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## Strangeness at SIS energies

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**Abstract.** In this contribution we discuss the physics of strange hadrons in low energy ( $\simeq 1 - 2$  AGeV) heavy ion collision. In this energy range the relevant strange particle are the kaons and anti-kaons. The most interesting aspect concerning these particles are so called in-medium modifications. We will attempt to review the current status of understanding of these in medium modifications. In addition we will briefly discuss other issues related with kaon production, such as the nuclear equation of state and chemical equilibrium.

### 1. Introduction

The production of strange particles in heavy ion collisions has been studied extensively for all available energies. While fits to particle yields [1] seem to indicate a common systematic for particle production over the entire energy range, as far as strange particle production and dynamics is concerned there is, at least from the theoretical point of view, a conceptual difference between the low energies and the ultra-relativistic regime. At low energies, the system is dominated by (non-strange) baryons, whereas for SPS-energies ( $\sqrt{s} = 20$  GeV) and higher the system is temperature dominated. In the limit of perfect flavor SU(3) symmetry a system at zero baryon chemical potential and finite temperature preserves the SU(3) flavor symmetry. Contrary to that, a system at low temperature, but large chemical potential, breaks the SU(3) flavor symmetry *explicitely*. The extreme example is a cold nucleus which consists only of protons and neutrons, but does not contain any hyperons. As a consequence, slow kaons and anti-kaons feel, contrary to pions, repulsive and attractive mean field potentials, respectively. This is analogous to pions in neutron matter, where the in-medium potentials for positive and negative pions are different due to the explicit *isospin* breaking of neutron matter. As the bombarding energy is increased, and the system becomes more temperature dominated, these effects are less relevant and more difficult to extract experimentally. Thus, low energy heavy ion collision provide a unique environment to study the SU(3) flavor dynamics and its effects on the strangeness sector at densities above the nuclear matter ground state density.

Historically, the interest in kaon production at low energies has been motivated by the search for the nuclear equation of state [2]. Since at these energies kaons are produced either sub or near threshold, kaon production should be sensitive to the equation of state. This approach, however, can only work if all other forces on the kaons, such as mean fields, are well understood. By now a rather consistent picture of kaon production has emerged, and the resulting equation of state is in agreement with the analysis of flow observables.

In recent years the production of anti-kaons has received considerable attention. Especially the connection to the structure of compact (neutron) stars, with the possible formation of a kaon ( $K^-$ ) condensate [3, 4], generated interest in anti-kaon production at high densities. Unfortunately, the environment generated in a heavy ion collision is different from that of a neutron star. The system is a finite temperature ( $T \simeq 70$  MeV) and the kaons observed in experiment have finite momenta. Therefore, a careful extrapolation to the conditions inside a compact star – zero temperature and momentum – needs to be carried out. This, as we shall discuss, introduces quite some ambiguities and model dependencies which require further detailed investigation.

This contribution is organized as follows. First, we will discuss the conceptual differences between kaon and anti-kaon production. Then we will briefly summarize the present understanding of kaon ( $K^+$ ) production, which is rather non-controversial. A large part of this contribution will be devoted to anti-kaon production, because here the interpretation of the data is not yet settled. Also, the in-medium properties for anti-kaons present a nice and possibly tractable example for in-medium modifications of hadronic properties. Before we conclude, we will briefly mention how kaon production can also be utilized to address the question of equilibration in these collisions.

Throughout this contribution we will concentrate on the SIS energy regime. While some of the effects are also seen at the lower AGS energies ( $\simeq 4$  AMeV), there, temperature effects wash out most of the interesting dynamics responsible for the anti-kaon in-medium properties.

## 2. Kaon and anti-kaon production in a density dominated environment

Initially, the properties of kaons in dense matter has been discussed in the framework of chiral perturbation theory. In ref. [3] the leading order interaction between a kaon and nucleon has been given by

$$\delta\mathcal{L} = -\frac{3}{8f^2}(\bar{K}i\overleftrightarrow{\partial}K)\bar{N}\gamma_0N + c(\bar{K}K)(\bar{N}N) \quad (1)$$

The first term reflects the vector interaction analogous to the Weinberg-Tomozawa term known from pion physics. This term is repulsive for kaons and attractive for anti-kaons. The second term, which is due to explicit symmetry breaking, is attractive for both, kaon and anti-kaon. The coefficient of this term is much less known than that of the vector interaction. The resulting interaction is repulsive for the kaons, in agreement with experiment, but attractive for anti-kaon, which is not supported by  $K^-$ -nucleon scattering data which also give a repulsive scattering length [5]. The reason for this discrepancy is the existence of the  $\Lambda(1405)$  resonance right below the  $\bar{K} - N$ -threshold, which couples strongly to the  $\bar{K} - N$  system. Thus, resummed chiral perturbation theory is required in order to describe the  $\bar{K} - N$  system correctly [6, 7]. As a result, the  $\Lambda(1405)$  is generated as a bound state, which in fact has already been proposed almost forty years ago [8].

The importance of the  $\Lambda(1405)$  illustrates the essential difference between the anti-kaon–nucleon and kaon–nucleon system. While the former is dominated by resonances, the latter does not show any significant structure in the scattering amplitude, since the strange anti-quark cannot be absorbed into a baryon resonance. This difference will also affect the in medium properties of kaons and anti-kaons. Since the kaon–nucleon interaction is non-resonant, we expect that the impulse approximation should

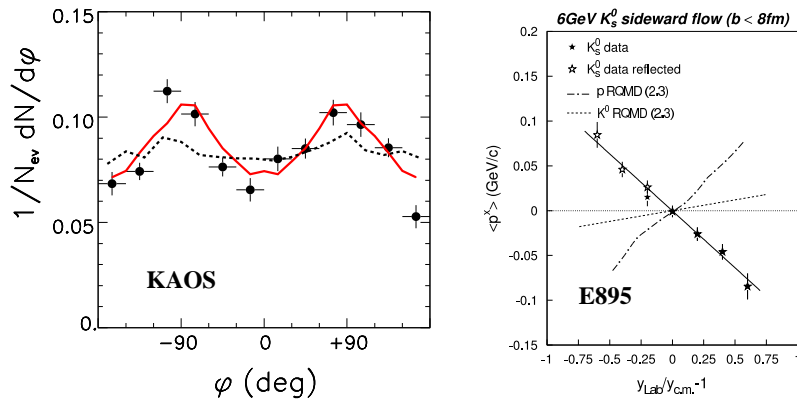
describe the kaon-nucleus system as well as kaon propagation in heavy ion collision rather well. We thus expect that a straightforward mean field description should be reasonable for kaons in nuclear matter. This is different for the anti-kaon. Here we expect strong mixing with resonance-hole states, similar to pion propagation in nuclear-matter. Thus a detailed coupled channel treatment is called for.

### 2.1. Kaon properties in dense matter

Let us first discuss the simpler case of kaons in matter. As already pointed out, we expect that kaons in matter should be reasonably well described by a mean-field obtained via the impulse approximation. And indeed this works rather well for the description of kaon-nucleus scattering experiments [9]. Since the scattering amplitude is non-resonant, corrections due to finite temperature should be small, and thus, the impulse approximation should provide a reasonable estimate for the kaon mean field potential. Using the measured scattering length one obtains

$$U_{\text{opt}} \simeq 20 \text{ MeV} \frac{\rho}{\rho_0} \quad (2)$$

which is slightly repulsive.



**Figure 1.** Left panel: Kaon squeeze out obtained by the KAOS collaboration [10]. The lines are transport calculations [13] with (full) and without (dashed) a kaon potential. Right panel: Kaon sideways flow at AGS energies obtained by the E895 collaboration [16]. Also shown are the results of transport calculations using the RQMD model.

As predicted by Ko et al. [12], this repulsion should be visible in kaon flow observables and, as can be seen in Fig. 1, the data clearly favor a repulsive mean field for the kaons. For SIS energies, where transport calculations are more reliable, the above mean field potential (2) leads to a quantitative agreement with the data [10, 11] for the so-called squeeze out and the sideways flow [12, 14, 15]. The repulsive potential for the kaons is even seen at AGS energies (left panel of Fig. 1). Strong flow away from the nucleons is observed [16]. Thus the presence of a repulsive mean field for kaons in nuclear matter up to twice nuclear matter density seems to be called for.

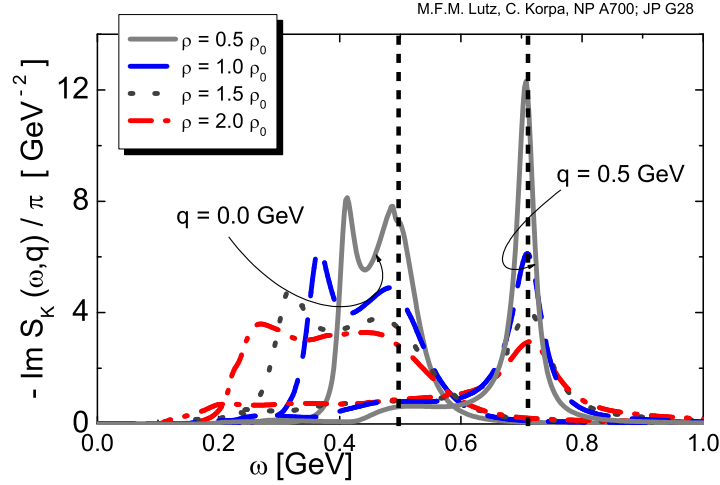
In addition, the resulting kaon yield as a function of system size can be utilized to extract information about the equation of state. Again, the data are reproduced, and, provided the kaon mean field is taken into account, the resulting equation of state is consistent with other observables such as nucleon flow [17, 18].

## 2.2. Anti-kaons in dense matter

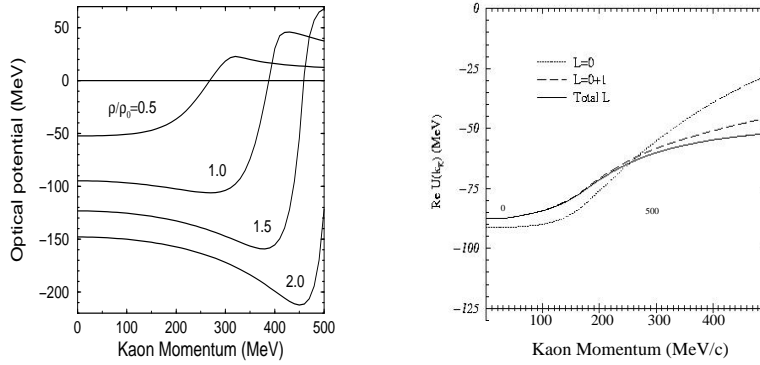
While the properties of kaons in dense matter seem to be rather well described by a simple repulsive mean field potential based on the impulse approximation, the situation for anti-kaons is much more complicated; the main reason being the aforementioned coupling to baryon resonances. The effect of this more complex dynamics becomes already apparent in the spectroscopy of kaonic atoms, where very low nuclear densities are probed. Whereas the  $\bar{K} - N$ -amplitude is repulsive, kaonic atoms call for an attractive mean field [19]. Thus, already at densities well below nuclear matter density the impulse approximation fails. The observed attraction in kaonic atoms can be naturally explained if one assumes that the  $\Lambda(1405)$  resonance is indeed a  $\bar{K} - N$ -bound state [20]. In this case, Pauli-blocking of the  $\bar{K} - N$  intrinsic wavefunction shifts this state up in energy above the  $\bar{K} - N$  threshold before it then dissolves. As a result, the underlying *attractive*  $\bar{K} - N$  interaction, which was responsible for the binding of the  $\Lambda(1405)$ , is revealed. The resulting attractive potential is then in reasonable agreement with the findings from kaonic atoms, which by themselves are somewhat model dependent [19]. This is similar to proton-neutron scattering in the deuteron channel, where the scattering amplitude is repulsive due to a bound state just below threshold. Again, the true interaction is attractive and is only revealed in an atomic nucleus where the deuteron is dissolved due to Pauli-blocking. While this idea has first been developed based on an effective  $\bar{K} - N$  interaction [20], more refined calculations employing re-summation techniques using chiral Lagrangians find the same result [21, 22, 26]. But the  $\Lambda(1405)$  is only one of many resonances the anti-kaon can couple to, and a consistent treatment requires the coupling of all these channels. As a result a rather complex spectral distribution for the excitations with the quantum numbers of the anti-kaon emerges. An example of a  $K^-$  spectral function based on a chiral Hamiltonian is shown in Fig.2. In this model not only the  $\Lambda(1405)$  but many other resonances are generated dynamically. The spectral function for zero momentum kaons shows the mixing of the kaon with resonance-hole states and, as the density is increased, the strength broadens considerably. Obviously, a simple quasi-particle plus mean field description of the anti-kaon will oversimplify this situation considerably.

In addition, a resonance dominated interaction also should lead to strong energy/momentum dependencies for the spectral distribution. Furthermore, one would also expect that the strong density dependent mixing of states should modify the transition rates between the states. In the simple model of ref. [20], where the essential in-medium effect is due to Pauli-Blocking of the  $\Lambda(1405)$  one immediately expects that for kaons with momenta that are large compared to the Fermi momentum of the nuclear matter, the free (slightly repulsive)  $\bar{K} - N$  interaction should re-emerge. This indeed is found as shown in Fig.3 (left panel). The right panel of Fig.3 shows the results of a calculation based on a different, more sophisticated interaction [28]. Again with increasing momentum, the  $\bar{K}$  potential becomes less attractive. But in this case, some net attraction remains even for momenta of the order of 500 MeV.

The momentum dependence of the  $\bar{K}$  in-medium modifications can also be read off from the spectral distribution shown in Fig.2. The set of curves on the right shows the spectral function for a anti-kaon momentum of  $q = 500$  MeV. Not only are the distributions much less broadened but they all peak at the energy of a free kaon. Thus, the effective kaon potential is essentially zero, whereas at zero momentum almost all the strength accumulates below the free value. Thus, this calculation also predicts a



**Figure 2.** Example for an in-medium anti-kaon spectral function [25]. The dashed vertical lines indicate the energies for a free anti-kaon at the given momentum.



**Figure 3.** Anti-kaon optical potential. Left from ref. [27], right from ref. [28]

reduced attraction as the momentum of the kaons is increased.

Finally, let us turn to the cross sections. One of the crucial channels for  $\bar{K}$  production in low energy heavy ion collisions is the strangeness exchange reaction



For example, the  $\Lambda(1405)$  resonance couples to both channels, and as this resonance moves in mass as a result of Pauli blocking, this cross section may change considerably [27, 23]. Actually, as shown in [23], this may explain the observed pion distribution from stopped anti-kaon reactions. In Fig.4 we show the results of two different calculations for the in-medium change of the cross section for the reaction (3). In both cases, the cross sections are enhanced, even though the calculations and results differ in the details.

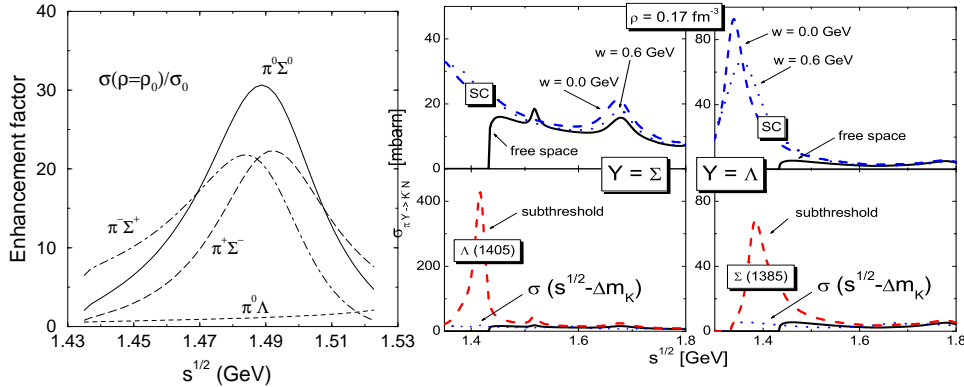


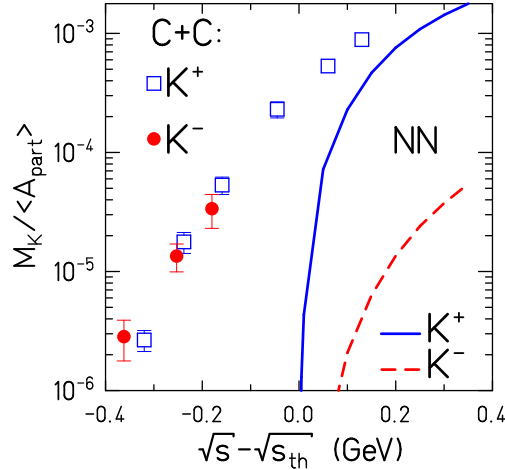
Figure 4. In-medium cross sections. Left from ref. [27], right from ref. [29]

While the general trends of all calculations concerning the the in-medium properties of anti-kaons agree qualitatively, there are obvious model dependencies. Those, be it the momentum dependence of the optical potential or the density/momentum dependence of the cross sections, can only be resolved with more detailed experimental knowledge about the underlying  $\bar{K} - N$  scattering amplitudes. At present the available data are rather poor and only better measurements of the elementary reactions will allow to make definitive conclusions about the rather interesting in-medium properties exhibited in the above figures.

**2.2.1. Experimental results and their interpretation** How are the above theoretical considerations born out in experimental data? As already discussed in the previous section, kaons appear to fit into a rather consistent framework. As for anti-kaons, the situation is, as expected, considerably more complex. Most prominent is the discovery by the KAOS collaboration [24], that the production of anti-kaons in heavy ion collisions compared to proton-proton collisions is much more enhanced then that of kaons. Indeed if plotted with respect to the threshold energy, the excitation function of the anti-kaons and kaons are identical (see Fig.5). Initially this observation gave rise to speculations about reduction of in-medium kaon masses, as predicted by simple first order chiral perturbation theory. However, from the above considerations, this scenario seems too naive. In particular, the kaons observed by the KAOS collaboration have a momentum larger than approx. 300 MeV in the matter rest frame. At these momenta, all microscopic calculations predict reduced if not vanishing attraction.

In addition, microscopic models predict a considerable modification of the cross section for the most important productions channel (3). So what is the correct interpretation of these data? Most disturbingly, at present transport models, which in this energy regime often serve as reference, do not agree on the anti-kaons yield even absent any in-medium modifications. While the calculations of [27, 30] more or less reproduce the measured  $K^-$  yield, the calculations of [14, 31] definitely call for some additional source of  $K^-$ . Fortunately, these discrepancies are presently being investigated [32].

But there is additional experimental information, which may guide us independent of the details of the transport model results. Namely, the kaon to anti-kaon ratio



**Figure 5.** Kaon and anti-kaon production as a function of energy as measured by the KAOS collaboration [24]. Also shown are the  $N - N$  thresholds.

is essentially independent of centrality. How can this be understood in terms of density dependent in-medium effects. The densities reached in central collisions are considerably higher than those in more peripheral ones. Maybe there is a much simpler explanation to the anti-kaons production, as proposed by Oeschler [33].

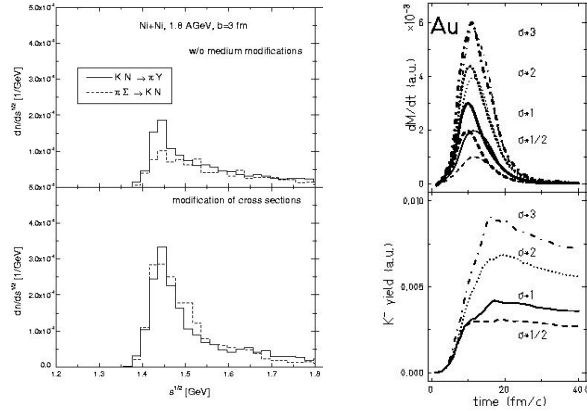
Suppose the strangeness exchange reaction as given by Eq.3 is fast compared to the lifetime of the system. Then a *relative* chemical equilibrium between hyperons and anti-kaons is established, with  $N(Y) \gg N(\bar{K})$ . Furthermore, in the initial hard collisions strangeness conservation requires that as many hyperons as kaons are produced. Consequently, given the number of kaons, the number of hyperons is determined and in turn the number of anti-kaons. Note that this process does not require any in-medium modifications and is consistent with the observation [1] that the anti-kaon yields follow a thermal model.

Indeed transport calculations give support to this picture. As shown in Fig.6, the rates for both directions of the reaction (3) are almost identical, meaning *relative* chemical equilibrium between hyperons and anti-kaons is essentially established. As an interesting consequence an increase of the cross section for these transition has only limited effect on the final anti-kaon yield [27, 30]. As shown in the lower part of the right panel of Fig.6 increasing the cross section by a factor of three does not enhance the  $K^-$  yield by the same amount.

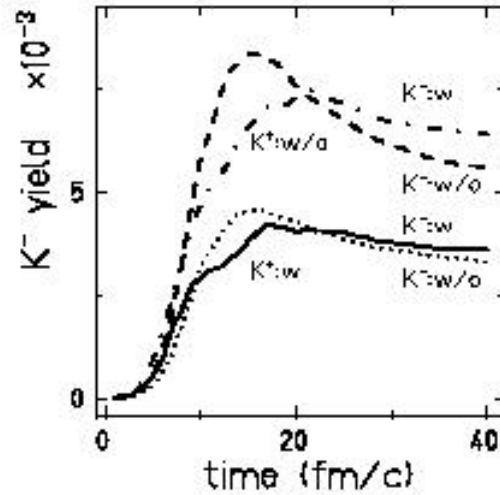
There is actually an even more amusing consequence of this scenario. As shown in Fig.7, in-medium potentials for *kaons* have a larger impact on the *anti-kaon* yield than in-medium potentials for the anti-kaons themselves. This is again a simply corollary of the relative chemical equilibrium between hyperons and kaons. Given the number of hyperons, the anti-kaon number is fixed at a rather late stage of the collision. The number of hyperons, however, is directly linked to the number of kaons and is established early on in the dense phase of the collision. Thus, a repulsive kaon potential, which reduces the kaon yield, affects the final anti-kaon yield much more effectively than an anti-kaon potential.

Another, more sobering consequence of this scenario is that heavy ion reaction may actually not be the right environment to study the rather rich in-medium





**Figure 6.** Left: Number of collisions  $Y + \pi \leftrightarrow K^- N$  [27] as a function of the c.m. energy. Right: Number of collisions  $Y + \pi \leftrightarrow K^- N$  [30] as a function of time (top) and number of  $K^-$  for different cross sections (bottom).



**Figure 7.** Number of  $K^-$  for different choices of kaon and anti-kaon mean field potentials [30].

properties of anti-kaons. If equilibrium physics dominates, then the subtle dynamics are hard to unravel. Anti-kaon nucleus scattering experiments, therefore, seem to be the better environment to study this interesting question.

In summary, the picture for the in-medium behavior of kaons seems to be reasonably well under control and consistent with simpler systems, such as kaon-nucleus scattering. Anti-kaons, however, are much more complex because of their strong mixing with baryon hole states. While the different theoretical models agree qualitatively, a quantitative agreement requires better knowledge of the underlying amplitudes. Therefore, in order to make progress in this interesting field, detailed  $K^-$ -nucleon scattering data are called for.

### 3. Other aspects: equilibrium

As already mentioned in the introduction, it is somewhat surprising that the strange particles, like all other particles, seem to follow the same universal chemical freeze-out curve which connects density dominated systems created at SIS with temperature dominated systems at SPS and RHIC. As we have argued before, in a dense system the properties of kaons and anti-kaons are quite different. And indeed, taking the in-medium spectral functions seriously, a fit to a thermal model should take these spectral distributions into account. Simply using free particle properties does not seem to be the correct procedure. In ref. [34] an attempt in this direction has been made. By weighting the in-medium spectral distribution with a thermal distribution the authors are forced to use much lower temperatures for the anti-kaons in order to reproduce that data. Or, in other words, they do not find chemical equilibrium in these reactions. However, one should interpret these result with some caution. The in-medium spectral function for the anti-kaons contains considerable strength from hyperon-hole pairs. What happens to this strength as the system expands? This will depend on the time scales involved. In the adiabatic limit, the spectral distribution de-mixes and all the strength will accumulate in the kaon branch. However, if the expansion is sudden, some of the strength will remain in the hyperon-hole branch, which then materializes as hyperons in the final state. Therefore, a more detailed dynamical calculation is required before any definite conclusions can be drawn about the effect of in-medium spectral functions on the final state anti-kaons number.

Another surprising aspect of the success of the thermal model is the fact that the kaon should be in chemical equilibrium with the rest of the matter. Kaons interact with small cross sections and it seems that the lifetime of the system is too short for any equilibrium to establish [35]. Luckily, kaons at SIS energies represent one of the few systems, where the degree of equilibrium can be determined experimentally. As discussed in [36] the number of kaon pairs, though difficult to determine experimentally, provides a direct measurement on the degree of equilibration. This is essentially due to the fact, that at SIS energies strangeness is rare and thus needs to be conserved explicitly and not only on the average as it is usually done in the grand-canonical approximation [37]. At higher energies similar arguments can be made, but much more complicated measurements are needed, since strangeness is not rare anymore [38]. If indeed, the measurement of the kaon pairs establishes chemical equilibrium, then additional processes, such as many body collisions or possible new in-medium effects need to be invoked in order to explain this. Thus, potentially new physics may emerge from these investigations.

### 4. Summary

In this contribution we have discussed strangeness at SIS energy heavy ion collisions. We have concentrated on the in-medium properties of kaons and anti-kaons and have pointed out the conceptual difference between the two in a density dominated environment.

In particular the anti-kaons in matter are an interesting example for in-medium modifications via coupling to hyperon-hole modes etc. Since strangeness is involved, the number of possible channels is limited and thus a quantitative understanding of these effects in the future is conceivable. However, in order to make progress, detailed information about the basic  $\bar{K} - N$  system is needed. We have also pointed out that

heavy ion collisions may not be the most appropriate tool to study this system, since efficient partial equilibrium may wash out most of the dynamics. It rather appears that  $K^-$ -nucleus scattering experiments are more appropriate to investigate all the interesting phenomena associated with the in-medium propagation of a hadron.

Finally, we have mentioned that kaons at SIS energies may actually be one of the few examples where the question of equilibrium can be addressed in experiment. In case of the anti-kaons, the subtle coupled channel dynamics needs to be controlled before this issue can be addressed with confidence.

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