What Determines the K^- Multiplicity at Energies Around (1–2)A GeV?

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In heavy ion reactions at energies around (1–2)A GeV the measured K^- yields appear rather high as compared to pp collisions as shown by the KaoS Collaboration. Employing quantum molecular dynamics simulations, we show that this is caused by the fact that the dominant production channel is not $BB \to BBK^+K^-$ but the mesonic $\Lambda(\Sigma)\pi \to K^-B$ reaction. Because the Λ (Σ) stem from the reaction $BB \to \Lambda(\Sigma)K^+B$, the K^+ and the K^- yield are strongly correlated, i.e., the K^-/K^+ ratio occurs to be nearly independent of the impact parameter as found experimentally. The final K^- yield is strongly influenced by the K^+N [due to their production via the $\Lambda(\Sigma)$] but very little by the K^-N potential.

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A while ago the KaoS Collaboration published results on the K^- and K^+ production in Ni + Ni reactions at 1.8A GeV and 1.0A GeV, respectively [1], which came as a surprise: As a function of the available energy, i.e., $\sqrt{s} - \sqrt{s_{\text{threshold}}}$ (where $\sqrt{s_{\text{threshold}}}$ is 2.548 GeV for the K^+ via $pp \to \Lambda K^+ p$ and 2.870 GeV for the K^- via $pp \to ppK^+K^-$) the number of K^- produced equals that of K^+ although in pp reactions close to threshold the cross section for K^+ production is orders of magnitude higher than that for K^- production. In addition, the K^- have a high probability for absorption via $K^-N \to \Lambda\pi$, whereas the K^+ cannot get reabsorbed due to its $\bar{s}$ content. Even more astonishing was the experimental finding that at incident energies of 1.8A GeV and 1.93A GeV the K^- and K^+ multiplicities exhibit the same impact-parameter dependence [1–3] although the K^+ production is above the respective NN threshold while the K^- production is far below. Equal centrality dependence for K^+ and K^- was also found at AGS energies [4]. All these observations have triggered a lot of activities [5,6].

It is the aim of this Letter to show that these observations have a simple explanation. For this purpose we use isospin quantum molecular dynamics (IQMD) simulations. The details of the IQMD approach have been published elsewhere [7]. Here we have introduced in our standard simulation program a (density-dependent) KN potential. We use the results of the relativistic mean field (RMF) calculation of Schaffner [8] which gives the same result as more sophisticated approaches such as the chiral perturbation theory or the Nambu-Jona-Lasinio Lagrangian. The relativistic mean field shifts the masses of the particles in the medium. Because this mass shift is applied to the phase space as well as to the flow, detailed balance in the production cross sections is conserved. We have supplemented our calculation as well by all revelant cross sections for kaon production and annihilation. The added cross sections are either parametrizations of the experimentally measured elementary cross sections or are based on one-boson-exchange calculations if measured cross sections are not available. The kaons are treated perturbatively. This means that in each collision with a sufficient center of mass energy there is a kaon produced with a probability given by the relative ratio $\sigma(NN \to K^+ + X)/\sigma_{\text{tot}}$. The final momenta of the nucleons, however, are calculated under the assumption that no kaon has been produced. If the kaon-nucleon potentials are switched on we assume that the inmedium cross section and the free cross section agree for the same relative momentum between the scattering partners.

The strange baryons Σ and Λ are treated as one particle and in the text we use only Λ which stands for both particles. The potential $U_{\Lambda N}$ is taken as 2/3 of U_{NN}. This yields a very good description of the K^+ and Λ production in these heavy ion collisions [9]. We have performed the calculations for the reactions Au + Au and $C + C$ at 1.5A GeV incident energy. This energy has been chosen because data on K^- and K^+ for three different systems are available [3] or will soon become available.

Figure 1 displays the production and absorption rates (top panel) of the K^- as well as the integrated number of produced K^- and the actual number of K^- present in the system as a function of time (middle panel) for two production channels $\pi\Lambda \to K^-B$ [10] and $BB \to BBK^+K^-$ where B is either a nucleon or a Δ. The third production channel $\pi B \to BK^+K^-$ has qualitatively the same structure as the BB channel. On the left (right) hand side we display the results for central reactions ($b = 0$) at 1.5A GeV for Au + Au (C + C) collisions. For reasons which we will discuss later, the K^- yields are divided by the final number of K^+. In the bottom panel the density, the number of free pions, and the number of K^+ (both divided by the mass number A of one of the nuclei) are given as a function of time. For both targets $\pi\Lambda \to K^-B$ is the dominant K^- production channel. The K^- from the BB channel are produced in the high-density phase and earlier than those from the $\pi\Lambda$ channel because the Λ

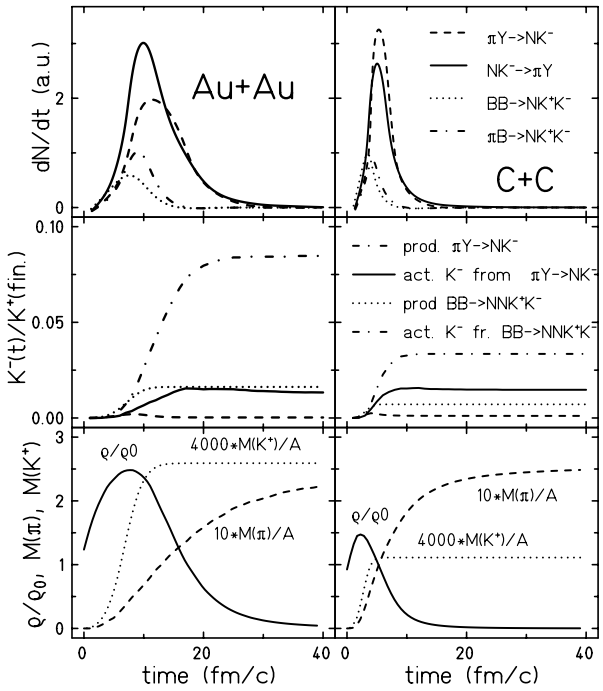

FIG. 1. Time evolution of rates and multiplicities for central collisions of Au+Au (left) and C + C reactions at 1.5A GeV incident energy. Top panel: rates for the production and absorption channels for K^-. Middle panel: Integrated number of produced K^- and the actual number of K^- (production minus absorption) present at time t for different K^- production channels (normalized to the final number of K^+). Bottom panel: Number of free pions/A and of K^+/A (with A the mass number of one collision partners) and the central density as a function of time.

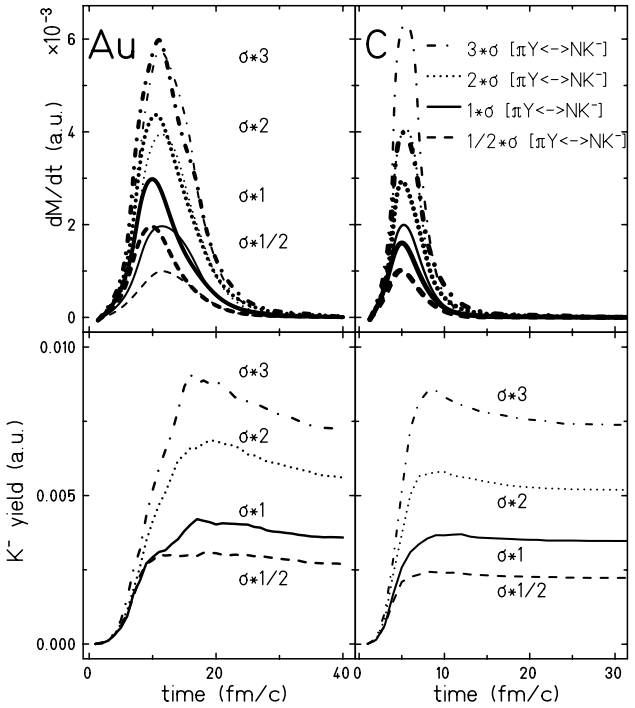

FIG. 2. Top panel: The rates for production (thin lines) and absorption (thick lines) of K^-. Bottom panel: The net number of K^- in the system. The effective cross sections we used in the calculation are denoted by $\sigma_{\text{eff}} = n\sigma_{\text{exp}}$ with n being a multiplication factor. On the left (right) hand side central Au+Au (C + C) reactions are shown, both at 1.5A GeV.

have to be produced first in $BB \rightarrow \Lambda K^+ B$ collisions. At a later stage of the collisions the available energy in the BB and πB channels is not sufficient anymore to create kaon pairs. Produced early, the K^- from the BB and πB channels have a higher chance to be reabsorbed and finally almost all (more than 90%) of them have disappeared. Absorption of K^- is very high: in C+C (Au+Au) collisions about 50% (20%) survive. We like to note that the final number of K^- divided by the K^+ is equal in both systems despite of the fact the many more K^- are produced in the Au + Au reaction.

Next we study the balance between production and absorption of K^-. In the upper part of Fig. 2 we plot the rate of production and absorption of the K^- in the dominant $\Lambda\pi$ channel as a function of time. A large difference in the rates is seen at the moment when the system is very dense. There the K^- are produced via K^-K^+ pair-production as already shown in Fig. 1. Later, during expansion, the rates become very similar. Finally the rates separate again but now the rate for K^- absorption dominates. The K^- production approaches zero because for this endothermic reaction the energy in a $\Lambda\pi$ collision is not sufficient anymore but the exothermic absorption can still continue. This dominance of exothermic reaction is a very general phenomenon in expanding systems where the locally available energy decreases with time [11].

The fact that the rates in both directions are almost identical testifies that the system has reached an equilibrium. This may be a thermal equilibrium which is characterized by the fact that the particle yields depend exclusively on the temperature and the chemical potential. It may be as well a steady state which occurs, for example, if creation and absorption are strongly connected by a very short life time.

If the system is in thermal equilibrium an (artificial) increase of the cross sections does not change the particle number ratios (and hence also not the number K^-). It only brings the system faster to equilibrium. Therefore we can test whether thermal equilibrium is obtained by multiplying the cross section in the $\pi\Lambda$ channel by a constant factor n. From the top part of Fig. 2 we see that both, production and absorption, increase with n, but differently. The net numbers are given in the lower part of Fig. 2 showing that a larger cross section produces more K^-. Thus we can conclude that for $n = 1$ the system is not yet in (local) thermal equilibrium. This interpretation is supported by the observation that only few of the Λ make a K^- and that only a negligible number of those Λ, which are produced by K^-N collisions, produce another time a

K^-. Therefore there are too few collisions in this channel to produce an equilibrium.

Thus in the present situation we observe a steady state. Its origin is easy to understand if one realizes that close to the threshold due to flow and phase space the cross section of the dominant channel, $\pi\Lambda \rightarrow K^-N$, is very small as compared to that of the inverse reaction. If a K^- is produced its mean free path and hence its mean lifetime is short. It will be destroyed shortly after its creation with the consequence that the rate of production and annihilation are locked and identical. Only close to the surface the K^- has a chance to escape.

Next we study how the K^-/K^+ ratio depends on the impact parameter. The results of the IQMD calculations are presented in Fig. 3. For the standard parametrization ($n = 1$) we observe for Au + Au collisions a rather constant K^-/K^+ ratio for impact parameters smaller than 8 fm in agreement with the preliminary experimental results [3]. This has been considered as remarkable because both the K^+ as well as the K^- yield increase with decreasing impact parameter.

For a grand canonical ensemble this would be of no surprise. Even in the canonical approach where strangeness is strictly conserved a constant K^-/K^+ ratio is expected as the terms depending on the system size drop out [12]. Our microscopic calculation shows that this impact-parameter independence is not of thermal origin. We have already seen that the dominant reaction channel for the K^- is $\Lambda\pi \rightarrow K^-B$. Because the Λ is produced together with the K^+, the K^- production is directly coupled to the Λ density and hence to the number of K^+. The calculations show that the length of the trajectory of the Λ in matter does not change for impact parameters smaller than 8 fm. For larger impact parameters less K^- are produced, whereas the percentage of reabsorption remains still almost constant. The K^-/K^+ ratio depends on the number of pions present. The relation between the K^-/K^+ ratio and the pion multiplicity is visible between 1A GeV and 10A GeV [6]. Pions are present only in heavy ions reactions and therefore the reaction mechanism in pp reactions is completely different, where at this energy a K^- can only be produced together with a K^+. This explains why the experimental results are that different. Already for systems as small as C + C, however, the pion number is sufficient for the $\Lambda\pi$ channel to dominate the K^- production. The K^- production stops before the number of pions has reached its asymptotic value as can be seen in Fig. 1. Therefore, in the K^- production the pion and Δ dynamics is encoded as well. (Please note that we have not taken into account the small $\Lambda\Delta \rightarrow K^-X$ cross section [13].)

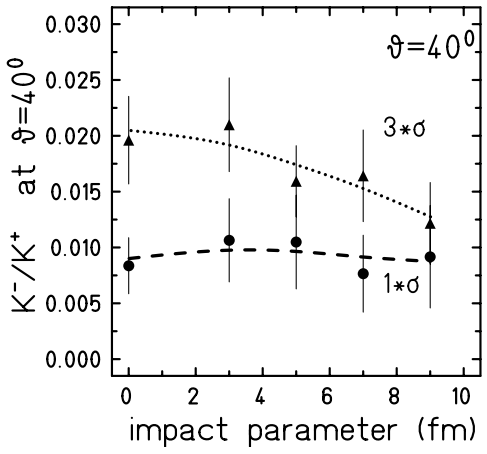

FIG. 3. Impact parameter dependence of the K^-/K^+ ratio in $\theta_{\text{lab}} = 40 \pm 4°$ for Au + Au collisions at 1.5A GeV. The effective cross sections used in the calculation are denoted by $\sigma_{\text{eff}} = n\sigma_{\text{exp}}$ with n being a multiplication factor.

Figure 3 exhibits another interesting feature: Increasing "artificially" the cross sections (for both production and absorption) by a factor of 3 one expects naively to get closer to the equilibrium condition, i.e., a constant K^-/K^+ ratio with impact parameter. However, the opposite is seen: the K^-/K^+ ratio drops towards peripheral collisions. There are two reasons for this effect. The first one is related to the increasing amount of spectator matter in peripheral collisions. In spectator matter K^- can only be absorbed but not produced. Increasing both cross sections, the effects of absorption becomes more pronounced leading to a decrease of the K^-/K^+ ratio for peripheral collisions. The second reason is connected with the expansion of the system. In an expanding system the locally available energy decreases as a function of time and therefore the endothermic reaction becomes suppressed. Therefore the system will run out of equilibrium during the expansion even if it has been in thermal equilibrium initially. This phenomenon we see for the case $n = 3$ where a larger K^- absorption is not compensated by a larger production.

Up to now we have studied the K^- production assuming that both the K^- and the K^+ have a mass as given by the relativistic mean field calculation [8]. These calculations are yet far from being confirmed by experimental results. It is therefore important to see how the predicted mass change of the kaons in the medium influences their multiplicity. The K^-N potential is attractive, leading to lower "in-medium" masses, while the K^+N potential is slightly repulsive. For this reason we study the time evolution of the K^- and K^+ yields under different assumptions on the KN potential: We compare the standard calculation (K^+:w, K^-:w; where w stands for "with potential") with those in which either the K^+N potential (K^+:w/o, K^-:w; where w/o stands for "without potential") or the K^-N potential (K^+:w, K^-:w/o) is switched off as well as with a calculation in which no KN potential is applied (K^+:w/o, K^-:w/o) and consequently the kaons have their free mass.

The result, shown in Fig. 4 (left) is evidence that the final K^- yield depends strongly on the K^+N potential but

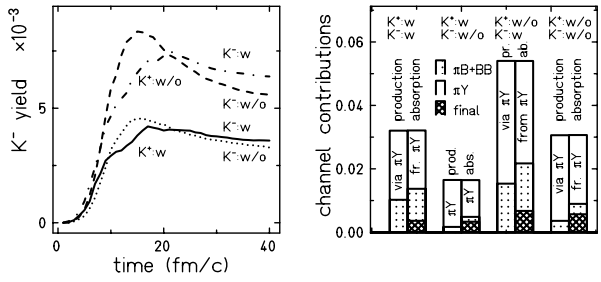

FIG. 4. Left panel: Influence of the $K^{+/-}N$ potentials on the final K^- yields for central Au + Au collisions at 1.5A GeV. We separately switch off (w/o) and on (w) the KN potentials for K^+ and K^-. For the two upper curves the K^+N has been switched off. Right panel: Production and absorption of the K^-: right hand column (from bottom to top) the production in BB collisions, πB collisions and $\pi\Lambda$ collisions, left hand column (from bottom to top) survival and absorption.

is almost independent on the K^-N potential. This has an easy explanation: the K^+N potential determines how many Λ are produced in the initial $BB \rightarrow \Lambda K^+ B$ reaction. This reaction takes place when the baryon density is high. The K^+N potential increases the "mass" of the K^+ and hence their production threshold and lowers therefore the Λ multiplicity. On the contrary, the mass change of the K^- has little influence on the result because the observed K^- are created very late by the mechanism described above and therefore at a density where the mass change due to the K^-N potential is small. Thus heavy ion reactions test the KN potentials at very different densities: The K^+N potential is tested around twice nuclear matter density, where the Λ and K^+ are produced, whereas the K^- potential is tested at low densities where it is small. The decrease of the K^- yield at the end of the reaction is exclusively caused by the (exothermic) absorption which still takes place but which is not counterbalanced by creation for which the available energy is too small.

The number of finally observed K^- is directly proportional to the number of Λ produced initially. This number is equivalent to the number of K^+. Therefore we have divided in Fig. 1 the K^- multiplicity by the K^+ multiplicity. We see in Fig. 1 that the ratio $M(K^+)/M(K^-)$ depends little on the system size [in distinction to $M(K^+)$].

In conclusion, we have given an interpretation of the experimental observation that (i) in heavy ion reactions the yields for K^- compared to K^+ is much higher than in pp collisions (compared at the same available energy with respect to their thresholds) and (ii) that the K^+/K^- ratio is independent of the impact parameter for semicentral and central reactions. The pair-production channel, which is the only channel in pp collisions, contributes in AA collisions only marginally to the finally observed K^- yield. Almost all K^- are produced by the pionic channel $\Lambda\pi \rightarrow K^- B$ which is not available in pp. Because the Λ is produced simultaneously with the K^+, the K^- and the K^+ production are strongly correlated. The naively expected impact-parameter dependence of the K^- yield due to absorption is not observed because creation and absorption occur at almost the same rate due to the large difference between the production and absorption cross section. Despite of the fact that thermal models predict [12] the K^- multiplicity and the impact-parameter independence of the K^+/K^- yield we observe in the simulations that both are determined by dynamical quantities like cross sections and by the locking of the K^- to the K^+. The systems are too rapidly expanding for reaching equilibrium in a channel which has a relatively small cross section. Furthermore, at the end of the expansion the cross section for the exothermic reaction is large due to the detailed-balance factors. This is a very generic phenomenon and not limited to the K^- production and leads the system to run out of equilibrium during expansion even if it had been in equilibrium before. The final yield of K^- depend on the K^+N potential (which determines how many Λ are produced initially) but does not depend on the K^-N potential because the observed K^- are produced very late at low densities where this potential is small.

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