What determines the $K^-$ multiplicity at energies around 1-2 AGeV?

Ch. Hartnack$^1$ H. Oeschler$^2$ and J. Aichelin$^1$

$^1$SUBATECH, Laboratoire de Physique Subatomique et des Technologies Associées
University of Nantes - IN2P3/CNRS - Ecole des Mines de Nantes
4 rue Alfred Kastler, F-44072 Nantes, Cedex 03, France

$^2$Institut für Kernphysik, Darmstadt University of Technology, D-64298 Darmstadt, Germany

In heavy ion reactions at energies around 1-2 AGeV the measured $K^-$ yields appear rather high as compared to pp collisions as shown by the KaoS collaboration. Employing Quantum Molecular Dynamics (IQMD)$^1$ simulations, we show that this is caused by the fact that the dominant production channel is not $BB \rightarrow BBK^+K^-$ but the mesonic $\Lambda(\Sigma)\pi \rightarrow K^-B$ reaction. Because the $\Lambda (\Sigma)$ stem from the reaction $BB \rightarrow \Lambda(\Sigma)K^+B$, 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. $K^-$ are continuously produced but also very quickly reabsorbed leading to an almost identical rate for production and reabsorption. 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 has published results on the $K^-$ and $K^+$ production in Ni+Ni reactions at 1.8 AGeV and 1.0 AGeV, respectively, [2] 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 $pp \rightarrow \Lambda K^+p$ and 2.870 GeV for the $K^-$ via $pp \rightarrow ppK^+K^-$) 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 $K^-N \rightarrow \Lambda\pi$, whereas the $K^+$ cannot get reabsorbed due to its $\bar{s}$ content. Even more astonishing was the experimental finding that at incident energies of 1.8 and 1.93 AGeV the $K^-$ and $K^+$ multiplicities exhibit the same impact parameter dependence [2–4] 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 [5]. All these observations have triggered a lot of activities [6] - [10].

It is the aim of this Letter to show that these observations have a simple explanation. For this purpose we use IQMD simulations. The details of the IQMD approach have been published elsewhere [1]. 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 [12] which gives, as shown in this paper, the same result as more sophisticated approaches like the chiral perturbation theory or the Nambu-Jona-Lasinio Lagragian. 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 as well our calculation by all relevant cross sections for kaon production and annihilation. The added cross sections are either parametrisations 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 \[ \frac{\sigma(NN \rightarrow K^+ + X)}{\sigma_{\text{tot}}}. \] 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 in-medium cross section and the free cross section agree for the same relative momentum between the scattering partners. Recently Lutz and al. [13] as well as Schaffner et al. [6,14] have calculated some of the relevant in-medium cross sections using a coupled channel approach for the t-Matrix. However, their results differ considerably and the former one is not adapted yet to simulation programs using spectral functions instead of quasi particles.

Therefore and because the physics discussed in this Letter depends only little on the transition matrix elements but predominantly on the mass difference between entrance and exit channel which does not change decisively in the medium we do not employ these improved cross sections here. It is sufficient to vary the experimental cross section by an artificial multiplication factor to see whether how the physics depends on the cross section.

The strange baryons $\Sigma$ and $\Lambda$ are treated as one particle and in the text we use only $\Lambda$ which stands for both particles. The potential $U_{AN}$ is taken as $2/3$ of $U_{NN}$. This yields a very good description of the $K^+$ and $\Lambda$ production in these heavy ion collisions [16]. Here we concentrate on an understanding of the $K^-$ production. We have performed the calculations for the reactions $Au+Au$ and $C+C$ at 1.5 AGeV incident energy. This energy has been chosen because data on $K^-$ and $K^+$ for three different systems are available [4] or will soon become available.
We start out by investigating in which channels the $K^-$ are produced and absorbed in the course of the reaction. 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

FIG. 1. Time evolution of rates and multiplicities for central collisions of $\text{Au+Au}$ (left) and $\text{C+C}$ reactions at 1.5 AGeV 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.
$K^-$ present in the system as a function of time (middle panel) for two production channels $\pi\Lambda \to K^-B$ and $BB \to BBK^+K^-$ where $B$ is either a nucleon or a $\Delta$. 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 1.5 AGeV 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. It has already been pointed out in ref. [7,11] that $K^-$ can also be produced in the strangeness-exchange channel $\pi\Lambda \to K^-B$ channel. Our calculation Fig. 1 shows that 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 $\Lambda$ have to be produced first in $BB \to \Lambda K^+B$ collisions. At a later stage of the collisions the available energy in the $BB$ and $\pi B$ channels is not sufficient anymore to create kaon pairs. Produced early, the $K^-$ from the BB and $\pi B$ channels have a higher chance to be reabsorbed and finally almost all (more than 90%) of them have disappeared. Therefore, the observed $K^-$ are essentially from the strangeness-exchange process. In this channel the rates of production and absorption after 15 fm/c are about equal in the Au+Au system and very similar in the C+C system. In general, absorption of $K^-$ is very high: in C+C collisions about 50% survive whereas in the Au+Au collisions this is only the case for less than 20% as can be seen from the middle part of Fig. 1. 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.
FIG. 2. Top panel: The rates for creation (thin lines) and absorption (thick lines) of $K^-$ 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 for absorption and production 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 inverse reaction can still continue. This difference of the rates in favor of the exothermic reaction is a very general phenomenon in expanding systems where the locally available energy decreases with time [17].

Next we study the balance between creation and absorption of $K^-$. In the upper part of Fig. 2 we plot the rate of absorption and production 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 for absorption and production 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 inverse reaction can still continue. This difference of the rates in favor of the exothermic reaction is a very general phenomenon in expanding systems where the locally available energy decreases with time [17].

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.

In view of this ambiguity it is useful to test whether the system has reached thermal
equilibrium: If it 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. However, changing the cross section by a factor of two changes the number of $K^-\) by 56 (42)% only in the Au+Au (C+C) system (and not by a factor of two). This interpretation is supported by the observation that only few of the $\Lambda$ make a $K^-\) and that only a negligible number of those $\Lambda$, 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. Rarely a $\Lambda$ produces a $K^-\). If it does, the mean free path and hence the mean lifetime of the $K^-\) is short. It will be destroyed shortly after its creation with the consequence that the rate of production and annihilation are identical. Only close to the surface the $K^-\) has a chance to escape. Thus we find here a system in equilibrium (in the sense that both rates are identical) but not in thermal equilibrium (in the sense that particle ratios are given by temperature, chemical potential).
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 [4] which confirm the independence already found in other systems [2,3]. This has been considered as remarkable because both, the $K^+$ as well as the $K^-$ yield increase with decreasing impact parameter.

If the system could be described as 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 [9]. This observation has triggered the conjecture that a chemical equilibrium is reached at these beam energies. Our calculation shows a microscopic understanding of this impact parameter independence. We have already seen that the dominant reaction channel for the $K^-$ is $\Lambda \pi \rightarrow K^-B$. Because the $\Lambda$ is produced together with the $K^+$, the $K^-$ production is directly coupled to the $\Lambda$ density and hence to the number of $K^+$. The calculations show that the length of the trajectory of the $\Lambda$ 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 1 and 10 AGeV [10]. Pions are only present 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 $\Delta$ dynamics is encoded as well. (Please note that we have not taken into account the small $\Lambda\Delta \rightarrow K^-X$ cross section [18].)

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, as discussed already in Fig. 2. At the same time, if the cross sections are very different for
the forward and backward reaction, the reaction with the larger cross section will continue for a much longer time. Close to threshold (where flux and phase space are quite different in both directions) both come together and therefore the system will run out of equilibrium during the expansion even if it has been in thermal equilibrium initially. Hence the final particle ratios will be defined by the cross sections. This phenomenon we see for the case \( n=3 \) where a larger \( K^- \) absorption which 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 [12]. 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 \( w \) stand for “with potential”) with those in which either the \( K^+N \) potential (\( K^+ : w/o, K^- : w \)) 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 is almost independent on the \( K^-N \) potential. This has an easy explanation: the \( K^+N \) potential determines how many \( \Lambda \) are produced in the initial \( BB \to \Lambda K^+B \) 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 \( \Lambda \) multiplicity. On the contrary, the mass change of the \( K^- \) has little influence on the result because the observed \( K^- \) are created very late in the reaction 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 \( \Lambda \) and \( K^+ \) are produced, whereas the \( K^- \) potential is tested at low densities where it is small. Furthermore, the final multiplicity of \( K^- \) does not depend on the \( K^-N \) potential because the two rates, production and absorption, both depending on the potential, balance each other almost completely as both rates depend on the \( K^-N \) potential. This can be seen from Fig. 4 (right) where the number of produced and absorbed \( K^- \) is displayed. As expected, the smaller mass of the \( K^- \) caused by the \( K^-N \) potential increases the rate (but in both directions by about the same amount). 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 \( \Lambda \) 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 \( M(K^+) \)).
FIG. 4. Left panel: Influence of the $K^+/N$ potentials on the final $K^-$ yields for central Au+Au collisions at 1.5 AGeV. 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, $\pi B$ collisions and $\pi \Lambda$ collisions, left hand column (from bottom to top) survival and absorption.

In conclusion, we have given an interpretation of the experimental observation that a) 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 b) 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 only marginally to the finally observed $K^-$ yield in AA collisions. Almost all $K^-$ are produced by the pionic channel $\Lambda \pi \rightarrow K^- B$ which is not available in pp. Because the $\Lambda$ 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 recreation and absorption occur at almost the same rate due to the large difference in the cross section between creation and absorption. Despite of the fact that thermal models predict [9] 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 $\Lambda$ 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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