Strangeness production in heavy ion collisions -
Constraining the KN - potential in medium

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Abstract. We review the strangeness production in heavy ion collisions at energies around the NN production threshold and discuss recent measurements of the FOPI collaboration on charged kaon flow over a wide impact parameter range. The data are compared to comprehensive state-of-the-art transport models. The dense nuclear matter environment produced in those collisions may provide unique opportunities to form strange few body systems. The FOPI detector is especially suited to reconstruct such states by their charged particle decays. Apart from strongly decaying states special emphasis will be put on the search for long living weakly decaying states, i.e. Hyper-Nuclei. Light hyper nuclei are reconstructed by their two body decay channels and the production of Hyper-Tritons is studied with respect to Λ and t(3He).

1. Introduction
Nuclear matter of twice to three times normal nuclear matter density $\rho_0$ at relative moderate temperatures ($\sim$100 MeV) is created in central heavy ion collisions in the energy range of the Heavy Ion Synchrotron at GSI ($E_{\text{beam}} = 0.1 - 2$ AGeV). Modifications of hadron properties, such as masses and decay widths, in such dense baryonic medium are a current subject of intensive theoretical and experimental research in hadron physics [1, 2, 3]. In particular strange mesons produced at or slightly above the production threshold in NN collisions are predicted to be influenced by such in-medium modifications. Various theoretical approaches [4, 5, 6, 7] agree qualitatively in predicting, for example, modifications of masses and coupling constants for kaons and anti-kaons. Generally the $K^+$ effective mass is expected to rise, whereas the mass of $K^-$ mesons is dropping with increasing density of nuclear matter due to an attractive $(KN)$ potential in medium Already two decades ago, Kaplan and Nelson [8] pointed out that due to additional attractive interactions with the surrounding nucleons a condensation of anti-kaons ($K^-$) may take place in a dense baryonic environment as encountered in the interior of neutron stars.

One may deduce from general arguments how the medium-modifications of the KN and $(KN)$ potentials influence particle production yields and phase space distributions, e.g. production yields are expected to drop with rising masses and vice versa. However, the depths of those potentials can only be accessed via microscopic transport codes modeling the dynamical evolution of heavy ion collisions. Nontrivial modifications of particle momenta and yields of the particles produced at the interesting period might be modified by both particle re-scattering and expansion of the fireball. Thus, these dynamical features have to be taken into account before conclusions on in-medium modifications can be drawn. A detailed understanding and modeling
of the dense baryonic phase is a prerequisite for a solid interpretation of all current data from heavy ion collisions.

At AGS energies clear evidence was found that the directed $K^0$ flow is opposite in sign to the flow of protons [9]. This experimental observation was explained by microscopic model calculation incorporating a repulsive KN potential [10]. Experimental data for charged kaons at those energies are available but lacking a consistent description [11]. At lower energies the sensitivity to the KN(KN) potential should be enhanced and several investigations by the KAOS, FOPI and lately HADES collaborations have been started at the SIS-18 accelerator at GSI.

In the following new data obtained with the FOPI detector at the SIS18 accelerator of GSI are shown for the reaction Ni+Ni at an incident energy of 1.91 AGeV elucidating some key aspects of strangeness physics in the threshold energy range.

2. Experiment: FOPI - Phase III
FOPI is a large acceptance detector system designed to measure charged particles emitted from heavy-ion collisions and installed at the SIS-18 accelerator at the GSI, Darmstadt (Germany). The modular structure allows to cover nearly the full solid angle in the laboratory frame. The core part of FOPI is a supra conducting solenoid with two drift chambers. The Central Drift Chamber CDC covering $30^\circ < \Theta_{lab} < 140^\circ$ and the forward drift chamber Helitron $7^\circ < \Theta_{lab} < 30^\circ$. Both drift chambers are augmented by time–of–flight–detectors for charge identification.

Apart from charged particles FOPI can measure neutral strange particles by their charged decay product ($K^0 \rightarrow \pi^+ + \pi^-$, branching ration BR = 69 %, $\Lambda \rightarrow \pi^- + p$, BR =64 %, $\Phi \rightarrow K^+ + K^-$, BR = 49.1 %) as well as short lived strange resonances $\Sigma^{*-}$ and $K^{*0}$.

In order to improve the detection of charged kaons the FOPI detector was upgraded with a new time-of-flight barrel based on Multigap–Resistive–Plate–Chambers (MRPC) [19] covering the polar angle range $30.5^\circ < \Theta < 52^\circ$. In the polar angle range $53^\circ < \Theta < 120^\circ$ a plastic scintillator barrel is used as a time–of–flight detector. The phase region in which charged kaons are thus identified in the FOPI Phase III setup is depicted in Fig. 1. This detector was used in several major data taking runs. The performance in identifying the emitted particles is depicted
for the reaction Ni+Ni at an incident energy of 1.91 AGeV in Fig. 2, a mass spectrum is shown determined from the momentum reconstructed in the Central Drift Chamber (CDC) and the velocity measured in the MRPC barrel. The overall time resolution is 90 ps, in which the MRPC resolution is $\sigma_{tof,MRPC} = 65$ ps. This time resolution and the granularity of the detector are sufficient to separate positively (negatively) charged kaons with a signal-to-background ratio in excess of 10 when the maximum momentum is limited to 1.0 (0.8) GeV/c, respectively.

3. Characteristics of heavy ion collisions at SIS energies

Apart from charged strange mesons neutral strange particles, $K^0_s$ and $\Lambda_s$, can be reconstructed by their charged decay products. For those particles which are produced abundantly close to complete phase space distributions can be obtained by fitting experimental transverse mass spectra with a thermal Boltzmann distribution as a function of rapidity.

$\Phi$ mesons are reconstructed via their dominant decay channel $\Phi \rightarrow K^+ + K^-$ and yields can be extracted [20]. The strange resonances $\Sigma^{*\pm}(1385)$ and $K^{0*}(892)$ ($\Sigma^*$ and $K^*$ further on) also decay into charged particles which are accessible to FOPI: $\Sigma^* \rightarrow \Lambda + \pi^\pm$ and $K^* \rightarrow K^\pm + \pi^-$. The short lifetimes of those resonances ($c\tau = 5$ fm/c and 4 fm/c) leaves their decay vertices to close to the event vertex to be separated. Hence, their decay products cannot be distinguished from the other charged particles by a vertex cut. Despite the resulting huge background about 3100 $\pm$ 500 and 6100 $\pm$ 850 resonances were found with a significance of 9 and 10 [22]. The efficiency corrections necessary to extract the particle yields are described e.g. in [22] or [21]. In total, 6 independent ratios of particle yields were constructed for central collisions of Al+Al at 1.91 AGeV beam energy. These ratios were compared to the statistical model predictions performed with the THERMUS code [23], as shown in Fig. 3. The calculations were done in the frame of a Grand Canonical ensemble for non-strange particles. Due to a necessity to constrain the strangeness number $S$ at low beam energies, a Canonical ensemble was used for particles characterized by $S \neq 0$ [24]. In general, a good fit–quality of the statistical model parameters Temperature $T$ and baryo–chemical potential $\mu_B$ was obtained, expressed by $\chi^2/\nu = 0.3$ for Al+Al. The best fits were found for $T$ of about 74 MeV and $\mu_B$ of about 780 MeV respectively. These values match the systematics of $T$ and $\mu_B$ extracted at other beam energies and systems [25]. In case of Al+Al it was possible to fit in addition the strangeness under-saturation factor $\gamma_S$, being non-equal to unity in case of non-equilibration of the yield of particles containing
strange quarks [26]. However, it was found to be consistent with unity within the experimental errors. These results demonstrate that the statistical model with two (three) free fit parameters of $T$, $\mu_B$ (and $\gamma_S$) is capable of reproducing the experimental yield ratios at 1.9 AGeV, despite the observation that the underlying assumption of a complete equilibration is not supported by the experimental rapidity profiles of nuclear bulk matter [27].

It is interesting to note that the measured particle ratios in central Al+Al collisions are reasonably well described by the microscopic transport code UrQMD [30]. UrQMD results were found to be in agreement not only with experimental data, but also with the predictions of the statistical model except for the $\Phi/K^*$ yield ratio. It is known, however, that the production yield of $\Phi$ mesons in UrQMD too low in this energy range [31]. Apart from the $\Phi$ meson the quality of description is equally good for both models. To draw further conclusions one needs more systematic studies on heavier collision systems and different energies.

4. Kaon flow

The excellent kaon identification capabilities of the new time-of-flight barrel based on Multi-gap–Resistive–Plate–Chambers (MRPC) surrounding the central drift chamber in allow to continue the FOPI efforts [34] to determine the in-medium potential for kaons and anti-kaons by the measurement of kaon and anti-kaon flow in heavy ion collisions.

The direction of the reaction plane is determined by the transverse momentum method [32] making use of particles detected in the forward wall of FOPI only in order to avoid autocorrelations. The data are corrected for the finite reaction plane resolution employing the Ollitrault formalism [33]. The azimuthal emission pattern is expressed by a Fourier series

$$dN/d\phi \left( 1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + \ldots \right),$$

where $\phi$ is the azimuthal angle of the outgoing particle with respect to the reaction plane. The first order Fourier coefficient $v_1$ describes the collective sideward deflection and the second order coefficient $v_2$ the emission pattern perpendicular to and into the reaction plane.

Model calculations have to take into account the acceptance of the detector when compared to the data, those are limited for this detailed analysis to the acceptance of the central drift chamber CDC covering a polar angle range of $26^\circ < \Theta_{lab} < 120^\circ$. For kaons additional constraints have to be put on the momenta necessary to obtain sufficient particle identification in the data. In the polar angular range from $30.5^\circ < \Theta_{lab} < 52^\circ$ (MRPC acceptance) kaons are included up to a momentum of 1.0 GeV/c, in the range $53^\circ < \Theta_{lab} < 120^\circ$ (plastic barrel acceptance) the laboratory momentum is limited to 0.5 GeV/c.

Former experimental directed flow data for positive kaons and protons in central collisions [34] are reproduced by the new measurements. This is shown in Fig. 4. The experimental data of $v_1$ show a strong dependence on $p_t$. The Fourier coefficient $v_1$ is positive at low transverse momenta $p_t$ and is getting negative at high momenta. Two opposing effects influence the value of $v_1$, namely, the repulsive KN potential accelerates the K$^+$ to the side opposite to that of the projectile/target spectator and $v_1$ changes sign with respect to the directed flow signal of the protons 4, whereas re-scattering of the K$^+$ off the nucleons tends to align the K$^+$ to the flow of the nucleons [3]. Therefore, a positive $v_1$ of K$^+$ at low transverse momenta may be a signal for a strong repulsion effect. As can be seen in Fig. 4 the new experimental data agrees with the old one.

The BUU transport code [2] is only able to reproduce these observations when a repulsive KN potential is considered. A potential of $U_{pot,KN}(\rho_0) = 20$ MeV at normal nuclear matter density is describing the data. The density dependence of the potential is assumed to be linear as predicted by various theoretical models e.g. [40]. This finding is consistent with a result from pion induced reactions measured by the FOPI collaboration [35]. In addition, the BUU
Figure 4. Directed flow $v_1$ of kaons as function of transverse momentum $p_t$ in comparison to the flow of protons for central (green triangles and black dots) Ni+Ni collisions at 1.91 AGeV. Data from the new MRPC barrel (magenta points) are compared to older results (red points) [34]. Red lines are predictions of the HSD transport code (solid) with or without (dashed) KN potential. The bright blue line is an HSD prediction for the flow of protons.

model describes the proton flow data measured in the same acceptance range reasonably well. Generally, measured Kaon directed flow data can only be reproduced by models when a repulsive Kaon potential is applied (see e.g. [36])

This picture changes when another centrality bin is selected [41]. In Fig. 5 directed flow $v_1$ as a function of transverse momentum $p_t$ is presented for two different centrality regions. The dependence of $v_1$ on transverse momentum $p_t$ is getting slightly stronger with increasing impact parameter. This finding can be explained with the larger spectator remnant which is repelling the Kaons and was reported already for the Ru+Ru system [34] confirming the previous results.

The experimental data are compared to two different models: a Quantum Molecular Dynamics code IQMD [37] and HSD [2], which employs an BUU-type approach. One other difference between the both models is the depth of the K and $\bar{K}$, in contrast to HSD a value of $U_{pot,KN} = 40$ MeV at normal nuclear matter densities is applied in IQMD. The functional dependence of the K meson mass on the nuclear density is linear in both models. Further details of these models and extensive comparisons to existing experimental data are presented in [3]. Generally, both models describe experimental yields and spectra of Kaons produced in heavy ion collisions employing a KN potential $U_{pot,KN}(\rho_0) = 40$ MeV reasonably well. In addition, results of the IQMD model have been compared systematically to experimental data in the SIS energy range and the overall agreement — in particular for the flow observables — is satisfactory [38, 27, 39].

HSD is reproducing the experimental data for central collisions when a repulsive Kaon nucleon interaction is applied, whereas — contrasting the experimental findings — the IQMD results predict a rather small dependence of $v_1$ on the transverse momentum $p_t$ and but do not satisfactory describe the experimental data. Employing a repulsive potential within the IQMD model leads to a overall shift of $v_1$ but does not enhance the momentum dependence as in the HSD approach. One explanation might be that the treatment of Kaon nucleon re-scattering in IQMD is different with respect to HSD. Consequently, the influence of re-scattering on flow and
Figure 5. Directed flow $v_1$ of kaons as function of transverse momentum $p_t$ for two different centralities at a given normalized rapidity bin ($-1.3 < Y^{(0)} < -0.5$ where $Y^{(0)} = y_{lab}/y_{cm,proj} - 1$). In the left panel results for central events are presented and for peripheral events on the right. Data are from the new MRPC barrel (black dots). Different model predictions are shown as lines. HSD results are shown in red, and predictions by the IQMD transport model are shown in blue. Full lines denote predictions with in-medium modifications of kaon masses and dashed lines without.

other observables is subject of further investigations.

At less central collisions (right panel of Fig. 5) the repulsive Kaon nucleon interaction leads to slight enhancement of the momentum dependence of $v_1$ in the IQMD model, but it is still not strong enough to account for the experimental data. The HSD model including a repulsive Kaon nucleon potential predicts a stronger transverse momentum dependence when going from central to peripheral collisions but this change is too large to fit to the experimental data which are best described by none or possibly a very shallow Kaon nucleon potential. Apart from the transverse momentum dependence the value of the directed flow for peripheral events in this rapidity region are over-predicted by both models. One may speculate that the models fail to describe the shape and dynamics of the target/projectile spectator which is the source of repulsion for the Kaons, however, flow observables measured in this energy range are described satisfactory [39], as an example proton directed flow can be seen in Fig. 4.

In Fig. 6 experimental data on Kaon and Anti-Kaon integrated directed $v_1$ and elliptic flow $v_2$ as a function of normalized rapidity for a large impact parameter range is presented together with IQMD and HSD predictions. As discussed above both models do neither account for the rather moderate transverse momentum dependence of the measured $v_1$ nor for the overall size of the directed flow when using a KN potential. When integrating over the transverse momentum the measured directed flow of Kaons is consistently described by both models but without using a KN potential, this puzzling finding needs definitely further experimental and theoretical investigation. The measured elliptic flow $v_2(y)$ is described by both models, but there is no obvious sensitivity to the depth of the Kaon nucleon potential at these energies. Elliptic flow of Kaons, similar to the directed flow, is influenced by the in-medium Kaon nucleon potential and re-scattering processes. The two effects and their influence on the elliptic flow signal have
Figure 6. Directed $v_1$ and elliptic $v_2$ flow of charged kaons as function of normalized rapidity $Y^{(0)} = y/y_{cm} - 1$ for NiNi collisions at 1.9 AGeV. The left/right panels show $v_1$ (upper) and $v_2$ (lower) of positive/negative kaons. Black dots represent the measured data points. Lines are results of model predictions. Dotted lines are predictions from model calculations assuming no modification of the (Anti)Kaon-nucleon interaction in medium, full lines are model predictions with in medium modifications.

been studied within the IQMD model [3]. It was found that they both tend to enhance the squeeze-out signal and it could be shown that the influence of the Kaon nucleon potential on the elliptic flow signal is larger at lower incident energies ($E_{\text{beam}} \leq 1$ AGeV), whereas at higher energies re-scattering processes are dominant and diminish the potential effects.

On the right hand side of Fig. 6 data and model predictions for $K^-$ are shown. The directed flow of Anti-Kaons $v_1(Y^{(0)})$ is rather small when integrated over the transverse momentum and tends to zero independent of rapidity. Directed flow of $K^-$ is as well influenced by two counteracting effects: the attractive Anti-Kaon nucleon potential will accelerate the particles towards the spectator leading to a flow signal which is similar to that of the protons being negative at target rapidities, whereas the absorption effects remove $K^-$ from this hemisphere and lead to a flow opposite to the nucleonic flow. In the upper right panel of Fig. 6 model results are shown by dotted lines where only $K^-$ absorption is considered and the in-medium Anti-Kaon nucleon potential is omitted leading a strong anti-flow signal of $K^-$. The agreement between the models is satisfactory.

Both transport codes use quite different methods to model the Anti-kaon nucleon interaction in dense matter. HSD employs a G-Matrix approach described in [7] leading to a momentum dependent interaction and an attractive Anti-kaon nucleon potential $U_{\text{RN}}(\rho_0, p) \approx -50$ MeV. Within IQMD Anti-kaons are treated as quasi particles with a momentum independent potential resulting in a close to linear mass dependence on density. At normal nuclear matter densities the potential has a depth $U_{\text{RN}}(\rho_0, p) \approx -90$ MeV in accordance to predictions of [40]. More
Counts
Signal
Mixed background
Mass
inv \((p, 3^\text{He}) \text{(GeV)}\)

Counts
Mean: \(2.992 \pm 0.0009 \text{ GeV}\)
Width: \(4.6 \pm 0.9 \text{ MeV}\)
Significance: \(6.5\)

Figure 7. Left: Reconstructed invariant mass of \(3^\text{He}\pi^-\) pairs. The solid histogram and crosses denote the data (red) and the scaled mixed-events background (blue), respectively (upper panel). Both distributions were normalized over the range indicated by the horizontal arrow. Right: Phase space of identified \(3^\text{He}\). The yellow boxes denote the phase space regions A (lower) and B (upper).

details can be found in [3]. As expected, inclusion of an Anti-Kaon nucleon potential changes the directed flow pattern of \(K^-\) predicted by the models from anti-flow to flow (full lines in the right upper panel of Fig. 6). Consequently, the magnitude of the directed \(K^-\) flow predicted by the two models differ. In first order, the difference between the model predictions is reflecting the different depths of the Anti-Kaon nucleon potential at normal nuclear matter densities. The deeper potential used in IQMD yields a stronger flow signal. However, none of the models accounts for the small flow values measured in the experiment. To clarify this finding further experimental studies are necessary.

The data for the elliptic flow \(v_2(y)\) of \(K^-\) is shown for completeness, the experimental error bars are still too large to draw definite conclusions.

5. Two particle decays of Hyper-nuclei
The Hyper-triton, which is predicted to be the lightest Hyper-nucleus, decays weakly with a half life of 200-300 ps. Its two particle decay channel \(\Lambda t \rightarrow 3^\text{He} + \pi^-\) is accessible with the FOPI set-up. The combination of time-of-flight detectors and momentum-measurement in the central drift chamber of the FOPI setup allows to distinguish \(Z=1\) and \(Z=2\) particles in this phase space region. The huge combinatorial background is suppressed by stringent selection criteria on the quality and topology of reconstructed trajectories of \(\pi^-\) and \(3^\text{He}\) pairs.

The solid, red histogram in the upper panel of Fig. 7 depicts the reconstructed invariant mass of \((\pi^-, 3^\text{He})\) pairs [42], selected in 56 million semi-central collisions. The dashed, blue line in Fig. 7 corresponds to the combinatorial background, which was reconstructed by the mixed-event method and normalized to the signal spectrum in the region depicted by the horizontal line \((3.03-3.6 \text{ GeV}/c^2\) ). The red histogram the lower panel of Fig. 7 shows the distribution obtained after subtracting the normalized background from the signal spectrum. The error bars correspond to statistical fluctuations.

The lifetime of the Hyper-triton can be estimated from the radial distance of the decay vertex to the primary vertex \(r_s\) and \(\beta\gamma\) of the Hyper-triton, i.e. \(t = r_s/(\beta\gamma)\). When taking into account detection efficiencies an average life time \(\tau = 273 \pm 40\) ps is deduced, which is in accordance to
other experimental data.

The characteristics of the mesonic two particle decay of the Hyper-triton is dominated by the heavy $^3\text{He}$ nucleus. Hence, the phase space where $^3\text{He}$ are identified — shown in the right panel of Fig. 7 — is nearly equivalent to the phase space region of the reconstructed Hyper-tritons. Hyper-tritons are not distributed in phase space like other light clusters (e.g. $t$, $^3\text{He}$). Comparing Hyper-triton production in Region A and B of Fig. 7, one reconstructs much more Hyper-tritons with respect to $^3\text{He}$ at low transverse momenta than at larger ones. Thermal model calculations or coalescence cannot account for this finding because the ratio $\Lambda/d$ is larger at higher momenta and consequently the chance to combine a $\Lambda$ and a deuteron to form a Hyper-triton. One may speculate that Hyper-tritons are formed when $\Lambda$ hyperons produced in the hot fireball are scattered into the cold spectator matter. Such a scenario would lead to Hyper-triton phase space distributions which are peaked at target/projectile rapidities [43].

6. Conclusion

We presented data on strangeness production in heavy ion Ni+Ni collisions at 1.9 AGeV measured with the upgraded FOPI setup. The high statistics and high quality data allows to determine the directed flow of charged Kaons and the investigation of strongly and weakly decaying states including strangeness. Hyper-tritons have been reconstructed by their two-particle mesonic decay and their phase space population is being investigated. While checking other two body decay channels of Hyper-nuclei accessible to FOPI, only one further reliable structure is found in the $\alpha + \pi^-$ invariant mass distribution. It may be attributed to $^3\Lambda\text{H}$ decay which is known to exist [44].

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