Strangeness production in heavy ion reactions at intermediate energies

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Abstract

Kaon production, in particular $K^+$ production in heavy ion collisions at intermediate energies is discussed. Main emphasis is put on the question if subthreshold $K^+$ production can serve as a suitable tool to test the high density phase of such reactions and to deliver information on the high density behavior of the nuclear equation of state. It is shown that the $K^+$ excitation function in heavy ($Au + Au$) over light ($C + C$) systems provides a robust observable which, by comparison to data, strongly favors a soft equation of state. A second question of interest is the existence of an in-medium kaon potential as predicted by effective chiral Lagrangians. Here it is argued that transport calculations support this scenario with, in the meantime, a significant level of consistency.

1 Introduction

The original motivation to study the kaon production in heavy ion reactions at intermediate energies, namely to extract information on the nuclear equation of state (EOS) at high densities is a matter of current debate. Already in the first theoretical investigations by transport models it was noticed that the $K^+$ yield reacts sensitive on the nuclear equation of state [1, 2, 3, 4]. The yields were found to be about a factor 2–3 larger when a soft EOS was applied compared to a hard EOS. At that time the available data [5] already favored a soft equation of state. However, calculations as well as the experimental data were still burdened with large uncertainties.

In [6] we studied the question if in the meantime decisive information on the nuclear EOS can be extracted from subthreshold kaon production in heavy ion collisions. There are several reasons why it appears worthwhile to do this: Firstly, there has been significant progress in the recent years towards a more precise determination of the elementary kaon production cross sections [7, 8], based also on new data points from the COSY-11 for the reactions $pp \rightarrow p\Lambda K^+$ very close to threshold [9]. Secondly, the KaoS Collaboration has performed systematic measurements of the $K^+$ production far below threshold in heavy ($Au + Au$) and light ($C + C$) systems [10]. Looking at the ratios built from heavy and light systems possible uncertainties which might still exist in the theoretical calculations should cancel out to a large extent which allows to draw reliable conclusions. Furthermore, far below threshold the kaon production is a highly collective process and a particular sensitivity to the compression of the participant matter is expected.
2 The Model

The present investigations are based on the Quantum Molecular Dynamics (QMD) transport model [11]. For the nuclear EOS we adopt soft and hard Skyrme forces corresponding to a compression modulus of K=200 MeV and 380 MeV, respectively, and with a momentum dependence adjusted to the empirical optical nucleon-nucleus potential [11]. The saturation point of nuclear matter is thereby fixed at $E_B = -16$ MeV and $\rho_{sat} = 0.17$ fm$^{-3}$ [11]. The calculations include $\Delta(1232)$ and $N^*(1440)$ resonances. The QMD approach with Skyrme interactions is well tested, contains a controlled momentum dependence and provides a reliable description of the reaction dynamics in the SIS energy range, expressed e.g. by collective nucleon flow observables as well as particle production. In contrast to AGS energies where the creation of resonance matter may lead to an effective softening of the EOS, baryonic resonances with masses above the $N^*(1440)$ can safely be neglected for the reaction dynamics at SIS energies.

We further consider the influence of an in-medium kaon potential based on effective chiral models [12, 13, 14, 15, 16]. The $K^+$ mean field consists of a repulsive vector part $V_\mu = 3/8 f_\pi^2 j_\mu$ and an attractive scalar part $\Sigma_S = m_K - m^2_K = m_K - \sqrt{m^2_K - \Sigma_{KN}/f_\pi^2 \rho_S + V_\mu}$. Here $j_\mu$ is the baryon vector current and $\rho_S$ the scalar baryon density and $\Sigma_{KN} = 450$ MeV. Following [15] in the vector field the pion decay constant in the medium $f_\pi^2 = 0.6 f_\pi^2$ is used. However, the enhancement of the scalar part using $f_\pi^2$ is compensated by higher order contributions in the chiral expansion [15], and therefore here the bare value is used, i.e. $\Sigma_{KN} \rho_S / f_\pi^2$. Compared to other chiral approaches [13, 14] the resulting kaon dispersion relation shows a relatively strong density dependence. The increase of the in-medium $K^+$ mass $\tilde{m}_K$, Eq. (2), with this parametrisation is still consistent with the empirical knowledge of kaon-nucleus scattering and allows to explore in-medium effects on the production mechanism arising from zero temperature kaon potentials. For the kaon production via pion absorption $\pi B \rightarrow Y K^+$ the elementary cross section of [17] are used. For the $NN \rightarrow BY K^+$ channels we apply the cross sections of Ref. [17] which give a good fit to the COSY-data close to threshold. For the case of $N \Delta \rightarrow BY K^+$ and $\Delta \Delta \rightarrow BY K^+$ reactions experimental data are rare. Thus we rely on the model calculation of ref. [8]. In the case that a $N^*$ resonance is involved in the reaction we used the same cross section as for nucleons. In the presence of scalar and vector fields the kaon optical potential in nuclear matter has the same structure as the corresponding Schroedinger equivalent optical potential for nucleons

$$U_{opt}(\rho, k) = -\Sigma_S + \frac{1}{m_K} k_\mu V_\mu + \frac{\Sigma^2_S - V^2_\mu}{2m_K}.$$ (1)

and leads to a shift of the thresholds conditions inside the medium. To fulfill energy-momentum conservation the optical potential is absorbed into an newly defined effective mass

$$\tilde{m}_K(\rho, k) = \sqrt{m^2_K + 2m_K U_{opt}(\rho, k)}$$ (2)

which is a Lorentz scalar and sets the canonical momenta on the mass-shell $0 = k^2_\mu - \tilde{m}^2_K$. Thus, e.g., the threshold condition for $K^+$ production in baryon induced reactions reads $\sqrt{s} \geq \tilde{m}_B + \tilde{m}_Y + \tilde{m}_K$ with $\sqrt{s}$ the center-of-mass energy of the colliding baryons. For a consistent treatment of the thresholds the scalar and vector baryon mean fields entering into eq. (2) are determined from two versions of the non-linear Walecka model with K=200/380 MeV, respectively [3]. The hyperon field is thereby scaled by 2/3 which yields also a good description of the $\Lambda$ flow [18]. Since the parameterizations chosen for the non-linear Walecka model yield the same EOS as the Skyrme ones, the overall energy is conserved. The kaon production is treated perturbatively and does generally not affect the reaction dynamics [19].

3 Probing the nuclear EOS by subthreshold $K^+$ production

The $K^+$ excitation function for $Au + Au$ and $C + C$ reactions starting from 0.8 A·GeV which is far below threshold $(E_{thr} = 1.58$ GeV) has been measured by the KaoS Collaboration [10, 20]. In [6] we
calculated this excitation function for a soft/hard EOS including the in-medium kaon potential. For both systems the agreement with the KaoS data \[10\] is very good when a soft EOS is used. In the large system there was a visible EOS effect which is absent in the light system. The inclusion of the repulsive in-medium $K^+$ potential is thereby essential to reproduce the data \[20\]. Already in the light system the $K^+$ yield is reduced by about 50%. To extract more clear information on the nuclear EOS, in Fig. 1 we considered the ratio $R$ of the kaon multiplicities obtained in $Au + Au$ over $C + C$ reactions, normalized to the corresponding mass numbers. The kaon potential is included since without the in-medium potential one is not able to reproduce the experimental $K^+$ yields \[6, 21\]. The calculations are performed under minimal bias conditions with $b_{\text{max}} = 11$ fm for $Au + Au$ and $b_{\text{max}} = 5$ fm for $C + C$ and normalized to the experimental reaction cross sections \[10, 20\]. Both calculations show an increase of $R$ with decreasing incident energy down to 1.0 A-GeV. However, this increase is much less pronounced when the stiff EOS is employed. In the latter case $R$ even decreases at 0.8 A-GeV whereas the soft EOS leads to an unrelieved increase of $R$. At 1.5 A-GeV which is already very close to threshold the differences between the two models become small. The strong increase of $R$ can be directly related to higher compressible nuclear matter. The comparison to the experimental data from KaoS \[10\] where the increase of $R$ is even more pronounced strongly favors a soft equation of state.

To obtain a quantitative picture of the explored density effects in Fig. 2 the baryon densities are shown at which the kaons are created. The energy is chosen most below threshold, i.e. at 0.8 A-GeV and only central collisions are considered where the effects are maximal. $dM_{K^+}/d\rho$ is defined as

$$dM_{K^+}/d\rho = \frac{\sum P_i}{d\rho_B(\mathbf{x}_i, t_i)}$$

where $\rho_B$ is the baryon density at which the kaon $i$ was created and $P_i$ is the corresponding production probability. For the comparison of the two systems the curves are normalized to the corresponding mass numbers. Fig.2 illustrates several features: Only in the case of a soft EOS the mean densities at which kaons are created differ significantly for the two different reaction systems, i.e. $<\rho/\rho_{\text{sat}}> = 1.46/1.40$ for $C + C$ and 1.47/1.57 for $Au + Au$ using the hard/soft EOS. Generally, in $C + C$ reactions densities above $2\rho_{\text{sat}}$ are rarely reached whereas in $Au + Au$ the kaons are created at densities up to three times
saturation density. Furthermore, for C+C the density distributions are weakly dependent on the nuclear EOS. The situation changes completely in Au+Au. Here the densities profile shows a pronounced EOS dependence. Moreover, the excess of kaons obtained with the soft EOS originates almost exclusively from high density matter which demonstrates that compression effects are probed.

The density effect is also clearly reflected in the $A_{\text{part}}$ dependence of the kaon multiplicities. Fig. 3 compares the $A_{\text{part}}$ dependence in $Au + Au$ and $C + C$ reactions, now for 1.0 AGeV laboratory energy. In both cases the kaon multiplicities as well as $A_{\text{part}}$ which has been derived within the geometrical model, are normalized to the corresponding mass numbers. As can be seen from there, in $C + C$ the $A_{\text{part}}$ dependence of the kaon production is completely insensitive to the nuclear equation of state. The large system, in contrast, shows a distinct EOS dependence. In $Au + Au$ the enhanced kaon production which is due to higher compression when a soft EOS is used, becomes more and more pronounced with
increasing centrality. However, one has to keep in mind that the large difference between the soft and hard EOSs in most central reactions is washed out to some extent in minimal bias reactions. There the bulk of kaons originates from semi-central reactions $b \sim 5$ fm, corresponding to $A_{\text{part}}/A_{\text{max}} \sim 0.7$. In this context it will be very helpful to study the EOS dependence also in $C + Au$ reactions and to compare to forthcoming data from KaoS [22].

### 3.1 How firm are the conclusions?

Of course now the question arises, how firm conclusions on the nuclear EOS are which can be drawn from kaon production in heavy ion reactions. Possible concerns might be based on the facts that subthreshold kaons are an extremely rare probe and not all elementary production cross sections have been measured.

In heavy ion collisions the $K^+$ production runs over two major channels, namely baryon-baryon induced reactions $BB \leftrightarrow BYK^+$ and pion-baryon induced reactions $\pi B \leftrightarrow Y K^+$ which are both about equally important [23]. In both cases the initial baryons can either be nucleons or nucleon resonances (mainly $\Delta(1232)$), the hyperons are $\Lambda$ or $\Sigma$ hyperons. Processes with nucleon resonances in the final state are energetically suppressed. Concerning the knowledge of the elementary reaction cross section the situation is presently as follows: the $NN$ and $\pi N$ cross sections are quite well under control since these channels have been measured in $pp$ reactions [9] and in $\pi^\pm p$ reactions. The reactions which involve nucleon resonances, in particular with $\Delta$'s in the initial states ($i = N\Delta, \pi\Delta, \Delta\Delta$) are less secure due to the lack of corresponding experimental data. Thus one has to rely on model assumptions. The cross sections which have been used in the present transport calculations are based on the effective Lagrangian model of Refs. [8, 17, 24]. The isospin dependence of the cross sections is thereby determined in the standard way by isotopic relations assuming iso-spin independent matrix elements.

Hence there exists still some uncertainty in the transport calculations due to the incomplete knowledge of the elementary reaction cross sections. There are, however, two good arguments why conclusions on the EOS dependence of the kaon production should be rather robust against such possible uncertainties:

- Changes of the production cross sections shift absolute yields but considering the ratio of different reaction systems such errors drop out in leading order.

- Conclusions are based on the slope of this ratio as a function of energy. It is rather unlikely that an incomplete knowledge of the cross sections, e.g. concerning their isospin dependence, can create the observed energy dependence. The systematics of spurious contributions should be flat as a function of energy. Otherwise one have to assume extremely unconventional threshold effects.

To be more quantitative we consider in the next figure the excitation function of $R$ for the various production channels. There the ratios $R_i$ are built separately for the production channels with initial states $i = NN, \pi N, N\Delta, \pi\Delta, \Delta\Delta$. As can be seen from Fig. 4 the shape of $R$ is not strongly influenced by the $N\Delta$, $\pi\Delta$ channels which are the most insecure ones. The excitation function for the $N\Delta$ contribution varies only little as a function of energy and is similar using the different EOSs. The contribution of the $\pi\Delta$ channel is decreasing for both, a hard and a soft EOS. The shape of $R$ is to most extent determined by the $NN$ and $\pi N$ contributions. In our calculations the latter channel is responsible for the decrease of $R$ very far below threshold when the hard EOS is applied. These findings are generally confirmed by independent transport calculations of the Nantes group using the IQMD transport model [21] shwon in Fig. 5. These calculations include an in-medium kaon potential derived in relativistic mean field theory (RMF) [25] which is somewhat less repulsive than that one used in our calculations. For the soft EOS the IQMD calculations coincide almost with the present results [6]. For the hard EOS there exist still deviations concerning the slope of $R$ going far below
threshold. This could be due to the different in-medium potentials and is an open question which has to be resolved by future investigations. However, the two sets of transport calculations show a good overall agreement and both rule out the hard EOS from the comparison with data. The shaded area in Fig. 5 can be taken as the existing range of uncertainty in the theoretical model description of the considered observable.

Moreover, the IQMD calculations were also repeated with an alternative set of $N\Delta; \Delta\Delta \rightarrow NYK^+$ cross sections taken from [26] which are about a factor of two larger than those from Tsushima et al. [8]. The ratio $R$ is almost completely independent on this change. Another prove for the robustness of this observable is the fact influence of the repulsive $K^+$ potential which decreases the total kaon yield by about a factor drops almost completely out when ratio of the two different mass systems is built [6, 21].

### 3.2 Are the conclusions consistent with information from other sources?

Finally the question arises up to which degree a consistent picture has emerged after more than ten years of intensive experimental and theoretical efforts to understand the kaon production at intermediate energies. In the following I will argue that concerning $K^+$ we have in the meantime a rather consistent picture while for $K^-$ the situation is not yet so clear.

The reason is that subthreshold $K^+$ production is easier to handle, both from the experimental and the theoretical side. Due to the lower threshold there are much more data with much higher precision available than for $K^-$. Also theoretically the medium dependence of the $K^+$ meson properties are better under control. The mean field approximation seems to work, i.e. mass shifts and can be taken from the leading order chiral Lagrangian [12, 15] and in the medium there exists still a well established quasi-particle pole [27, 16]. This allows a treatment within standard transport based on the quasi-particle approximation. The $K^- - N$ system, on the other hand, lies in the vicinity of the $\Lambda_{1405}$ resonance which implies a strong coupling to this state. Hence a simple mean field picture will not work but a coupled
Figure 5: Excitation function of the ratio $R$ of $K^+$ multiplicities obtained in inclusive $Au + Au$ over $C + C$ reactions. Our results are compared to independent IQMD calculations [21]. The shaded area indicates thereby the range of uncertainty in the theoretical models. In addition IQMD results based on an alternative set of elementary $K^+$ production cross sections are shown.

channel treatment of the $K^-$ in the medium is necessary [27, 28, 29]. As a consequence, the $K^-$ has complicated spectral properties in the medium and a simple quasi-particle picture is not more suitable [28, 29]. This requires a more sophisticated treatment within transport simulations which accounts at least approximately for the off-shell contributions of the spectral functions [30]. In the latter case the interpretation of existing data with the help of transport simulation has not yet reached a level which allows to say that the $K^-$ properties are settled.

Coming back to the $K^+$ the situation is much more satisfying. Most transport calculations agree on the necessity of a repulsive $K^+$ potential in order to understand total yields as well as the collective motion of $K^+$ mesons, i.e. in-plane and out of-plane flow [31, 32, 33, 34, 35, 36]. This picture was recently complemented by measurements of the $K^+$ production in proton-nucleus reactions [37]. Although such reactions test only subnormal nuclear densities they are much easier to handle than the complicated dynamical evolution of heavy ion reactions. Corresponding data $pA$ from ANKE revealed strong evidence for a repulsive $K^+$ potential which is of the order of magnitude as predicted by effective chiral lagrangians.

### 3.2.1 Many-body calculations

Concerning the nuclear equation of state one has to confront the information from subthreshold $K^+$ production with the knowledge obtained from other sources: At intermediate energies heavy ion reactions test the density range between two and three times nuclear density. The information from kaon production implies that in this density range the EOS should show a soft behavior. One has of course to be aware that the adopted Skyrme forces are simplified interactions which are easy to handle but must not be very realistic. A microscopic approach to nuclear matter which is based on realistic nucleon-nucleon interactions has to solve the correlated quantum-mechanical many-body problem. Such an approach is, e.g., the Brueckner-Hartree-Fock approach which accounts for the two-body correlation in the medium solving the Bethe-Goldstone equation, i.e. the Lippmann-Schwinger equation in the medium. The relativistic version, i.e. the Dirac-Brueckner-Hartree-Fock (DBHF) approach delivers quite reasonable values for the nuclear saturation mechanism [38] and can thus be considered as a reliable method to extrapolate the many-body approach to higher nuclear densities. In Fig. 6 we compare DBHF results obtained with two slightly different NN-interactions, i.e. Bonn A and Bonn B [39] to the
simple Skyrme type equations of state. The results of advanced DBHF calculations are taken from \cite{40}. In this context it may worthwhile to mention that very similar results to \cite{40} were recently obtained by Weise and coworkers in a treatment of the nuclear many-body problem based on chiral perturbation theory \cite{41}. Generally such many-body calculations predict a relatively soft behavior of the EOS in the relevant density range, i.e. for densities below about three times saturation density. In the microscopic approach the high density behavior is, however, only loosely connected to the curvature at saturation density. For Bonn A and B the compressibilities are quite different while the EOSs at high densities are very close. Below $3\rho_0$ both are not too far from the soft Skyrme EOS.

### 3.2.2 Nucleon Flow

Another observable which helps to constrain the nuclear mean field and the underlying EOS at super-normal densities is the collective nucleon flow \cite{42}. The transverse flow $v_1$ has been found to be sensitive to the EOS and, in particular in peripheral reactions, to the momentum dependence of the mean field \cite{43,44}. The elliptic flow $v_2$, in addition, is very sensitive to the maximal compression reached in the early phase of a heavy ion reaction. The cross over from preferential in-plane flow $v_2 < 0$ to preferential out-off-plane flow $v_2 > 0$ around 4-6 AGeV has also led to speculations about a phase transition in this energy region which goes along with a softening of the EOS \cite{45}.

The present situation can be summarized as follows: At SIS energies existing flow data are consistent with the usage of mean fields which are close to those obtained from microscopic DBHF calculations, both concerning their density and momentum dependence \cite{43,44}. A detailed comparison to FOPI data \cite{46} for $v_1$ and $v_2$ between 0.2 and 0.8 AGeV favors thereby a relatively soft EOS \cite{44} such as the DBHF result for Bonn A (K=230 MeV, shown in Figure 6). The full flow excitation function, ranging from low SIS up to top AGS energies, has been studied in \cite{47}. The conclusion from this study was that, both, super-soft equations of state (K=167 MeV) as well as hard EOSs (K>300 MeV) are ruled out by data. Hence the picture is again consistent with the information obtained from kaon production.

### 4 Summary

To summarize, we find that at incident energies far below the free threshold $K^+$ production is a suitable tool to study the dependence on the nuclear equation of state. Using a light system as reference
frame there is a visible sensitivity on the EOS when ratios of heavy \((Au + Au)\) over light \((C + C)\) systems are considered. Transport calculations indicate that the \(K^+\) production gets hardly affected by compressional effects in \(C + C\) but is highly sensitive to the high density matter \((1 \leq \rho/\rho_{sat} \leq 3)\) created in \(Au + Au\) reactions. Results for the \(K^+\) excitation function in \(Au + Au\) over \(C + C\) reactions as measured by the KaoS Collaboration, strongly support the scenario of a soft EOS. This statement turns out to be rather robust against possible model uncertainties: It is almost independent on the variation of particular reaction channels where elementary cross sections are uncertain. It is also insensitive to the inclusion/neglection of a changing in-medium kaon mass as predicted by chiral models. The idea of a soft EOS in the considered density range is also consistent with the knowledge from microscopic many-body theory and from nuclear flow analysis in heavy ion reactions.

Concerning the quest for in-medium modification of the kaon properties transport calculation have in the meantime reached a certain level of consistency: The explanation of the total \(K^+\) yields and the \(K^+\) flow requires the presence of a repulsive in-medium potential. This picture has been complemented by measurements of kaon production in \(p + A\) reactions.

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