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Strange resonances measured in Al+Al collisions at $\sqrt{s_{NN}} = 2.65$ GeV with the FOPI detector

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Abstract. The FOPI collaboration performed a high statistic experiment to study the strangeness production in Al+Al collisions at a beam kinetic energy of 1.9A GeV. The collected huge data sample allows for the first time the reconstruction of sub-threshold resonances production such as the $\Sigma(1385)$ and the $K(892)$. These measurements constrain the parameters of statistical model and provide informations on in medium cross sections for the different processes involved in the strangeness production close or below their thresholds.

1. Introduction: Heavy Ion Collisions at SIS energies

Relativistic heavy ion collisions at SIS energies provide interesting opportunities for studying hot and dense nuclear matter. It allows to address fundamental aspects of nuclear physics such as the equation-of-state for nuclear matter [1, 2, 3] and the question whether hadronic properties undergo modifications in such environment [4, 5]. This field is also of great interest for astrophysics, in particular to investigate the characteristics of the core of neutron stars [6].

The SIS energy range 1-2A GeV is best suited to study the in-medium properties of strange particles since they are produced below or close to their thresholds. The density of the nuclear system created during the reaction is expected to reach up to three times the normal nuclear matter density and its temperature is about 90 MeV [7, 8]. Theoretical works predict that chiral symmetry can be partially restored in these conditions, leading to changes in hadron properties [9, 4] which affect both their production and propagation. Indications for in-medium modifications of charged kaons have been already observed experimentally by the FOPI and KaoS collaborations [10, 11, 12].

Recent theoretical calculations predict an important coupling in the medium of the K^- with resonances $\Sigma(1385)$, $\Lambda(1405)$ and $\Lambda(1520)$ [13]. Different models agree on the important role played by the $\Sigma(1385)$ in the cross section of the strangeness exchange reactions, but predictions differ widely concerning the evolution of the cross section in the medium [13, 14, 15, 16]. Therefore, an experimental measurement of sub-threshold $\Sigma(1385)$ production cross-section can be expected to provide important information regarding the complex reactions involved in sub-threshold K^- production. Furthermore, the short life time of strange resonances such as the $\Sigma(1385)$ and the $K(892)$ (5 and 4 fm/c, respectively) allow for an unique possibility to probe the dense medium in the earlier stage of the collision.

The paper is structured as follows. Section II consists of a short description of the apparatus, the event characterization and the centrality selection. The reconstruction method of $\Sigma(1385)$ and $K(892)$ measured in Al+Al collisions at 1.9A GeV are discussed in section III. In section IV we present a comparison of the experimental results with statistical and transport models. Finally, we summarize and give an outlook in section V.

2. The FOPI detector

The experiment has been performed with the FOPI detector at the Heavy-Ion Synchrotron SIS of GSI-Darmstadt by using an Al beam of kinetic energy of 1.9A GeV on an Al target. The beam intensity was chosen to be $8 \cdot 10^5$ ions/s and the target thickness was 567 mg/cm^2.

The FOPI detector is an azimuthally symmetric apparatus made of several sub-detectors which provide charge and mass determination over nearly the full solid angle. The central part of the detector is placed in a super-conducting solenoid and consists of a Central Drift Chamber (CDC) surrounded by plastic scintillators (Barrel). The forward part is composed of a wall of plastic scintillators (PLAWA) and another drift chamber (Helitron) placed inside the super-conducting solenoid.

For the present analysis, K^0, Λ and $\Sigma(1385)$ were reconstructed from their decay products measured in the CDC ($23^\circ < \theta_{lab} < 114^\circ$). Particles measured in the CDC are identified by their mass, which is determined by the correlation between magnetic rigidity and specific energy loss. More details on the configuration and performances of the different components of the FOPI apparatus can be found in [17, 18, 19]. For the reconstruction of $K(892)$ in the channel $K^+\pi^-$, we used the matching informations of the Barrel and the CDC ($32^\circ < \theta_{lab} < 57^\circ$) providing a better identification of the K^+ (see next section).

The events are selected by their centrality which is determined with the charged particle multiplicities measured in the CDC and in the PLAWA. The results presented in the following are for the most central collisions corresponding to 20% of the total geometrical cross section.

3. Reconstruction of strange resonances

3.1. Reconstruction of the $\Sigma(1385)$

Because of the strong decay of the $\Sigma(1385)$ (call Σ^* in the following) in Λ and π (branching ratio 88%), the short life time of the resonance does not permit to reconstruct its decay vertex. Therefore, the invariant mass analysis consists of correlating primary

Λ's and pions. Note that the reconstructed Λ includes decay Λ from Σ^0 which cannot be isolated with the FOPI detector because Σ^0 decays into a Λ and a photon. The Σ^* is a triplet state of isospin, and while the Σ^{*0} cannot be reconstructed with our apparatus (decay into Λ and π^0), the charged decay products of $\Sigma^{*\pm}$ which are mesons $\pi^\pm$ allow their identifications with the CDC. The Σ^* are reconstructed from a topological analysis of their double two-body decay:

$$\begin{array}{lllll} \Sigma^{*\pm} & \rightarrow & \Lambda \; + \; \pi^\pm & & (\mathrm{BR} = 88\%, c\tau = 5 \text{ fm}) \\ & & \hookrightarrow & p \; + \; \pi^- & (\mathrm{BR} = 64\%, c\tau = 7.89 \text{ cm}). \end{array}$$

A total of about 10^5 Λ are reconstructed with a signal-to-background ratio close to 10 from the analysis of 290 million events (inset of Fig. 1). The invariant mass spectra of the $\Sigma^{*\pm}$ is shown in Fig. 1. The combinatorial background is calculated with the event mixing method [20] consisting of correlating a Λ from one event with pions from another event. In addition, the two events are aligned with respect to the reaction plane in order to have the same reference system for both particles. This latter is estimated event by event according to the standard transverse momentum procedure detailed in [21]. In order to reconstruct the Σ^* invariant mass, a mass selection at two σ around the nominal mass of the Λ is applied (shown by the dashed lines in the inset of Fig. 1).

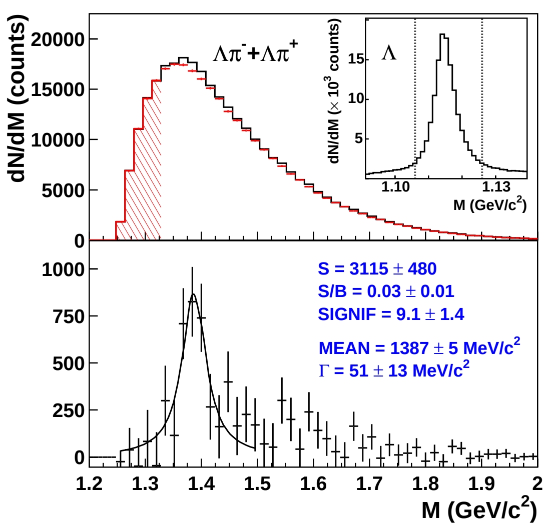

Figure 1. Invariant mass spectra of $p\pi^-$ pairs (inset, upper panel) and $\Lambda\pi^\pm$ pairs. The solid histogram and crosses denote the data and the scaled mixed-events background, respectively (upper panel). The lower panel shows the signal after background subtraction. The following characteristics of the signal are shown: number of counts in the signal (S), signal-to-background ratio (S/B) and significance (SIGNIF). The parameters extracted from the fit to the data (mean mass value (MEAN) and the width (Γ)) are also reported.

In the invariant mass range 1.35 to 2 GeV/c^2, 16 excited states of Σ's have been already observed [22]. Therefore, the normalization of the mixed background was calculated in the mass range 1.25 - 1.32 GeV/c^2 (grey zone in the upper panel of

Fig. 1) in order not to bias the reproduction of the combinatorial background. The shape of the resulting mixed-event background describes the combinatorial background and is indicated by crosses in Fig. 1 (upper panel). The vertical bars of the crosses correspond to the statistical errors. After background subtraction (Fig. 1, lower panel), the remaining peak in the mass spectra is fitted with a Breit-Wigner function. Within the width interval (Γ), about 3100 $\Sigma^{*\pm}$ are found for the applied set of cuts in the analysis. The mean mass value and width extracted from the fit are in a good agreement, within statistical errors, with the values reported by the Particle Data Group [22].

3.2. Reconstruction of the $K(892)$

The reconstruction of the $K(892)$ (call K^* in the following) follows the same procedure used for the Σ^*. The life time of this mesonic resonance is even shorter (4 fm/c) and we reconstruct the K^{*0} in the decay channel: $K^{*0} \rightarrow K^+ + \pi^-$ (66%). More details on the K^+ identification with the FOPI detector are provided in [10, 11].

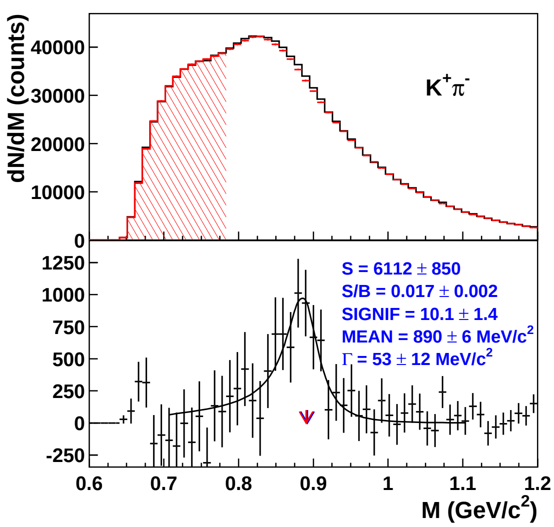

Figure 2. Invariant mass spectra of $K^+\pi^-$ pairs. The solid histogram and crosses denote the data and the scaled mixed-events background, respectively (upper panel). The lower panel shows the signal after background subtraction. See caption of Fig. 1 for the nomenclatures.

This measurement corresponds to deep sub-threshold production (800 MeV) since the threshold energy to create a K^* in elementary reaction is 2.75 GeV. The combinatorial background evaluated with the event mixing method was normalized on the left and right side of the nominal mass of the K^*. Since no differences were found on the choice of the normalized area, the Fig. 2 shows the normalization on the left side (grey zone, upper panel of Fig. 2). After background subtraction (lower panel of Fig. 2), around 6000 counts of K^* are reconstructed. As it was observed for the Σ^*, the mean mass value and width extracted from the fit are in a good agreement, within statistical errors, with the values reported by the Particle Data Group [22].

4. Model comparisons

The yield of P($\Sigma^{*\pm}/\Lambda$) and P(K^{*0}/K^0) ratios are compared to the predictions of a statistical model [23] and to a transport model [24] for Al+Al collisions at $\sqrt{s_{NN}} = 2.65$ GeV. The systematic errors on the measurements were evaluated in two steps. First the reconstruction efficiency was estimated from simulated signals with two values of the radial flow velocity ($\beta = 0$ and $\beta = 0.3$ for $T = 90$ MeV) used in the Siemens-Rasmussen formula [25, 26] which describes an expanding system with a temperature T and a radial expansion velocity β. Then the signals were reconstructed under different sets of conditions on the relevant quantities used to reconstruct and identify these particles (p_{lab}, DCA, d_t and $\Delta\phi$).

The statistical model, based on the canonical ensemble, reproduces the ratios with a temperature of 76 MeV and a baryonic chemical potential of $\mu_B = 816$ MeV. The volume was chosen to be V = 100 fm^3 and the fit quality is $\chi^2 = 1.36/2$. The same model was used to extract thermal parameters from Au+Au collisions at $\sqrt{s_{NN}} = 2.7$ GeV [23] and reproduced particle ratios with T = 64 MeV and $\mu_B = 760$ MeV. It is surprising to note that at the same energy, a lighter system (Al+Al) bring out higher temperature and baryonic chemical potential, while the volume is only 10% of the Au+Au one. Finally, a higher temperature appears better suited to describe particle ratios when including baryonic resonances. The measurement is also compared to the prediction from the UrQMD transport model [24] for Al+Al collisions [27]. The results of both comparisons, statistical and transport models with the measurements are summarized in Tab. 1.

Yield ratio	Data	Therm. Model	UrQMD
$\frac{\mathrm{P}(\Sigma^{*-}+\Sigma^{*+})}{\mathrm{P}(\Lambda+\Sigma^0)}$	0.125 ± 0.042	0.097	0.177
$\frac{\mathrm{P}(K^{*0})}{\mathrm{P}(K^0)}$	0.032 ± 0.012	0.034	0.1

Table 1. Experimental yield ratios and predictions from statistical and transport models. The errors of the measurements correspond to the quadratic sum of statistical and systematic errors.

The transport model prediction is in relatively good agreement with the measurement of the P($\Sigma^{*\pm}$)/P(Λ) yield ratio when taking into account the upper limit of the error bars. In the other hand, the model over-estimate by a factor 3 the ratio P(K^{*0})/P(K^0). The dominant process involved in the UrQMD model in order to produce Σ^* is the fusion of Λ and pions (76%) with an average cross section of about 37 mb [27]. This cross sections results from an assumption using an additive quark model. Similarly to Σ^*, the dominant process to create K^* is the fusion of kaons and pions (70%) with an average cross section of about 20 mb. The time dependence of these reactions exhibit a maximum around 7.5 fm/c which is in agreement with the predictions of an other transport model [28] on the time production of strange particles such as kaons [29].

5. Conclusion

In summary, we have presented new results about the P($\Sigma^{*\pm}$)/P(Λ) and P(K^{*0})/P(K^0) ratios in Al+Al collisions at 1.9A GeV. For the first time, the $\Sigma^{*\pm}$ and K^{*0} resonances were measured 400 and 800 MeV below their production thresholds. The experimental result was compared to the predictions of a statistical model and a transport model. The comparison with the thermal model suggests that a chemical freeze-out temperature of about 80 MeV is needed to describe the measured ratios. On the other hand, the comparison with the transport model shows that the two yield ratios could not be reproduce at the same time.

The reported measurements should be used as an input for other transport codes for testing calculations on sub-threshold strangeness production. In addition, a measurement of the system size dependence of the $\Sigma^*(K^*)$ productions, as well as other strange resonances, will give the opportunity to assess effects of a partial restoration of the chiral symmetry at high baryon density that can be reached at SIS energies.

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