Kaon production at subthreshold and threshold energies

Jörg Aichelin* and Christoph Hartnack
SUBATECH
Université de Nantes, EMN, IN2P3/CNRS
4, Rue Alfred Kastler, 44070 Nantes Cedex 03, France

We summarize what we have learnt about the kaon production in nucleus-nucleus collisions in the last decade. We will address three questions: a) Is the $K^+$ production sensitive to the nuclear equation of state? b) How can it happen that at the same excess energy the same number of $K^+$ and $K^-$ are produced in heavy ion collisions although the elementary cross section in pp collisions differs by orders of magnitudes? and c) Why kaons don’t flow?

I. IS THE $K^+$ PRODUCTION SENSITIVE TO THE NUCLEAR EQUATION OF STATE?

Already in the eighties it has been observed in theoretical calculations \cite{1} that the total $K^+$ production cross section at subthreshold or threshold energies in collisions of heavy ions depends on the nuclear equation of state (EOS). This has been confirmed in the mean time by many other groups. For light ions such an observation could not be made. Therefore it was suggested that the ratio of the production yield of $K^+$ in heavy and that in light systems can serve as a signal for the nuclear EOS.

Motivated by the fact that $K'$s are Goldstone bosons it has been assumed in these calculations that their mass does not change in a nuclear environment. Following earlier suggestions \cite{2} it has been further assumed that they are created in the baryonic reactions

$$B + B \rightarrow \Lambda + K^+ N$$

where B is either a nucleon or a $\Delta$. At the energies considered the pionic channel is negligible.

Detailed studies have revealed that this dependence on the EOS can be easily understood. The softer the EOS the higher is the average density the nuclear system reaches in central collisions. As a consequence the mean free path becomes shorter and therefore collisions are more frequent. This effect is even amplified in the case of the $\Delta$: If the density increases the chance that a $\Delta$ has a collision with another baryon before it disintegrates becomes higher.

For the standard soft and hard EOS’s \cite{3,4} the $K^+$ yield differed by a factor of two and hence it seemed possible to achieve an experimental determination of the nuclear equation of state. However, the calculations were plagued by the poor knowledge of the elementary cross sections (eq.1) of which at the relevant energies not even the order of magnitude was known experimentally. Theoretical calculation have just started to be advanced at that time \cite{7}.

In the mean time, thanks to an intensive program at COSY \cite{5,6} the $pp \rightarrow \Lambda K^+ N$ and $pp \rightarrow \Sigma K^+ N$ cross sections close to the threshold have been measured. Although the relative ratio

*invited speaker
of both is not yet understood, as far as $K^+$ mesons are concerned this is of no importance. The problem is, however, how to extrapolate the cross section to np and nn reactions. Depending on whether a kaon or a pion is exchanged between the nucleons the isospin coefficients differ up to a factor of 2. The cross section including a $\Delta$ in the entrance channel have been calculated theoretically \[8\]. They await an experimental confirmation in pA and $\pi$A experiments. Also the $\pi B \rightarrow \Lambda(\Sigma)K^+$ cross section is understood now theoretically \[9\]. Using these cross sections the simulation programs reproduce the experimental excitation functions. However the error bars due to the uncertainties of the elementary cross sections are still large. It is this incertitude which limits presently the predictive power of the simulation programs for heavy ion reactions, as we will see later.

Parallel to the experimental and theoretical investigation of the elementary reaction cross sections detailed studies on the behavior of kaons in the medium have been advanced \[10\]. Today very different approaches ( based on the chiral perturbation theory \[11\], on the Nambu-Jona-Lasinio model \[12\] and on a coupled channel approach \[13\] ) result almost in the same modification of the $K^+$ mass in a nuclear environment as we can see in fig.1. We see also that for moderate densities the mass of the $K^+$’s change about linearly with the density.

The mass of the $K^+$ increases by about 35 MeV per density unit whereas that of the $K^-$ decreases with about the same amount.

Despite of its smallness the change of the mass of the $K^+$’s in a nuclear environment has rendered the kaons useless for a experimental determination of the EOS \[14\]. The larger collision frequency for a soft EOS is counterbalanced by a larger threshold due to a larger kaon mass and consequently by a smaller production cross section. The small differences which are still observed in the simulation programs between a soft and a hard EOS are too small in order to
surmount the uncertainties imposed by the limited knowledge on the elementary cross section.

How the change of the kaon mass in medium and the incertitude of the elementary cross sections influence the kaon yield obtained in the simulation programs for heavy ion collisions is shown in fig. 2 and 3, see as well\textsuperscript{[15]}. In fig. 2 we compare the rapidity distributions measured by the FOPI\textsuperscript{[17]} and the KAOS\textsuperscript{[20]} collaborations with several IQMD calculations\textsuperscript{[4]} using a different description of the kaons in the medium. In the No Pot calculations it is assumed that the properties of the kaons are not modified in the medium. The other three calculations refer to the change of the kaon mass as displayed in fig. 2. In fig. 3 we have exchanged our cross section set ($\sigma$ Nan) for the kaon producing channels by the that of the Giessen group ($\sigma$ GI)\textsuperscript{[16]} in the otherwise unchanged time evolution of the IQMD approach. We see a change of about 30\% of the $dN/dy$ at midrapidity, which is solely caused by the different cross section parametrisations. This can be verified by a comparison with the results published by the Giessen group (fig. 5.5 of ref.\textsuperscript{[10]}). For the same kaon production cross section both calculations agree quantitatively. This shows that the overall dynamics of the heavy ion reactions is almost identical in these both completely independent simulation programs. One may therefore conjecture that it is well under control.

![FIG. 2. The rapidity distribution of $K^+$'s for Ni(1.93 AGeV) + Ni, central collisions, measured by the FOPI and KaoS collaborations as compared with the calculations for different kaon potentials](image)

![FIG. 3. The rapidity distribution of $K^+$'s for Ni(1.93 AGeV) + Ni, central collisions, measured by the FOPI and KaoS collaborations as compared with the calculations using different production cross sections](image)

**II. HOW CAN IT HAPPEN THAT AT THE SAME EXCESS ENERGY THE SAME NUMBER OF $K^+$ AND $K^-$ ARE PRODUCED ALTHOUGH THE ELEMENTARY CROSS SECTION IN PP COLLISIONS DIFFERS BY ORDERS OF MAGNITUDES?**

Three years ago the KAOS collaboration has confronted us with the fact that in Ni + Ni reactions $K^-$ and $K^+$ meson are produced with the same probability if the difference between the beam energy per nucleon and the production threshold is the same. This is very surprising
because the elementary cross sections $pp \rightarrow K^+\Lambda(\Sigma)N$ and $pp \rightarrow K^-K^+pp$ differ by several orders of magnitude close to the threshold as a function of $\sqrt{s} - \sqrt{s_{\text{thres}}}$. This puzzle has been resolved only recently. $K^-$ mesons produced at high density in initial $NN \rightarrow NNK^-K^+$ reactions have almost no chance to escape from the reaction zone without being absorbed. This is due to the strongly exothermic reaction $K^-N \rightarrow \Lambda(\Sigma)\pi$ which has an appreciable cross section. Hence the $K^-$ observed in the detector do not come from the initial collisions but are produced in the inverse reaction $\Lambda(\Sigma)\pi \rightarrow K^-N$ at low densities, where the mass change is negligible. Indeed, during the expansion an equilibrium is built up in this reaction channel. This secondary interactions are absent in the $K^+$ channel. Consequently, the variable $\sqrt{s} - \sqrt{s_{\text{thres}}}$ which make reference to the $NNK^+K^-$ channel is not relevant at all and the agreement of the kaon yields at the same excess energies has to be considered as accidental.

Fig. 4 displays the influence of the in medium properties of the kaons on the observed $K^-$ yield where the spectra obtained for the systems C+C, Ni+Ni and Au+Au at different energies are compared to data from the KaoS collaboration [22]. We observe the largest cross section if the kaons have their free mass (NoPot). This is astonishing. One could believe that the reduction of the $K^-$ mass in the medium increases the $K^-$ yield because the threshold is lower. This is true of course but this effect is counterbalanced by a strong decrease the $\Lambda(\Sigma)\pi$ because less $K^+$'s are produced if the mass of the $K^+$ increases in the medium. Independent of how the kaon mass is modified in the medium (see fig. 2) the final $K^-$ yield is identical in between the error bars as long as the $K^+$ masses are not changed. This is due to the fact that the finally observed $K^-$'s are created at low density where the mass differences are small.
III. WHY DON’T KAONS FLOW?

The in-plane flow of kaons [17] has gained in the past a lot of interest because it is very small (as compared to that of the protons) and it was claimed that its observation allows a distinction between a vector potential and a scalar potential of the kaons [18]. It is, however, not evident what one can learn from separating vector and scalar potential because both are large and have opposite sign and only both together describe the behavior of kaons in the medium. The interesting quantity to look at is the comparison between the in-plane flow with and without interaction of the $K^+$ with the nuclear medium. This effect is quite small.

Much more interesting is the question why the in-plane flow $K^+$’s is that small, a phenomenon which has been also addressed by the AGS collaborations. Being produced in the elementary pp collisions the in-plane velocity of the $K^+$ should equal that of the protons or $\Lambda$’s. This is obviously not the case. There are two reasons [19]: 1) Nucleons which pass the high density zone (where the $K^+$’s are dominantly produced) have only half of the in-plane flow observed by averaging over all nucleons. This explains why the $\Lambda$ in-plane flow is only half of that of the protons. 2) In addition, the three body phase space distribution places the $K^+$’s at rapidities which are far from the rapidity of the source which determines the in-plane flow. Hence at a given rapidity kaons come from very different source rapidities and hence have very different in-plane flows. The negative and positive contributions cancel almost and renders the net flow small.

IV. PERSPECTIVES FOR AGS AND SPS

We have discussed three major results obtained in the last years in the field of kaon production close to threshold energies. Which relevance have these results at higher energies, at the center of interest of this conference? I see three perspectives for heavy ion collisions at higher energies: A) The search for the kaon flow and the hope to learn something about the properties of the surrounding matter is, as we have learnt, a hot topic as well at AGS energies. There the theoretical challenge is much larger in view of the many mesons and resonances produced in the reaction. Also the puzzle that different particles show a different in-plane flow continues into this energy domain and the presented results at lower energies may help for an understanding. B) We have seen that the kaon production close to threshold can only be described by simulation programs if one assumes that the masses of the kaons change in the medium. Otherwise we miss the experimental cross sections by about a factor of 2. The simulation programs for SPS and AGS energies presented at this conference like URQMD or NEXUS are able to reproduce quantitatively the observed spectra without invoking mass changes. This is very puzzling because the density obtained at AGS or SPS is still higher than that seen at SIS. C) We have learnt that from these threshold energies up to the highest energies available today the yield of particles, and especially that of the kaons, can be well described in thermal or statistical models [20]. This is very puzzling because at these low energies the rapidity distribution of kaons is incompatible with the assumption of thermal equilibrium. If this is not only an accident the reactions at threshold energies which are much easier to access theoretically may be useful to understand the physics behind this observation.
[1] J. Aichelin and C.M. Ko, Phys. Rev. Lett. 58 (1987) 1926
[2] J. Randrup and C.M. Ko, Phys. Phys. A343 (1980) 519; A411 (1983) 537
[3] J. Aichelin, Phys. Rep. 202, 233 (1991)
[4] C. Hartnack et al. Eur. Phys. J. A 1 (1998) 151
[5] J.T. Balewski et al., Phys. Lett B420 (1998) 211.
[6] S. Sewerin et al., Phys. Rev. Lett. 83 (1999) 682.
[7] J. M. Laget, Phys. Lett B259 (1991) 24
[8] K. Tsushima et al., Phys. Rev. C59 (1999) 369
[9] K. Tsushima et al., Phys. Lett. B337 (1994) 245; J. Phys. G21 (1995) 33
[10] J. Schaffner et al., Nucl. Phys. A625 (1997) 325
[11] T. Waas et al., Phys. Lett. B365 (1996) 12; B379 (1996),34
[12] R. Nebauer, Thesis, University of Nantes (2000)
[13] J. Schaffner-Bielich et al. Nucl. Phys. A669 (2000) 153
[14] C. Hartnack and J. Aichelin, Proceedings of the International Workshop XXVII on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria, January 2000, edited by M. Buballa et al.
[15] P. Crochet, proceedings of this conference
[16] W. Cassing and E. Bratkovskaja, Phys. Rep 308 (1999) 65
[17] J.L. Ritman et al., Z. Phys. A352 (1995) 355
[18] G.Q.Li and C.M. Ko Nucl. Phys. A594 460
[19] C. David et al, Nucl. Phys. A650 (1999) 358
[20] H. Oeschler, Proceedings of this conference and KaoS coll. accepted in PLB
[21] C. Sturm et al, GSI Jahresbericht 1998, p. 51
[22] F. Laue et al, Phys. Rev. Lett 82 (1999) 1640