Strangeness Production at 1 – 2 $A$ GeV

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Abstract

The production of $K^+$ and $K^-$ mesons below and at the NN threshold is summarized, based on a comparison of data with transport model calculations. $K^+$ mesons are created in associate production together with hyperons (e.g. $\Lambda$) in multi-step processes involving $\Delta$ resonances. These processes occur mainly during the high-density phase of the collision and this makes the $K^+$ an ideal tool to extract the stiffness of the nuclear equation of state, found to be rather soft with a compressibility modulus $K$ below 240 MeV. In contrast, the major part of $K^-$ mesons are produced via strangeness exchange. Most of the created $K^-$ are absorbed and the surviving ones are emitted quite late and at low densities.

1 Introduction

Pion production in heavy-ion collisions at a few GeV per nucleon is the dominant channel for particle emission. Kaon emission, however, is a rare processes at these energies. In nucleon-nucleon interactions, the threshold for pion production is 0.29 GeV, for $K^+$ it is 1.58 GeV and for $K^-$ it is 2.5 GeV. For kaons the required energy also contains the mass of the lightest associate partner to be produced in order to conserve strangeness, being a $\Lambda$ for the $K^+$ and a $K^+$ for the $K^-$. Pions are predominantly produced in first-chance nucleon-nucleon collisions, while kaons being created below threshold, require that energy is accumulated by various means. As a consequence, the $K^+$ mesons are produced only during the high-density phase, and therefore these particles are considered as ideal probes for the hot and dense fireball.

Being produced inside the collision zone, the fate of these particles is quite different. The pion-nucleon cross section is large and thus pions are absorbed through the $\Delta$ resonance and re-emitted by the decay of this resonance. This creation and disappearance occurs during the entire time evolution of the collision. The $K^+$-nucleon cross section, on the other hand, is small, which is due to strangeness and energy conservation. There are no partners to react with and only elastic scattering and charge exchange can happen.

The $K^-$ production process is quite different from $K^+$. The production threshold is much higher. Yet there is an alternative production channel possible, as suggested by Ko [1] and demonstrated in Refs. [2, 3]. The strangeness-exchange reaction $\pi Y \leftrightarrow K^- N$ has a large cross section (with $Y$ being $\Lambda$
or Σ). The inverse channel causes the produced \( K^- \) to be able to be absorbed [3]. As in the pion case, the succession of absorption and creation causes the \( K^- \) emission to be in the late stage of the reaction.

In addition, strange hadrons carry information on the properties of the medium in which they are created and through which they are propagating due to KN potential interaction [4]. The effective in-medium mass of \( K^+ \) mesons increases with density, since the potential is slightly repulsive, while the \( K^- \) potential is strongly attractive and decreases with density.

Early experiments have been carried out at the Bevalac accelerator. Systematic, high-statistics measurements of pion and kaon production became feasible with the advent of the SIS accelerator at GSI. In this short review, mainly results from the KaoS Collaboration [5] are given, and some examples of recent IQMD calculations [6]. A recent review on pion emission can be found in [7].

2 Particle production yields

A survey of the production yields of pions and kaons in inclusive collisions of a light (C+C) and a heavy (Au+Au) system are given in Fig. 1 as a function of beam energy where the ordinate is \( \sigma/A^{5/3} \) which represents the multiplicity per mass number \( A \) of the colliding system. As can be seen from this figure the pion multiplicity per \( A \) is higher in the lighter system which reflects likely the influence of absorption of pions and holds only at these low incident energies. In contrast, for \( K^+ \) production the inverse observation is made.

The key mechanism for the \( K^+ \) production in heavy-ion reactions close to the threshold is a multi-step process where the energy necessary for the production is accumulated and stored in intermediate resonances. Higher densities increase the number of these collisions and especially second generation collisions like \( \Delta N \) with sufficiently high relative momentum to create a \( K^+ \) occur most frequently during the high-density phase of the reaction. This has nicely been demonstrated by IQMD calculations [6] showing that also well above the corresponding NN threshold the channel \( \Delta N \) dominates the \( K^+ \) production. The yield of \( K^- \) is about two orders of magnitude lower due to the much higher threshold.

Figure 2, left, shows the multiplicities of \( K^+ \) mesons per mass number \( A \) from inclusive reactions as a function of \( A \) at several incident energies as well as those of \( K^- \) mesons at 1.5 GeV. The lines in Fig. 2 are functions \( M \sim A^\gamma \) fitted to the data with the resulting values for \( \gamma \) given in the figure. For \( K^+ \) production the extracted values of \( \gamma \) decrease with incident energy. This reflects the decreasing influence of the intermediate energy storage via \( \Delta \) and hence the influence of the density. Considering the much higher threshold for \( K^- \) production, one would expect that \( \gamma \) is much larger at comparable
incident energies. However, at 1.5 $A$ GeV the values for $K^+$ and for $K^-$ production are about equal. This confirms that the $K^-$ production is linked to the $K^+$ production. $K^-$ mesons are dominantly created by strangeness exchange converting a hyperon and a pion into a $K^-$ and a nucleon.

Figure 2 right, shows the multiplicity per number of participating nucleons $M/A_{\text{part}}$ for Ni+Ni and Au+Au collisions at 1.5 $A$ GeV as a function of $A_{\text{part}}$ and demonstrates that the multiplicities per $A_{\text{part}}$ of pions does not change with $A_{\text{part}}$ while both kaon species exhibit the same rise despite the fact that the thresholds for the production of the two particles species in binary NN-collisions are very different. This is observed in Au+Au as well as in Ni+Ni collisions with comparable multiplicities at the same $A_{\text{part}}$. Again, this observation confirms the strong relation between $K^+$ and $K^-$ production. As a consequence of this observation, the $K^-/K^+$ ratio as a function of $A_{\text{part}}$ is constant as a function of $A_{\text{part}}$ and is even the same for two different systems. Again, at first glance it is astonishing that in central collisions with high densities the $K^-/K^+$ ratio is the same as in peripheral ones. Yet, considering the observation from Fig. 2, right, it is expected. Remarkable is that a statistical model is able to describe these ratios [5]. All these observations indicate that $K^-$ are essentially created by the strangeness-exchange mechanism and it has been shown by applying the law-of-mass action that this channel might reach chemical equilibrium [9].

3 Spectra

Both $K^+$ and $K^-$ mesons are produced in a complicated sequence of interactions. Figure 3 shows $K^+$ and $K^-$ spectra at midrapidity as a function of the kinetic energy $E_{\text{c.m.}}-m_0c^2$ for three different systems and various beam energies. The spectra have a Boltzmann shape to a very good approximation. Two general trends can be seen from this figure: (i) The slopes of the $K^+$ are always higher than those of $K^-$. (ii) Heavy systems exhibit higher slopes than lighter ones.

It is interesting to study the different components and effects contributing to the $K^+$ slope in an IQMD study [6]. Initially, the energy available for $K^+$ production is low and the slope at creations is therefore quite steep as can be seen from Fig. 4. The final slopes are influenced by re-scattering of
Figure 3: Inclusive invariant cross sections as a function of the kinetic energy $E_{\text{c.m.}} - m_0c^2$ for $K^+$ (left) and for $K^-$ (right) for three collision systems and various beam energies at mid-rapidity ($\theta_{\text{c.m.}} = 90^\circ \pm 10^\circ$). From [5].

the $K^+$ in the medium and by the repulsion from $K^+N$ potential as demonstrated in this figure. Rescattering dramatically increases the slope. This effect increases as the beam energy increases and as the mass of the system increases as there is more scattering in heavier systems. The expected repulsive $K^+$ potential increases the production threshold and might modify the spectra only at low momenta which are difficult to detect due to the kaon decay. For experimental reasons kaons at low momenta can be studied best with neutral $K^0_s$ mesons [10, 11]. One might be astonished that scattering contributes so strongly as the mean free path of $K^+$ is about 5 fm. Yet, $K^+$ are produced at about twice normal nuclear matter density and mostly inside the collision zone. Hence, the mean free path decreases drastically and $K^+$ have to travel a distance before leaving the system as shown in [6].

The slope of the $K^-$ is influenced by scattering the same way as the $K^+$, yet scattering occurs less frequently since absorption dominates when $K^-$ interact with nuclei. According to IQMD calculations only about 20% of the $K^-$ produced in $Au+Au$ finally leave the system as shown in Fig. [5]. Furthermore, due to the momentum dependence of the absorption, the low momenta of the $K^-$ undergo stronger absorption which leads to an increase in slope or apparent temperature. The influence of the $KN$ potential is only visible at low momenta which are very difficult to measure.

In order to put these various observables in relation to the expected in-medium properties of kaons, it is useful to study the emission time of the two kaon species and the corresponding density profiles. Figure [6] shows on the left side the time distributions of kaons at the point of production and at the time of last contact. As discussed before, $K^-$ are produced later than $K^+$ and they also leave the system later. The right hand side of Figure [6] shows the corresponding density distributions. The bulk of the $K^+$ is produced when the density is twice nuclear matter density and their yield cannot be changed between production and emission due to strangeness conservation. This fact is the key property as to why the $K^+$ gives access to the high-density phase and thus allows one to extract the nuclear equation of state. In contrast, the $K^-$ are predominantly produced and emitted later and from a region of density below nuclear matter density. From this model study, it is obvious that heavy-ion reactions in the 1 to 2 $A$ GeV regime are well suited to also study $K^+$ potential effects, but they are not likely to yield results on $K^-$ potential effects since those effects are expected to be small at densities below nuclear matter density.
Figure 4: Influence of rescattering of the $K^+$ and of the repulsive KN potential demonstrated for central Au+Au collisions at 1.5 $A$ GeV. Left: Influence of the rescattering of $K^+$ mesons by selecting kaons which have scattered twice or more ($N_C > 2$), showing their initial and final distribution. Right: Influence of the KN potential on the spectral shape demonstrated by selecting kaons that never scattered ($N_C = 0$) and comparing the initial and final spectra [6]. Without potential the initial spectrum is also the final one.

Figure 5: Left: Influence of absorption of $K^-$ mesons demonstrated for Au+Au at 1.5 $A$ GeV based on IQMD calculations. Right: Effect of rescattering of $K^-$ and of the attractive KN potential [6].

4 The Nuclear Equation of State

One of the challenging questions of nuclear physics is the determination of the nuclear equation of state (EoS). One of the very successful strategies refers to the study of monopole vibrations which yields a value for the compression modulus $K$ of $235 \pm 14$ MeV [12] with $K = -V \frac{d \rho}{d \rho} = 9 \rho^2 \frac{d^2 E/A(\rho, T)}{(d \rho)^2} |_{\rho=\rho_0}$ which measures the curvature of $E/A(\rho, T)$ at the equilibrium point. This information is however, limited to tiny density variations around $\rho_0$. Heavy-ion collisions are ideally suited to reach high densities and they might allow us to extract further information on the EoS. In semi-central heavy-ion collisions, an in-plane flow is created due to the transverse pressure on the baryons outside of the interaction region with this flow being proportional to the transverse pressure. These studies have not yet lead to clear results [13] and earlier conclusions [14] have to be taken with care. The most promising method seems to be the strangeness production and its sensitivity to the energy available during the hot and compressed phase as first pointed out in [15]. However, a comparison of the $K^+$ excitation function with model calculations suffers from uncertainties in the input quantities and also on the unknown influence of the $K^+ N$ potential. It has been realized that many of the theoretical and experimental uncertainties disappear if ratios of $K^+$ multiplicities are used [16]. The double ratio $(M_{K^+/A}^{Au+Au}/(M_{K^+/A}^{C+C})$ turns out to be directly sensitive to the stiffness of EoS. In C+C collisions the densities hardly exceed $\rho_0$ providing a good normalization to cancel out systematic uncertainties both in the experimental data and in unknown input quantities.
Figure 6: Left: Time profiles for production (dashed lines) and last contact (solid lines) of $K^+$ (top) and $K^-$ (bottom) mesons. Right: Density distribution of the medium at the point of production (dashed lines) and at the point of last contact (solid lines) for $K^+$ (top) and $K^-$ (bottom) mesons. The simulations are for central $Au + Au$ collisions at 1.5 $A GeV$.

of the transport model calculations. This ratio is plotted in Fig. 7 as a function of the beam energy for a soft (bold red lines) and a hard (thin blue) EoS. The dotted lines refer to RQMD calculations by Fuchs [17] and both calculations agree quite well. This figure elucidates again the sensitivity of the EoS being higher at the lowest beam energies, and demonstrates that only a soft EoS is compatible with the experimental data of the KaoS collaboration [16, 17].

Furthermore, in order to have a robust observable one has to demonstrate that the uncertainties of the input variables do not render the conclusion useless. Therefore, detailed calculations with different $N + \Delta \rightarrow K^+ NN$ cross section, with and without KN potential and for different lifetimes of the Delta resonance have been performed and none of these uncertainties is able to weaken the previous conclusion that only a soft EoS is compatible with the observed excitation function of the $K^+$ yield [18].

Figure 7: Left: Comparison of the experimental $K^+$ excitation functions [16] of the double ratio $(M_{K^+}/A)_{Au+Au}/(M_{K^+}/A)_{C+C}$ (the $K^+$ multiplicities per mass number $A$) obtained in Au+Au divided by the one in C+C with RQMD [17] (dotted) and with IQMD calculations [18] (dashed). Comparing the results of a soft (bold red) with a hard (thin blue) EoS. Right: The exponent $\alpha$ is shown as a function of the compression modulus $K$ determined from IQMD calculations (with and without momentum-dependent interactions, mdi) and compared to the values extracted from Au+Au collisions at 1.5 $A GeV$ (Fig. 2 right).

Can this conclusion on the EoS be confirmed independently? Instead of varying the size of the system one can also vary the centrality. Because a higher centrality of the collisions yields a higher compression we expect that the $K^+$ yield per participant as a function of the centrality depends as well on the EoS. The measured dependence of $M/A_{part}$ with $A_{part}$ exhibits a rise $\propto A_{part}^{\alpha}$ shown in Fig. 2.
right. The extracted value of $\alpha = 1.34 \pm 0.16$ for Au+Au collisions at 1.5 $A$ GeV \[5\] is shown, as the band in Fig. 7 right. The dashed line shows IQMD calculations and also for this observable the data of the KaoS collaboration are only compatible with values of $K$ around 200 MeV. Thus two independent observables point towards a rather low compression modulus.

5 Conclusion

The two kaon species exhibit quiet distinct differences when produced in heavy-ion reactions below or at the threshold in NN collisions.

$K^+$ mesons are created in associate production together with hyperons. This happens mainly in multi-step processes via the intermediate $\Delta$ resonance. According to transport model calculations, they are produced early – around 7 fm/c – and at densities around twice normal nuclear matter. Before leaving the collision zone, they scatter quite often which causes their spectral slopes to be increased, but not changing their yield.

$K^-$ mesons, in contrast, are mainly created by strangeness exchange $\pi Y \leftrightarrow K^- N$ but they are as well easily reabsorbed by the inverse reaction and those finally emitted test the late phase of the collision.

Hence, the production yields of $K^+$ mesons have been used to extract the stiffness of the nuclear equation of state. Hints for a repulsive $K^+ N$ potential have been found, but this remains an open issue. Experimental hints for an attractive $K^- N$ potential exist, but are still strongly debated.

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