accuracy. The dynamics of the reaction was investigated by studying the angular distributions in the CMS, G-J and helicity frames. The CMS distributions of the hyperon and the proton show anisotropies, which is the expected behavior if the pion exchange mechanism dominates the particle production process in a simple one-boson exchange formalism. In addition, the anisotropy seen in the K^+p G-J frame indicates a non-negligible contribution of a kaon exchange mechanism. The helicity angular distributions are not isotropic, which shows that a pure phase space description of experimental data is not sufficient. The influence of different nucleon resonances has been tested by scaling the incoherent sum of phase space and nucleon resonances that might contribute at this energy to match the experimental distributions.

[1]The phase space simulation was weighted simultaneously by the Legendre fit parameters obtained from Σ^0 CMS and the $p\Sigma^0$ G-J experimental distributions. This weighting provides an acceptable description of the experimental distributions [9].

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References

[1] A. M. Gasparian *et al.*, Nucl. Phys. A **684** (2001)
[2] D. Ronchen *et al.*, Eur. Phys. J. A **49** (2013)
[3] G. Agakishiev *et al.* [HADES], Eur. Phys. J. A **41** (2009)
[4] G. Agakishiev *et al.* [HADES], Eur. Phys. J. A **48** (2012)
[5] J. Rafelski and B. Muller, Phys. Rev. Lett. **48** (1982)
[6] K. Gottfried and J. D. Jackson, Nuovo Cim. **33** (1964)
[7] M. Abdel-Bary *et al.* [COSY-TOF], Eur. Phys. J. A **46** (2010)
[8] P. Koch, *et al.*, Phys. Rept. **142** (1986)
[9] W. A. M. Esmail, Ruhr-Universität Bochum, "Deep learning for track finding and the reconstruction of excited hyperons in proton induced reactions" (2022)