Nuclear matter properties from subthreshold kaon production

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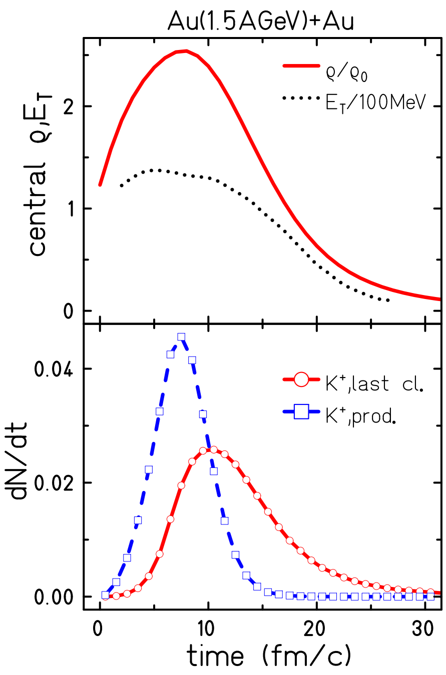
Abstract
The stiffness of the hadronic equation of state has been extracted from the production rate of K^+ mesons in heavy ion collisions around 1 A GeV incident energy. The data are best described with a compression modulus K around 200 MeV, a value which is usually called "soft". This is concluded from a detailed comparison of the results of transport theories with the experimental data using two different procedures. Furthermore we discuss the idea of determining the optical potential of kaons in the nuclear medium from the analysis of the low energy behaviour of K^0.

1 Introduction

The quest for extracting the nuclear equation of state (eos) from heavy ion collision has already a long history - as a non-exhaustive list of examples we refer to [1–6]. In this contribution we want to focalize on the aspect of the production of kaons in heavy ion collisions at incident energies below the elementary threshold. For this purpose we use the Isospin Quantum Molecular Dynamics Model (IQMD) as described in [7–9]. IQMD is a semiclassical model with quantum features propagating nucleons, deltas, pions, kaons and hyperons by use of two- and three-body interactions. This allows the description of a nucleus-nucleus interaction on the N-body level on an event-by-event basis.



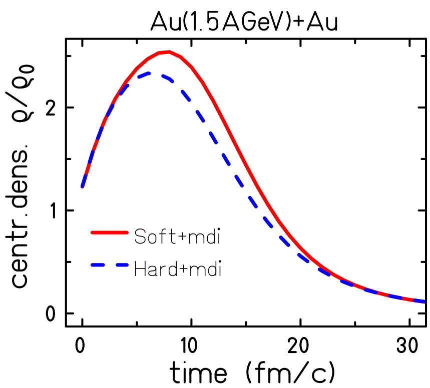


Fig. 1: Left: time evolution of the central density, the transverse energy (upper part) and distribution of the times when kaons have been produced and when they underwent their last collisions. Right: central density for a hard and a soft equation of state

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Figure 1 shows the time evolution of a central Au+Au collision at 1.5 AGeV incident energy. On the left side we see in the upper part the evolution of the central density (full line) and of the central transverse energy (dashed line, scaled to units of 100 MeV). We see that at times of about 8 fm/c the system reaches its maximum in density and "temperature" to decrease afterwards. The bottom part on the left side shows the distribution of the times when the kaons are produced (dashed line) and when they undergo their last collision with the nuclear medium (full line). We see that the maximum of the distribution of the production times coincidences with the maximum of the central density. Therefore we can assume a correlation of the kaon production with the phase of highest density. This assumption has already been discussed in [10–12]. The time of last contact (full line) shows its maximum at later times when the densities already decrease. Therefore the cinematical properties of the kaons might be less related to the high density properties of the nuclear matter.

The right side shows the influence of the nuclear equation of state on the time evolution of the densities. We see that a soft eos (full line) yields higher densities than a hard eos (dashed line). This is related to the weaker repulsion of the soft equation of state which resists less to the compression due to the inertial confinement.

2 The relation of the kaon yield to the equation of state

Figure 2 demonstrates the relation of the production of kaons to the density. On the left side we see the distribution of densities (normalized to the ground state density ρ_0) where the kaons have been produced. We see that most kaons stem from densities around twice normal nuclear matter density. A soft eos (full line) reaches not only higher densities than a hard eos (dashed line) but also higher total yields. This can be understood by the following processus: the kaons need very much energy to produce a kaon. Since the energy available in the very first collsions are not sufficient (the incident energy is below the elementary threshold) the energy has to be cumulated during several collisions. An ideal tool of cumulating energy is the production of resonances, like the Δ. However, since these resonance are instable, the next collision has to take place before the decay of the resonance. This requires a short mean free path and thus a high density. Since the maximum density is related to the nuclear equation of state, the yield of the kaons are also related to the eos.

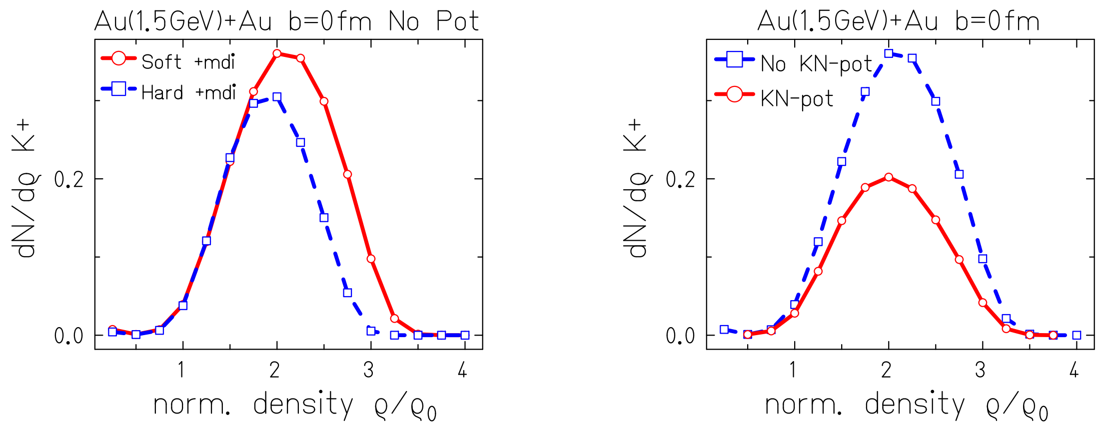

Fig. 2: Distribution of the densities at which the kaons have been produced. Left: influence of the eos, right: influence of the optical potential

However, we should also mention that the optical potential of the kaon in medium enhances its production threshold and therefore penalizes the production at high densities. This can be seen on the right side of figure 2 where we compare the production of kaons in a calculation where we do not apply an optical potential (dashed line) to a calculation with an optical potential (full line). We see a strong decrease of the yield caused by the optical potential.

The optical potential applied is a parametrization to RMF-results of Schaffner-Biellich [13] shown as full line in figure 3, which presents the energy necessary to produce a kaon at rest. It should be noted that for the graph in figure 3 the nuclear medium is also assumed to be at rest, otherwise momentum dependent interactions will alter that energy. The upper branch shows the energy necessary to produce a kaon (like K^+), the lower branch that for producing an antikaon (like K^-). We see that the nuclear medium penalizes the production of kaons at high densities while the production of antikaons is favored.

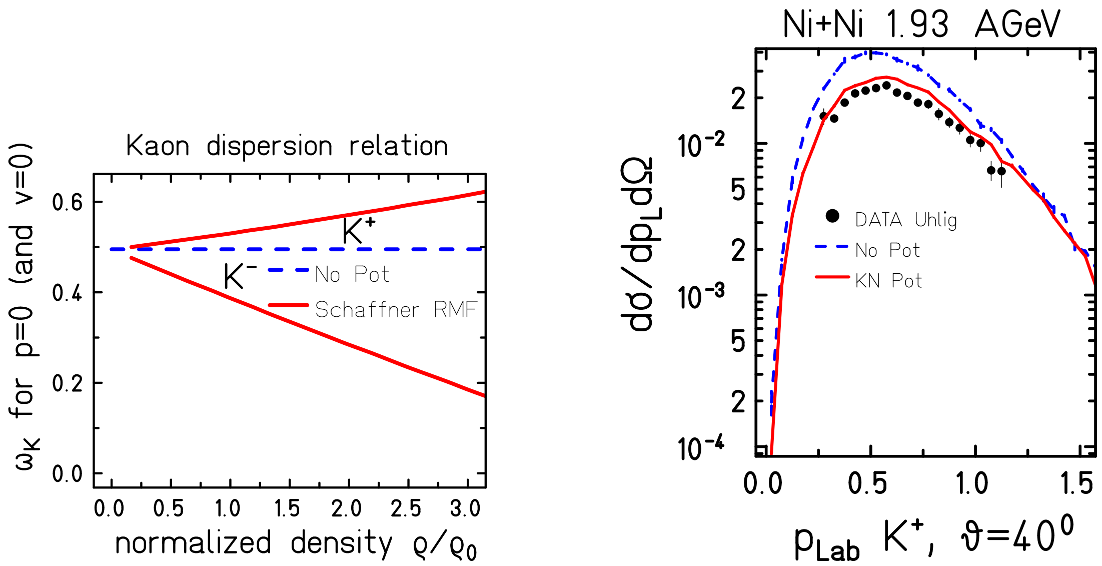

Fig. 3: Left: kaon dispersion relation used in IQMD, right: influence of the optical potential on the lab momentum spectra in Ni+Ni collisions at 1.93 AGeV

The right hand side of figure 3 compares IQMD calculations for Ni+Ni at 1.93 AGeV with an optical potential (full line) and without an optical potential (dashed line) to experiments performed by the KaoS-collaboration [14]. We see that the experiment seems to favor the calculation with an optical potential. However, we should take this result with caution: since the major channel of kaon production (which is the two step process of first producing a Δ in an inelastic NN-collision and afterwards producing a hyperon-kaon pair in a $N\Delta$-collision) has no experimental accessible cross section, there is range for assumptionss of this cross section. In [15] it was reported that the experimental data could also be described without an optical potential when assuming another cross section.

In IQMD we use the NN cross sections of Sibirtsev [16] and the $N\Delta$ cross sections of Tsushima [17], a choice which is also taken by other models like HSD [18]. However, other propositions are possible, for instance taking the Δ as a heavy nucleon and assuming $\sigma(N\Delta) = 0.75\sigma(NN)$ (the factor 0.75 comes from the possible combination of different charges allowing to produce a kaon). Due to these incertainties a direct comparison of experimental yields to calculations is not conclusive.

For this reason it has been proposed to use the ratio of the yields of the kaon production in a heavy system (like Au) to the production in a light system (like C) to extract more conclusive information [19, 20]. Since the light system shows no compression effects the incertainties of the cross sections may cancel but the effect of the eos may remain. The comparison of RQMD calculations [20] to experimental KaoS data [19] favored significantly a soft eos. This finding is supported by IQMD calculations, although IQMD and RQMD report differeces in the absolute kaon yield.

Figure 4 demonstrates that indeed the effects of unknown cross section (left side) and of the optical potential (right side) are strongly reduced with respect to the effect of the equation of state. A soft eos (full lines) is more compatible to the experimental data (bullets) than a hard eos (dashed lines). It should be noted that the different cross section parametrizations used on the left side ($N\Delta$ cross sections from

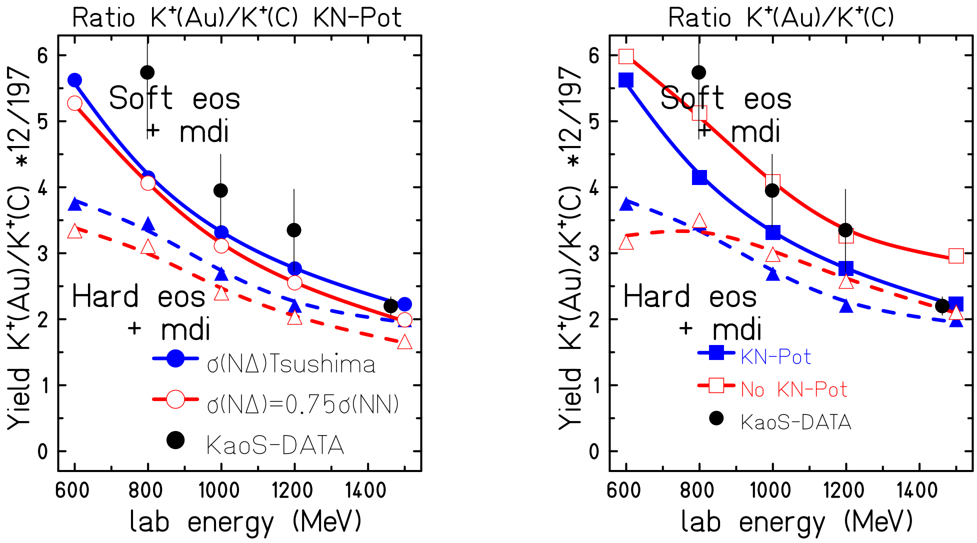

Fig. 4: Excitation function of the ratio of the kaon yields of Au+Au over C+C compared to experimental data from KaoS. Left: influence of different cross section assumptions, right: influence of the optical potential

Tsushima versus the assumption that $\sigma(N\Delta) = 0.75\sigma(NN)$) were those parametrizations which caused some puzzling on the comparison to experimental data. In comparison to experimental data of KaoS and FOPI the parametrization using the Tsushima cross section concluded the existence of an optical potential while the conclusion of the calculations using the other parametrization was the non-existence of that potential [15].

It should also be noted that this analysis has been extended to other parameters that may influence the kaon yield (Δ lifetimes, stopping of the nucleons) and that this ratio was found to be robust: it always favors a soft equation of state.

One can refine this method by analysing the Au/C in calculation using different compression modulus K: a small value of around 200 MeV corresponds to a soft equation of state while a high value around 380 MeV corresponds to a hard eos. On the left side of figure 5 we see the value of the Au/C ratio as a function of the compression modulus K for incident energies of 1.0 AGeV (top) and 0.8 AGeV (bottom) compared to band given by the experimental error. We see that we need a compression modulus of $K < 250 - 300$ MeV to become compatible to the experimental data. This corresponds to a soft eos.

There is also another method to extract information on the nuclear equation of state: if we look on the centrality dependence of the kaon yield we can trace a relation between the kaon yield (scaled by the participant number in order to get flatter curves) and the participant number (related to the centrality). A high participant number denotes a central event, a low participant number characterizes a peripheral event. The kaon yield can be related to the participant number by the relation

$$M_K = M_0 \cdot A_{\rm part}^{\alpha} \tag{1}$$

where α corresponds to the slope of the graph in the double logarithmic representation on the upper right side of figure 5. We see that although different calculations using a soft eos (dotted/dashed lines) show differnt M_0 and thus different yields, their slope parameter α is similar. However a calculation with a hard eos (full line) does not change very much M_0 but yields a much smaller slope α.

The lower right side of figure 5 now compares the experimental value the slope factor α to those obtained with calculations using a different compression modulus K. Again we see constraints of $K < 250$ MeV, i.e. a claim for a soft eos. It should be noted that a similar analysis can be applied on inclusive reactions by using the system size of the reaction partners instead of the participant number. The results are consistent with the analysis of the participant number and the conclusion is quite the same.

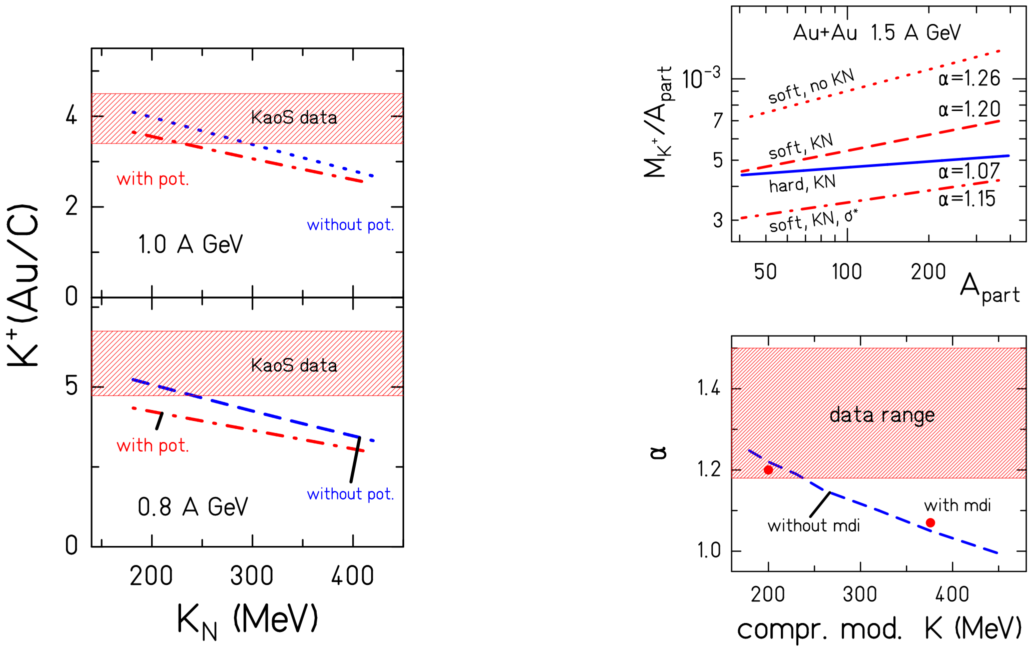

Fig. 5: Constraints on the compression modulus from KaoS data Left: comparison of the Au/C ration for 1.0 and 0.8 AGeV, right: participant number scaling at 1.5 AGeV

3 The kaon nucleon optical potential

Let us now turn to the analysis of kaon spectra. Figure 6 shows on the left side a comparison of Au+Au spectra at different centralities: the data of the KaoS collaboration [21] agree quite well to IQMD calculations performed with a soft eos and KN optical potential. This comforts our conclusion from the centrality analysis in figure 5. Furthermore we should note that the slopes of the spectra and thus the temperatures of the kaons are quite comparable. In order to make the figure more visible the spectra have been scaled by powers of 10 (for the experiment and the calculation).

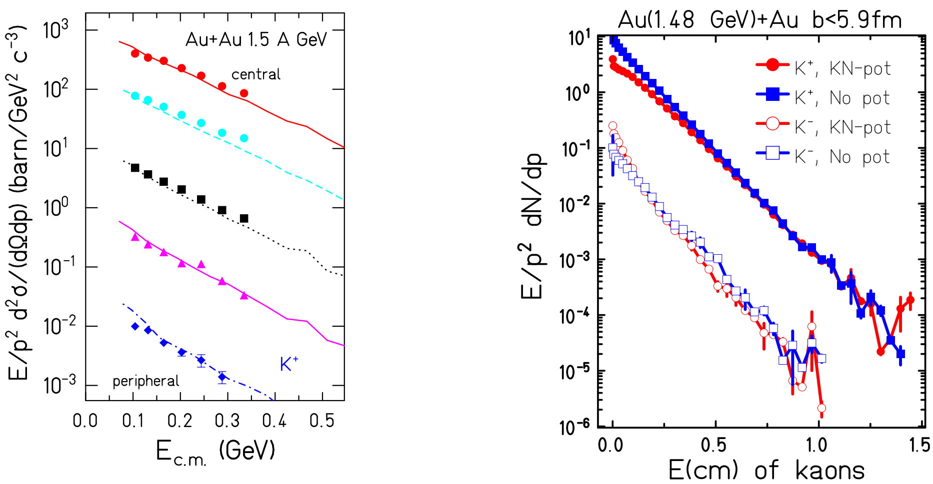

Fig. 6: Kaon spectra of Au+Au at 1.48 AGeV. Left: comparison of the centrality dependence of the K^+ spectra with data, right: influence of the optical KN-potential on the spectra of K^+

The right side of figure 6 shows the influence of the optical potential on the spectra of kaon (filled symbols) and antikaons (open symbols) where the calculation without potential are marked with squares and the calculations with potentials by circles. We see that the KN-potential lowers the spectra of K^+ at low energies while the spectra of low-energy K^- are enhanced. The high energy parts show no significant influence of the KN-potentials. The spectra at high energies are dominated by kaons which underwent several collisions with the nuclear medium [22]. They give information rather about the expanding medium than about the optical potential. However, the potential may give an extra-push to the leaving kaons which is repulsive for kaons and attractive for antikaons. Since this effects the low energy kaons stronger than the high energy kaons this may yield some differences in the final temperatures of kaons and antikaons which may be related to the KN optical potential [23].

Since the KN-potentials effect the low energy part significantly, but the high energy kaons quite weakly, a comparison of low and high energy kaons may yield information on the KN optical potential.

However, acceptance problems do not allow actually to get low energy K^+ from KaoS or FOPI experiments. First analysis of low energy K^0 measured by FOPI in Ni+Ni at 1.93 AGeV seem to favor a calculation with KN-potentials [24].

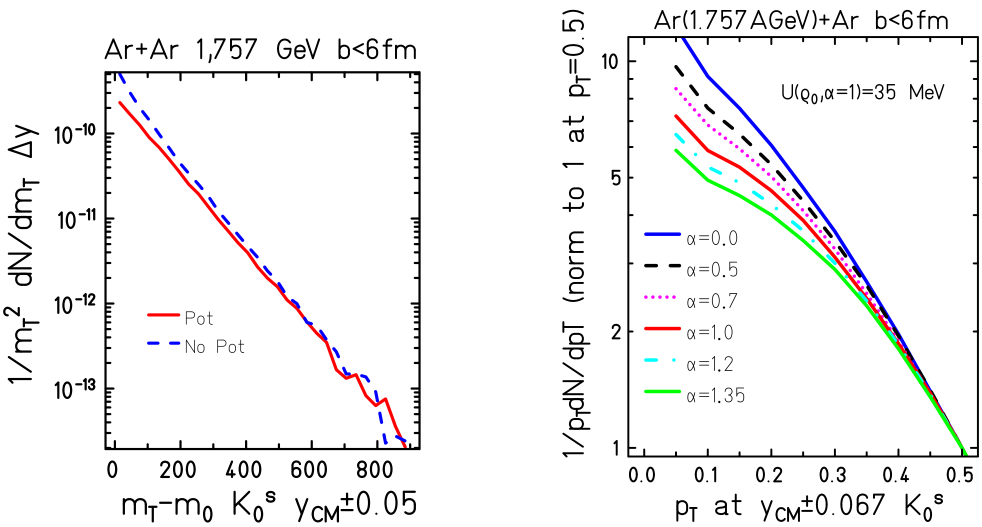

Fig. 7: Kaon spectra of Ar+KCl at 1.757 AGeV. Left: influence of the optical KN-potential on the m_T-spectra of K^+, right: p_T spectra normalized to 1 at $p_T = 0.5$GeV/c.

However, recent experiments of the HADES collaboration may shine new light on this subject. They analysed low m_T K^0 at midrapidity in Ar+KCl collisions at 1.757 AGeV. First comparisons to IQMD calculations seem also to favor a calculation with the KN-optical potential [25].

Figure 7 shows on the left side the m_T spectra of K_s^0 at midrapidity calculated with IQMD. The calculation with optical potential (full line) yields less low energy kaons than the calculation without an optical potential (dashed line).

The right side shows the effect of the potential in more detail: we divide the p_T spectrum at midrapidity by the value obtained at p_T=0.5 GeV/c (i.e. we normalize the graph to be 1 for $p_T = 0.5$GeV/c) and compare calculations where we modify the potential parameter by a factor α. $\alpha = 1$ corresponds to our standard calculation with potential, $\alpha > 1$ yields a stronger potential and $\alpha < 1$ a weaker one. $\alpha = 0$ corresponds to a calculation without an KN optical potential. We see that an enhancement of the potential strength yields a reduction of K^0 at low p_T.

A similar analysis is presented in figure 8 where we do the same analysis for the systems of Ag+Ag at 1.65 AGeV (left) and Au+Au at 1.25 AGeV (right). Again we see a visible effect of the KN optical potential. It will be task of further analysis to determine wheth er the significance of that effect is

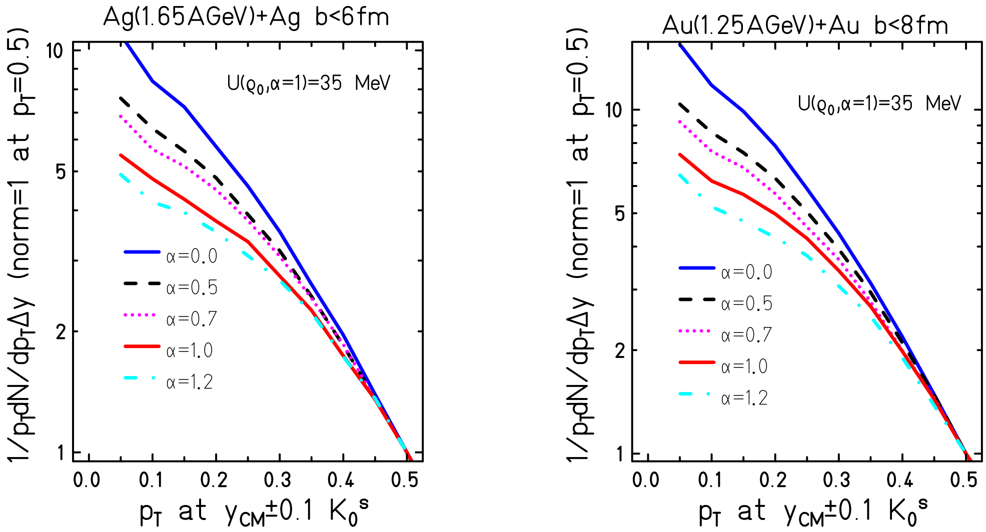

Fig. 8: p_T spectra normalized to 1 at $p_T = 0.5$GeV/c: Left: Ag+Ag at 1.65 AGeV, right Au+Au at 1.25 AGeV

sufficient to get quantitative information on the KN optical potential.

4 Conclusion

We analyse the production of kaons in heavy ion collisions. We find that the analysis of scaling laws like Au/C or A^{α}_{part} give very robust results and raise evidence for a soft nuclear equation of state. The anlaysis of the low energy tail of midrapidity kaons may help us to get further information on the optical potential of kaons in the nuclear medium. First preliminary results favor the existence of such a potential.

5 Acknowledgement

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