Strange Mesons as a Probe for Dense Nuclear Matter

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Abstract

The production and propagation of kaons and antikaons has been studied in symmetric nucleus-nucleus collisions in the SIS energy range. The ratio of the excitation functions of $K^+$ production in Au+Au and C+C collisions increases with decreasing beam energy. This effect was predicted for a soft nuclear equation-of-state. In noncentral Au+Au collisions, the $K^+$ mesons are preferentially emitted perpendicular to the reaction plane. The $K^-/K^+$ ratio from A+A collisions at beam energies which are equivalent with respect to the threshold is found to be about two orders of magnitude larger than the corresponding ratio from proton-proton collisions. Both effects are considered to be experimental signatures for a modification of kaon properties in the dense nuclear medium.

1 Introduction

Relativistic heavy ion collisions provide the unique possibility to study nuclear matter at high densities. At bombarding energies of 1 - 2 AGeV, baryonic densities of 2 - 3 times saturation density are reached over a timespan of about 15 fm/c. The abundances and phase-space distributions of produced particles contain information on the properties of the fireball and thus can be linked to the compressibility of nuclear matter [1, 2, 3]. In particular $K^+$ mesons are well suited to probe the hot and dense stage of a nucleus-nucleus collision because of their long mean free path in nuclear matter. The properties of kaons and antikaons are expected to change significantly inside the dense and hot nuclear medium [4, 5, 6]. The effective mass of $K^+$ mesons is predicted to increase weakly with increasing nuclear density whereas the effective mass of the antikaon strongly decreases. The latter effect may have consequences for the maximum size of neutron stars and the formation of low mass black holes [6]. Experiments on kaon and antikaon production in nucleus-nucleus collisions allow to study both the nuclear equation-of-state and the properties of hadrons in the dense nuclear medium. In this article we concentrate on data which have been measured recently with the Kaon Spectrometer [8] at the heavy ion synchrotron (SIS) at GSI in Darmstadt.

2 Subthreshold kaon production in nucleus-nucleus collisions

The kaon production threshold in free nucleon-nucleon collisions is $E_{\text{beam}} = 1.58$ GeV (for $NN\rightarrow \Lambda K^+N$). In nucleus-nucleus collisions, however, $K^+$ production is possible at beam energies far below this value. Fig. [8] shows the $K^+$ and $\pi^+$ multiplicity per participating
nucleon $M/A_{\text{part}}$ for Au+Au collisions at 1 AGeV as function of $A_{\text{part}}$. The $K^+$ multiplicity scales with $A_{\text{part}}$ according to $M_{K^+} \propto A_{\text{part}}^{1.8 \pm 0.15}$ whereas the $\pi^+$ multiplicity scales approximately linearly with $A_{\text{part}}$. The increase of $M_{K^+}/A_{\text{part}}$ with increasing size of the collision system is an experimental signature for kaon production via collective effects. Within the framework of transport models calculations, "subthreshold" kaon production predominantly proceeds via sequential processes involving intermediate pions or $\Delta$ resonances: in a first step a $\Delta$ (or a pion) is produced which collides subsequently with a baryon and produces a kaon: $\Delta N \rightarrow KYN$ or $\pi N \rightarrow KY$ with $Y=\Lambda, \Sigma$ \cite{1, 9, 10}. In these processes, the $\Delta$ resonance or the pion serves as an energy reservoir which significantly lowers the $K^+$ production threshold.

Figure 1: $K^+$ and $\pi^+$ multiplicity per participating nucleon $M/A_{\text{part}}$ as a function of $A_{\text{part}}$ for Au+Au collisions at 1 AGeV \cite{11, 12}. The data are taken at $\Theta_{\text{lab}}=44^\circ$ and extrapolated to the full solid angle assuming an isotropic angular distribution in the center-of-mass system. The line corresponds to a parameterization according to $M_{K^+} \propto A_{\text{part}}^{1.8}$.

3 Probing the nuclear equation of state

The equation-of-state of nuclear matter (EOS) plays an important role for the stability of neutron stars or the dynamics of a supernova explosion. The observation, that the masses of neutron stars ($3\rho_0 < \rho < 10\rho_0$) have values around 1.5 solar masses excludes a very stiff EOS. The prompt explosion mechanism of a supernova ($\rho \leq 4\rho_0$) is only possible for a very soft EOS. However, if the star has angular momentum or if the shock wave is revived by neutrino heating, the explosion may also happen for a stiffer EOS \cite{13}. Therefore, information on the EOS can hardly be extracted from astrophysical observations but rather is needed as an input for stellar models.

Properties of nuclear matter can be studied in laboratory experiments. The analysis of data on the giant monopole resonance ("breathing mode") in heavy nuclei finds compressibilities of $\kappa = 210\pm30$ MeV \cite{14}. However, in this case the nuclear density varies only by less than 1% around $\rho_0$. From data on the refractive elastic scattering of two oxygen nuclei at bombarding energies of 9 - 30 AMeV values of $\kappa = 170-270$ have been extracted \cite{15}. In relativistic heavy ion collisions at SIS energies, nuclear matter is compressed up to baryonic densities of $\rho \approx 3\rho_0$. The decompressional collective motion of nucleons and light fragments is related to the stiffness of the EOS. However, the analysis of data on the
directed flow of nucleons into the reaction plane has not yet resulted in an unambiguous determination of the nuclear compressibility because of the influence of the momentum dependence of the nucleon-nucleon interaction on this observable [16]. Recent theoretical studies predict a robust sensitivity of the "elliptic" flow on the EOS [17].

Figure 2: Double-differential $K^+$ production cross section measured in A+A collisions at 1.0 AGeV ($\Theta_{lab} = 44^\circ$) as function of laboratory momentum (circles: Au+Au [12], squares: Ne+NaF [20]). The lines represent results of RBUU calculations for a soft ($\kappa = 200$ MeV, solid line) and a hard ($\kappa = 380$ MeV, dashed-dotted line) equation of state [21]. For the Ne+NaF system no difference between soft and hard EOS is visible.

Data on particle production in nucleus-nucleus collisions have also been analyzed with respect to nuclear matter properties. The first attempt to determine the nuclear compressibility via meson observables was made using the total pion multiplicity as a thermometer [18]. Subthreshold $K^+$ production in relativistic nucleus-nucleus collisions has been considered to be a promising probe to study the properties of nuclear matter at high densities. The sensitivity of kaon production on matter properties is based on (i) the collective production processes via multiple interactions which are strongly enhanced in the dense phase of the collision and on (ii) the long mean free path of $K^+$ mesons which may serve as nearly undisturbed messengers. Transport model calculations predict that the $K^+$ yield obtained in Au+Au collisions at 1 AGeV is about 2 times higher for a soft EOS than for a stiff EOS [19]. This is demonstrated in Fig. 2 which shows experimental results for two different system sizes: Ne+NaF and Au+Au collisions at 1.0 AGeV [12, 20]. The data are compared to relativistic transport calculations (RBUU) with a soft (solid lines) and stiff EOS (dashed line) [13, 21]. For the light system Ne+NaF no difference is visible between a stiff and a soft EOS. However, the calculations use a parameterization of the NN→KYN process [22] which was found to give a too large cross section near threshold. Moreover, the process $\pi N \rightarrow KY$ is neglected. Therefore, the absolute agreement of calculations and data as shown in fig. 2 should not be overinterpreted. On the other hand, the theoretical uncertainties affect both the light and the heavy collision system in a similar way. Hence the relative agreement of the model calculation with both the Ne+NaF and the Au+Au data favors a soft EOS.

Fig. 2 demonstrates that the $K^+$ yield is sensitive to the nuclear compressibility for heavy collision systems at subthreshold beam energies. The sensitivity of the $K^+$ yield to the EOS vanishes for light systems and at beam energies well above the kaon production threshold [23]. Therefore, the excitation functions for $K^+$ production in Au+Au...
collisions should be different from the one in C+C collisions: the cross section ratio \( \frac{\sigma_{K^+}^{Au+Au}(E_{beam})}{\sigma_{K^+}^{C+C}(E_{beam})} \) is expected to increase with decreasing beam energy \( E_{beam} \) for a soft EOS. The measured \( K^+ \) excitation functions are presented in the left part of fig. 3 for Au+Au and C+C collisions \[24\]. The total cross sections have been calculated from the differential cross sections for \( K^+ \) production which are integrated over momentum and extrapolated to the full solid angle assuming a nonisotropic polar angle distribution. This distribution was determined from measurements of \( K^+ \) mesons at different laboratory angles and was found to be slightly forward-backward peaked \[24, 25\]. The right part of fig. 3 presents the ratio of the excitation functions as given by the lines in the left part of the figure. The width of the band corresponds to the uncertainty of the data points. It can clearly be seen that the ratio increases with decreasing beam energy. However, this cannot be considered yet as a proof for a soft EOS. It remains to be studied to what extend the increase of the ratio towards lower beam energies is caused by a reduced kaon yield in C+C collisions due to the small number of participating nucleons. A detailed analysis of these data using state-of-the-art transport models should clarify this question and put further constraints on the compressibility of nuclear matter.

4 In-medium modifications of kaons and antikaons

The formation of a nuclear fireball in nucleus-nucleus collisions provides the possibility to study the properties of hadrons under extreme conditions. It has turned out, that the produced K-mesons are promising candidates for the experimental study of in-medium modifications. The properties of kaons and antikaons in dense nuclear matter have been investigated using chiral perturbation theory \[4, 6\], chiral dynamics \[5\], relativistic mean field models \[26\] and a self-consistent coupled-channel approach \[27\]. The calculations find
an attractive kaon-nucleon (scalar) potential which is related to explicit chiral symmetry breaking due to the large strange quark mass. The kaon-nucleon vector potential is repulsive for kaons but attractive for antikaons. Hence the total KN interaction in the medium is weakly repulsive for kaons but strongly attractive for antikaons. These in-medium KN potentials influence the propagation of kaons and antikaons in nuclear matter. As a consequence, their azimuthal emission pattern is expected to be modified according to the density profile of the nuclear medium: K$^+$ mesons will be repelled from the regions of increased baryonic density whereas K$^-$ mesons will be attracted [28].

Figure 4: K$^+$ azimuthal distribution for semi-central Au+Au collisions at 1 AGeV (full dots). The data are analyzed at 0.4 < $y/y_{proj}$ < 0.6 (left) and 0.2 < $y/y_{proj}$ < 0.8 (right) [29]. The lines represent results of transport calculations using a RBUU model (left [28]) and a QMD model (right [30]). Both models take into account rescattering, the QMD version also considers Coulomb effects. Solid lines: with in-medium KN potential. Dashed lines: without in-medium KN potential.

Fig. 4 presents the K$^+$ azimuthal angular distribution measured in Au+Au collisions at 1 AGeV [29]. The kaons were accepted within a range of transverse momenta of 0.2 GeV/c ≤ $p_t$ ≤ 0.8 GeV/c for two ranges of normalized rapidities 0.4 ≤ $y/y_{proj}$ ≤ 0.6 (left) and 0.2 ≤ $y/y_{proj}$ ≤ 0.8 (right). The data are corrected for the uncertainty of the determination of the reaction plane by a Monte Carlo simulation. The K$^+$ emission pattern clearly is peaked at $\phi=\pm90^0$ which is perpendicular to the reaction plane. Such a behaviour is known from pions [31] which interact with the spectator fragments. The K$^+$ mesons, however, have a long mean free path of about 5 fm and therefore are less sensitive to rescattering. This is demonstrated in fig. 4 by the dotted lines which represent the results of a transport calculation taking into account K$^+$ rescattering only (left [28]) and additional Coulomb effects (right [30]). However, if a repulsive in-medium KN potential is assumed, the calculations reproduce the pronounced anisotropy of the data (solid lines in fig. 4).

Another manifestation of the in-medium KN potentials is a modification of the K$^+$ and K$^-$ effective mass in nuclear matter. Fig. 5 shows the effective mass of kaons and antikaons as function of nuclear density as calculated by various models [26]. The different calculations exhibit a common trend: with increasing nuclear density the K$^+$ effective mass increases weakly whereas the K$^-$ effective mass decreases considerably.
The reduction of the $K^-$ effective mass in the dense nuclear medium as indicated in fig. 5 lowers the $K^-$ production threshold and thus enhances the $K^-$ production cross section in nucleus-nucleus collisions [3, 32]. The enhancement of the $K^-$ yield should be very pronounced at beam energies below the kinematical threshold (which is 2.5 GeV for the process $NN \rightarrow K^- K^+ NN$) because of the steep excitation function. We have found experimental evidence for an enhanced $K^-$ yield in Ni+Ni collisions at 1.8 AGeV [33]. Recent experiments on antikaon production in C+C collisions confirm the previous results. Fig. 6 shows the excitation function of $K^+$ and $K^-$ production in C+C collisions as function of the Q-value in the NN system [25]. The kaon and antikaon data nearly fall on the same curve (open and full symbols) in contrast to the parameterizations of the nucleon-nucleon data (lines). The parameterizations are fitted to the available proton-proton data and averaged over the isospin channels [34, 35, 36]. The multiplicities are calculated from the production cross sections via $M_K = \sigma_K/\sigma_R$ with the total reaction cross section $\sigma_R=0.95$ b for C+C and $\sigma_R=47$ mb for p+p. The average number of participants is assumed to be $<A_{\text{part}}>=6$ for C+C (according to a geometrical model) and $<A_{\text{part}}>=2$ for p+p. The large difference in the $K^+/K^-$ ratio for C+C and p+p provides strong experimental evidence for an enhanced antikaon production in nucleus-nucleus collisions.
Figure 7: Invariant cross sections for kaon and antikaon production in C+C collisions at 1.8 AGeV (left) and 2.0 AGeV (right) as function of the kinetic energy in the center-of-mass system [25]. The data were taken near midrapidity. The lines represent predictions of RBUU transport calculations assuming bare K meson masses (solid lines) and modified K meson masses (dashed lines) [37].

Transport models predict a significant enhancement of the K\(^-\) yield even in light collision systems such as C+C. Fig. 7 shows the K\(^+\) and K\(^-\) spectra measured in C+C collisions at beam energies of 1.8 AGeV and 2.0 AGeV [25] in comparison to RBUU results [37]. The calculations were performed with different assumptions: (i) with bare masses of the K mesons (solid lines) and (ii) with modified effective masses according to m\(^*\) = m\(^0\) (1 - \(\alpha\) \(\rho/\rho_0\)) with \(\alpha\)=0.24 for K\(^-\) and \(\alpha\)=-0.06 for K\(^+\) (dashed lines). Both the calculated and measured kaons were taken at \(\Theta_{lab}=44\pm4^\circ\). The K\(^+\) data are not very sensitive to the variation of the in-medium masses and are compatible with the assumption of bare masses. The antikaon spectrum, however, shows a very distinct dependence on the K\(^-\) effective mass in the medium. The K\(^-\) data clearly favor the calculation based on the reduced effective mass.

The systematic uncertainties of the calculations and of the experimental data are reduced when looking at K\(^-\)/K\(^+\) spectral ratios. Fig. 8 presents the K\(^-\)/K\(^+\) ratio as function of the kinetic energy for C+C collisions at 1.8 AGeV in comparison to the RBUU results (same as in fig. 7). The K\(^-\)/K\(^+\) ratio steeply decreases with increasing kinetic energy of the K mesons. This is not a trivial observation as K\(^-\) mesons with low energies are stronger affected by absorption than K\(^+\) mesons with higher energies [38]. Relativistic transport calculations predict a constant K\(^-\)/K\(^+\) ratio if in-medium mass modifications of the K mesons are neglected (solid line in fig. 8). The model calculations are in good agreement with the data if in-medium effects are taken into account (dotted line).
5 Conclusions and outlook

We have presented data on kaon and antikaon production in nucleus-nucleus collisions at SIS energies. Emphasis was put on the study of in-medium effects using strange mesons as probes. We propose to use the ratio of the excitation functions for $K^+$ production in very heavy and light systems as an indicator which is sensitive to the compressibility of nuclear matter at high densities. A systematic analysis of the $K^+$ yield as function of system mass and beam energy within the framework of transport models allows to reduce the uncertainties due to the reaction mechanism (cross sections, momentum dependent interactions) and enhances the sensitivity of the kaon yield on nuclear matter properties.

The comparison of the data to published results of transport codes favor a soft EOS.

In noncentral Au+Au collisions at 1 AGeV we found that $K^+$ mesons are emitted preferentially perpendicular to the reaction plane. A similar effect was observed for pions and attributed to rescattering at the spectator matter. The $K^+$ mesons, however, have a larger mean free path in nuclear matter and should be much less affected by the spectators. Transport calculations have to assume a repulsive kaon-nucleon potential in the medium in order to reproduce the azimuthal anisotropy of kaon emission.

We found experimental evidence for an enhanced production of antikaons in nucleus-nucleus collisions at beam energies below the free NN threshold. The $K^-/K^+$ ratio determined for the same Q-value ($\sqrt{s}\sim\sqrt{s_{\text{thresh}}}$) in Ni+Ni or C+C collisions exceeds the ratio measured in proton-proton collisions by about two orders of magnitude. Transport models cannot explain the yield of antikaons when neglecting in-medium modifications of the $K^-$ meson. The strangeness exchange reaction $Y\pi \rightarrow K^-N$ (with $Y=\Lambda, \Sigma$) produces only about 10% of the measured $K^-$ yield, another 10% is due to the process $\pi N \rightarrow K^+K^-N$. Only about 1% of the $K^-$ mesons stem from nucleon-nucleon collisions $NN \rightarrow K^+K^-NN$. However, if the effective mass of the antikaon drops with increasing baryonic density, the in-medium thresholds for all these processes are reduced and the total $K^-$ yield is enhanced by a factor of about 5 [10, 35]. Recent coupled-channel calculations find that the in-medium effects are reduced with increasing momentum of the antikaon [27].

The behaviour of strange particles in dense nuclear matter is expected to play an im-
An important role in astrophysics. It is still an open question why the masses of the observed pulsars don't exceed a value of about 1.5 solar masses. In order to explain this upper limit, stellar evolution models would need a high density EOS which is much softer than generally thought. Glendenning and Weber suggested that pulsars might consist of neutrons, protons and hyperons because the EOS of these hybrid stars is considerably softer than the one of pure neutron stars [39]. Bethe and Brown proposed another mechanism which softens the EOS of the compact core of a collapsing star: if the effective mass of the $K^-$ meson decreases with increasing nuclear density then the total $K^-$ meson energy will become smaller than the electrochemical potential ($\mu_e \approx 230$ MeV) above a certain value of the nuclear density. In this situation the $K^-$ mesons may replace electrons and form a Bose condensate. The condensation of negative particles enhances the proton to neutron ratio and this effect softens the EOS. Consequently, a supernova core with 1.5 - 2 solar masses will collapse into a black hole rather than form a neutron star [7]. The authors claim that a prominent example for this scenario is Supernova 1987A. Recently, Brown and coworkers analyzed antikaon yields measured in Ni+Ni collisions at 1.8 AGeV [33]. They extracted from the data the density dependence of the effective mass of the antikaon and predicted $K^-$ condensation in neutron stars above 3 times saturation density $\rho_0$ [40].

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