Strangeness in strongly interacting matter

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Abstract. This talk is devoted to review the field of strangeness production in (ultra-)relativistic heavy ion collisions within our present theoretical understanding. Historically there have been (at least) three major ideas for the interest in the production of strange hadronic particles: (1) mass modification of the kaons in a (baryon-)dense environment; (2) (early) $K^+$-production probes the nuclear equation of state (EoS); (3) enhanced strangeness production especially in the (multi-)strange (anti-)baryon channels as a signal of quark gluon plasma (QGP) formation. As a guideline for the discussion I employ the extensive experience with microscopic hadronic transport models. In addition, I elaborate on the recent idea of antihyperon production solely by means of multi-mesonic fusion-type reactions.

1. Introduction: The original strange ideas or ‘how we got where we are’

I want to start with a citation of the introduction of an over twenty year old paper by Randrup and Ko [1]: ‘Since the threshold for their production is relatively high on the scale of presently available beam energies, the kaons are predominantly produced before the initial motion is substantially degraded. They are therefore expected to be better suited as messengers of the primary violent stage of the collision which might otherwise remain quite elusive.’

This statement is robust and I will come back to it throughout this review. Although not intended at that former time, today even up to CERN-SPS energies our strong feeling is that the overall strangeness in heavy ion collisions is being produced at the beginning of the reaction when the system is still far from being near to any (quasi-)equilibrium stage.

A little later, in the mid-eighties, when the Bevalac had successfully started since a couple of years with their relativistic heavy ion physics program and the AGS as well as the SPS era were on its way, strange particles had been proposed as an intriguing diagnostic probe for a variety of interesting questions and phenomena. In the following I want to list three of them which I personally consider as the potential ‘smoking guns’ for the then evolving field of ‘strangeness in strongly interacting matter’ probed with relativistic heavy ion physics.

Strange Goings in Dense Nuclear Matter [2]: It was raised by Kaplan and Nelson that the kaons do feel strongly attractive (scalar) potentials in the background of a dense nuclear environment due to the KN-sigma term, resulting in a significant lowering of their mass with increasing baryon density. As higher baryonic densities do occur either in relativistic heavy ion collisions or in the deep interior of neutron stars, it was furthermore proposed that such an attraction actually can ultimately

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lead to the condensation of kaons. In addition, there exists also a vector-type interaction given in leading order (within an effective chiral perturbative expansion) by the Tomozawa-Weinberg term, which acts repulsive for the kaons and further attractive for the antikaons. Hence, one was led to the conclusion that the antikaons should feel a stronger attraction whereas the kaons might feel a slight repulsion, if at all, with increasing nuclear density. Such a behaviour, predicted by a mean field calculation, is depicted in fig. 1. Here the free parameters were fixed to the KN scattering length. However, one should keep in mind that because of the large kaon mass and momenta involved within a chiral expansion higher order terms might become significant already at moderate nuclear densities. Be it as it is, to leading order such an effect for the antikaon is a nice demonstration that hadronic particles might significantly change their property if situated in a nuclear environment. Modifications of the properties of hadronic particles are eagerly looked after experimentally in a variety of different nuclear experiments ($\gamma$, $e^-$, $\pi$, $p$ + $A$ setups and heavy ion collisions) as they would prevail new knowledge about the manifestation of strong interactions in the nuclear medium. In heavy ion collisions a lowering of the threshold of kaon pair production compared to the vacuum via the reaction

$$N + N \rightarrow N + N + K^+ + K^-$$

should lead to a dramatically enhanced production of antikaons especially for subthreshold energies. This indeed has been observed experimentally. Is this a clear hint for strong attractive potentials for the antikaons?

**Subthreshold Kaon Production as a Probe of the Nuclear Equation of State**

It has been shown by Aichelin and Ko within a premature microscopic Boltzmann-Uehling-Uhlenbeck transport approach that the number of produced kaons can vary by

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**Figure 1.** The energy of kaons and antikaons situated at rest in cold nuclear matter obtained within a relativistic mean field calculation (taken from Schaffner et al).
a factor of $\sim 3$ at subthreshold energies for central collisions (subthreshold with respect to $N + N \rightarrow N + K + \Lambda$), depending on the stiffness of equation of state employed. To understand the idea, one first has to accept that most of the $K^+$s are produced via a second step process by the more massive $\Delta$s via the reaction $\Delta + N \rightarrow N + K + \Lambda$, with the threshold strongly diminished. The $\Delta$s in turn have been produced initially via inelastic nucleon-nucleon scattering. The argument now goes as follows: For a softer EoS larger nuclear densities are being built up, lowering the mean free path $\lambda_\Delta$, thus leading to more inelastic collisions of the $\Delta$, e.g.

$$\Delta + N \rightarrow N + K + \Lambda,$$

and hence to more kaons. This proposal has lead to a considerable interest in the physics of kaon production at subthreshold energies, in particular, because of the chances to survey the nuclear EoS being the sought after ‘holy grail’ at that days. Considerable progress in the concepts of microscopic transport approaches and in the various reaction channels had been achieved so far. In addition the kaons might feel a slight repulsion. What is the status of this idea today?

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.png}
\caption{Chemical equilibration of antihyperons and kaons as a function of time in a thermal hadronic gas taken from the seminal report by Koch, Müller and Rafelski [7].}
\end{figure}

Strangeness Production in the Quark Gluon Plasma [5]: As the first example, strangeness enhancement has been predicted a long time ago by Müller and Rafelski as a diagnostic probe to prove for the short-time existence of a QGP. The main quantitative idea is that the strange (and antistrange) quarks are thought to be produced more easily via the fusion of gluons and hence also more abundantly in such a deconfined state as compared to the production via highly threshold suppressed inelastic hadronic collisions. Enhanced strangeness production via the QGP should thus been seen most easily in the yield for the most dominant strange particles, the
kaons. Here, it was argued, however, that a factor of 2-3 enhancement in the $K/\pi$-ratio relative to the one obtained in p+p collisions can only be seen as an indirect signal for QGP creation\cite{6}. With respect to the high production thresholds in the various binary hadronic reaction channels, especially the antihyperons and also the multistrange baryons were then advocated as the appropriate candidates\cite{7}. Fig.\,\ref{fig:2} intriguingly shows the approach to chemical equilibrium as a function of time for the various particle densities of strange hadrons containing at least one antistrange quark within a hot and baryonrich hadronic system. Even after 1000 fm/c the antihyperons do not approach by far their chemical equilibrium values. It was argued that for a thermalized fireball of hadronic particles the strange antibaryons are mainly produced via subsequent binary strangeness exchange reactions with the kaons, e.g.

$$K + \bar{p} \leftrightarrow \pi + \Lambda,$$

with low crossections. On the other hand, assuming the existence of a temporarily present phase of QGP and following simple, statistical coalescence estimates the abundant (anti-)strange quarks can easily be redistributed to combine with the light (anti-)quarks to form the strange (anti-)baryons\cite{8}, which do then, in return, come close to their chemical equilibrium values. Such a behaviour of nearly chemically saturated populations of the (multi-)strange (anti-)baryons has been experimentally demonstrated with the Pb+Pb experiments at CERN-SPS. (This statement can, of course, only be made by invoking an analysis by a thermal model and fitting the thermal parameters to the set of individual hadronic abundancies\cite{8,9}. Indeed, the extracted value for the temperature parameter is significantly close to the critical temperature $T_C$ obtained by thermodynamical QCD lattice calculations.) However, Leupold and myself have recently conjectured that a sufficiently fast and simple redistributions of strange and light quarks into (strange) baryon-antibaryon pairs might equally well be achieved by multi-mesonic fusion-type reactions of the type

$$n_1\pi + n_2 K \leftrightarrow \bar{Y} + p$$

for a moderately dense hadronic system\cite{10}. The beauty of this argument lies in the fact that (at least) these special kind of multi-hadronic reactions have to be present because of the fundamental principle of detailed balance. Are (anti-)hyperons thus still a good diagnostic tool for the onset of QGP formation in central ultrarelativistic heavy ion collisions?

In the following sections I will continue to elaborate in more theoretical detail on the understanding of strangeness production in relativistic heavy ion collisions and the three questions raised. Strangeness production can best be described microscopically within a hadronic transport approach. This is my personal prejudice. Therefore, as a basic guideline for the discussion, I will employ our extensive experience with such a description. By detailed comparison to data these approaches should provide theoretical evidence whether each of the above ideas does manifest in nature or not. As the basic input are vacuum cross sections for the various binary hadronic reaction channels, transport approaches do have a profound and solid foundation: relativistic kinetic theory (being, in principle, superior to any thermal or hydrodynamical description) and known vacuum physics. However, caution comes into the description and the character of a model enters when cross sections are asked which can not be measured experimentally. Besides the dynamics of all kinds of hadronic resonances this is, in particular, true for the modelling of the highly energetic inelastic binary hadronic reactions (by e.g. string fragmentation) and their collective incorporation into space-time dynamics.
An alternative and (to a certain part) complimentary theoretical description of the final hadronic yield being explored in tremendous detail over the last years is given by various thermal model analyses as already mentioned above. Why complimentary? As it cannot make any predictions for the initial phase and how the (pre-)final hadronic system might have reached some approximate thermodynamical equilibrium, it exactly does not rest on any (microscopic) model assumptions. This description helps to extract global properties and systematics from experimental data like, being specific, strangeness saturation in the hadronic abundancies. Here I want to refer to the recent review by Redlich [11].

In the next section 2 I discuss the production of kaons at SIS energies. Section 3 then deals with kaon and (anti-)hyperon production at SPS energies. I will end with a brief conclusion what I do believe what has been learned at present.

Although important, I will not touch on p+A physics (for a recent review containing a brief summary please see [12]). I will also not discuss the physics of strangelets [13] or multihypernuclear objects [14], although these exotic states would clearly represent ‘strongly interacting strange matter’, if they do exist in nature. For a review and the experimental situation I refer to [13]. In addition, microscopic studies of single hypernuclei (please see [16] for some new developments) and the role of strangeness on the structure of neutron stars (see [17]) deserves attention, but will not be reviewed here. Last but not least on this list of topics not covered are the encouraging and brand new results on production of strange hadronic particles within the RHIC program, which now do ask for more detailed theoretical studies.

2. Strange Physics at SIS

The production of kaons and antikaons, respectively, in relativistic heavy ion collisions below and around the individual threshold energies up to 2 AGeV has been addressed with significant progress over the last ten years by the FOPI and the KAOS collaboration with the SIS at GSI. It has become clear by now that the data has to be understood in complete and careful detail within the various transport models in order to pin down possible in-medium effects for the antikaons or to extract the nuclear EoS. The main competing approaches are the QMD model (Nantes), the RQMD model (Tübingen), the URQMD model (Frankfurt), the RBUU or HSD model (Giessen) and the RBUU model (Stonybrook,Texas). I will concentrate in the following to discuss the recent progress in theoretical understanding being made, but also point out some present conflicts, at least to my understanding, which has to be addressed in order to come to solid conclusions.

As will become evident below one first has to understand the production mechanism(s) of the kaons before considering the antikaons, being more rarer and thus more exotic. A detailed analysis in comparison to data for $K^+$ production was first made by Bratkovskaya et al. [18]. It was found that the inclusive momentum spectra for various systems and different bombarding energies can be best described without employing slightly repulsive in-medium potentials for the kaons. Inclusion of the potentials would lower the total yield by roughly 30%. It should be remarked, though, that the kaon flow on the other hand seems to be more consistent with data by including a slight repulsion [18]. In addition, it was found that the reaction

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

(5)

dominates considerably compared to the $\Delta$-induced production via (3). On the other
hand, rather opposite findings have been obtained recently by Hartnack and Aichelin [19]. Here the later reaction (2) is the most important for producing the kaons, although different channels do contribute differently for different energies and for different masses of the system. They do obtain an agreement to the rapidity spectra for Ni+Ni at 1.93 AGeV when including a repulsive potential. It might well be that the main difference between the two approaches stems from a different parametrization of the, in principle, unknown production cross section (2). A comparison between both implementations of this channel seems to reveal that at least for the higher energies (at 1.93 AGeV, where the comparison has been made) this could be the sole reason: Implementing the same parametrization of the cross sections gives rather identical results for the kaon rapidity spectra within the two different transport algorithms [19]. A consistent check also for lower energies and different systems is, however, mandatory. In any case, as the reaction (3) is of definite relevance, a final consensus on its parametrization should be striven for. This seems to be one of the major ambiguities at present.

Experimental [20] as well as theoretical [21] efforts concerning the idea on extracting the nuclear EoS from the $K^+$ excitation function has been made just recently. Because of the uncertainty in the one cross section as explained, it was found that the ratios of $K^+$ spectra for heavy an light ion reactions is a more robust indicator [21, 19]. Also the kaon yield for light systems should be less sensitive to the EoS than for heavy systems. From the theoretical analysis it turns out that the new data do favor a soft (and momentum dependent) nuclear EoS. Still, if in addition one does employ a moderately repulsive in-medium potential for the kaons, the difference in the yield for the kaons between a soft and a hard EoS shrinks from a factor of 3 down to only 40% [19]. Refering to the reasoning in the introduction, this counter effect is understood as for a soft EoS one produces the kaons at higher baryonic densities where the repulsive potential then increases the threshold. Hence, an identification of the EoS has become more delicate compared to the original idea. Establishing cross correlations with other observables being also potentially sensitive to the EoS is definitely needed for. It is worth mentioning that looking at the standard signal of in-plane and out-of-plane proton and neutron flow experimental data seems to be mostly consistent with a soft and strongly momentum dependent EoS (with emphasis more on the strong momentum dependence of the potentials) [22]. Encouragingly, within this same RBUU code the yields of the kaons are found to be most consistent by employing this same EoS [23].

The (subthreshold) production of kaons either via the two step process of energetic $\Delta$s or pions does happen still at the onset of the reaction when the build up baryon density is high. Afterwards, more or less no further strangeness is being produced in any of the microscopic simulations. This reflects the early statement of Randrup and Ko remarked in the introduction. Putting it differently, when the momenta of the nucleons sufficiently degraded and the system has to some extent thermalized, the timescale for production of strange particles via the considered kinetic reactions becomes incredibly large, exceeding two order of magnitude the lifetime of the system. Fig. 3 shows this statement in a dramatic way: Within the RBUU model the chemical saturation of the kaons has been investigated microcanonically for a static box with isosymmetric baryon content [24]. It is found that for low energy densities as expected at SIS energies the saturation time scale exceeds $10^3$ fm/c. (In the figure actually only energy densities as expected for situation for lower AGS energies ($\sim 4$ AGeV) up to SPS energies are given. For even lower densities to be expected at SIS see [24].) A
similar conclusion with a dynamical simulation has been recently shown by Pal, Ko and Lin \cite{25}. Referring e.g. to the reaction (3), the fundamental and simple kinetic reason for the large saturation timescale is the fact that the probability for a $K^+$ to meet with a $\Lambda$ and then to annihilate becomes tinely small. It are these kind of annihilation rates of the kaons which in sum equals the rate towards chemical equilibrium. Kaon production at SIS energies is an initial nonequilibrium phenomena as is the overall strangeness production.

It might accidentally be that the amount of produced kaons might resemble a chemical equilibrium population at some very late stage of the reaction as advocated in \cite{26}. (The overall population at equilibrium is very sensitive on the temperature parameter and thus there is a good chance to ‘fit’ to the data with a particular value. In \cite{25} it was found within the employed microscopic calculation that at the very late stage there exists temporarily a situation where the Gain and Loss contribution, although tinely small, do become equal in size. Although the number of kaons does not change anymore throughout this final evolution, this particular situation resembles qualitatively that of a system at equilibrium.)

Being prepared with a good understanding of the production of the kaons, I want to go over to our present knowledge of the production of the more exotic probe, the antikaons. One should be aware that at all SIS energies the kaons and hyperons are nearly equal in number and the antikaons are much rarer than the kaons. In principle, there is a good chance that the antikaons are made by redistributing the strange quarks of the hyperons to mesonic degrees of freedom. Indeed, it was pointed out nearly 20 years ago by Ko that the kinetic reaction

$$\pi + Y \leftrightarrow N + K^-$$

(6)

should play a dominant role in the production of subthreshold antikaons. The cross section of the back reaction is known experimentally quite well and becomes very large close to threshold. The direct reaction can then be obtained by means of detailed balance. As (2) is thought to be rather dominant for kaons, one might think similarly...
also of a second step process involving the $\Delta$, 
\[
\Delta + Y \rightarrow N + N + K^- ,
\]  
(7)
for the production of the kaons \[28\]. (Here, however, again the cross section is not known experimentally and thus has to be modelled.) Also, as shown in \[29\], the more direct pion induced reaction with energetic, incoming nucleons 
\[
\pi + N \rightarrow N + K^+ + K^- ,
\]  
(8)
does contribute considerably to the yield, especially when turning on the attractive potentials \[30\].

Comparing the two microscopic approaches, \[29\] and \[28\], both dealing with a detailed description of antikaon production, one has to clearly admit, that a comprehensive emerging picture is at present still not really given. Both approaches do have in common, that they show, that the elementary NN-reaction (1) in the vacuum is of no importance. The antikaons are produced via second or higher step processes. Within the RBUU model an attractive potential for the antikaons is definitely needed in order to describe the various $K^-$-spectra \[29\]. (The $K^+$ are calculated without any - in this case repulsive - potentials as this is shown to describe the various data as outlined above.) Reabsorption on the nucleons, i.e. the backward reaction of (1) is shown to be important so that it is argued that a sufficient fraction of kaons has to be produced via (8) when the baryon density is still high and the mass reduction of the antikaons is at work. Within the QMD model, however, it is shown that the reabsorption and production via (1) is by far the most important channel \[28\]. Production and Absorption do happen on a very fast timescale and do occur hand in hand. The mass law action seems to be at work so that the antikaons and the hyperons are in chemical equilibrium relative to each other. (This picture gives a microscopic justification for the use of a thermal and chemical equilibrium model \[26\] at SIS energies at least for the antikaons.) When all particles do freeze out, the baryon density is rather low, so that the possible attractive potentials have not any significant influence on the abundance of the antikaons any longer. Any potential antikaons of the early high-density phase, when the reduction in mass is of most importance, will get reabsorbed with a probability near to one in the ongoing evolution of the system \[28\]. This view stands in contrast to the findings and argumentations of \[29\].

Does one see the medium effects of the antikaons, i.e. a significant lowering in mass when the baryon density is high? Yes and no, at present. The RBUU analysis does require a strong attractive selfenergy for the kaons to account for the measured yield. QMD does not, although they do need some repulsive potential for the kaons to get the number in kaons and thus also in the hyperons correct. Here, however, as just explained, due to the strong reabsorption it does not really matter as with or without the potentials the final yield in antikaons is calculated to be more or less the same \[28\]. The experimental data by KAOS and FOPI have become much refined in quality over the years and now do ask for a clear theoretical (re-)analysis. My presumption is that the parametrization and implementation of the cross sections for the reaction (1) has to be accurately cross checked by the various competitors in the field. It is somewhat suspicious that the one group sees a much stronger reabsorption of early produced antikaons than the other group. This might well be only one possible source of some (minor) mismatches. A certain ‘unification’ in the various parametrizations and implementations of cross sections is again mandatory.

Before finishing the discussion on SIS physics, I want to mention that indeed the medium effects of the antikaons might not be as simple as advocated above and
as incorporated simplistically by mean field type potentials in the various transport approaches. It is known for a long time from coupled channel analyses of $K^-N$-scattering data that the $\Lambda(1405)$-resonance strongly couples in the $s$-channel slightly below threshold to the two particle system. In medium, roughly spoken, this coupling results in an additional $\Lambda(1405)$-hole branch for the kaon(-like) excitations with a nontrivial form for their spectral function \cite{31,32} having a structure much different from a simple quasi-particle. This is an intriguing topic. Over the years nontrivial possible medium modifications of spectral functions of e.g. vector-mesons (because of their electromagnetic decay channel) has attracted a lot of interest in the heavy ion physics community. However, considering solely the kaons, it is a delicate question at present whether such effects really are visible by means of a final yield of onshell antikaons. In addition a full understanding of a consistent transport scheme for continuous, off-shell particle-like excitations has not yet emerged.

### 3. Strange Physics at AGS and SPS

A first and thorough attempt to understand strangeness production for AGS and SPS energies within one microscopic model, the RQMD model, was carried out over many years by Sorge and coworkers. For a nice discussion of the various results, pre- and postdictions, and physics points of view I like to refer to \cite{33}.

![Figure 4.](image)

**Figure 4.** Excitation function for $K^+/\pi^+$ around midrapidity for central Au+Au reactions (open squares) from SIS to RHIC energies obtained within the HSD model in comparison to experimental data and elementary p+p collisions (open circles) \cite{36}.

As outlined in the previous section, certain differences in the implementations of particular cross sections already had some profound influence on the production of kaons and antikaons within the various transport descriptions. Turning now the discussion to the higher incident bombarding energies, it should not be a too big surprise that the predictions for strangeness productions should possibly vary even more. This is indeed the case, at least for all AGS energies, ranging from 2 to 11 AGeV,
and the lower SPS energies, and will be briefly reported below (see also the contribution of Bass [34]). Dealing with the description of the various inelastic reactions, a certain physics point of view and hence a true character of a model enters: The very first nucleonic and hadronic collisions are highly energetic. Particle production is not directly calculable and can only be described with phenomenological descriptions being adjusted to data like the well known Lund model with string fragmentation. In addition, certain classes of inelastic hadronic reactions at intermediate energies might still be modelled by various (baryonic and mesonic) resonances being not so much well established.

In a recent systematic study the properties of $K^+$, $K^-$ and $\Lambda$ particles in nuclear reactions from SIS to CERN-SPS energies have been investigated within the microscopic HSD model [35]. The outcome for the excitation function of the most dominant strange particles, the $K^+$-mesons, relative to the $\pi^+$-yield within the HSD model is summarized in fig. 4. Since a relative enhancement of strangeness is observed already in hadron-hadron collisions for increasing energy the to be measured strangeness should be compared relative to p+p collisions at the same energy. After the primary string fragmentation of intrinsic p-p-collisions the hadronic fireball starts with a $K^+/\pi^+$ ratio still far below chemical equilibrium with $\approx 6 - 8\%$ at AGS to SPS energies before the hadronic rescattering starts. Secondary (meson-baryon) and ternary (meson-meson) induced string-like interactions do then contribute significantly to additional strange particle production, particular for reactions at SPS energies. Via these channels about the same number of strange and anti-strange quarks is produced as in the primary p+p collisions. This then can explain the factor 1.75 as the relative enhancement compared to p+p (compare fig. 5). Hence, the major amount of produced strange particles (kaons, antikaons and $\Lambda$s) at SPS-energies can be understood in terms of early and still energetic, non-equilibrium interactions.

As the average kinetic energy and the particle density increases monotonically with incoming kinetic energy of the projectile while the lifetime of the fireball increases with the system size, a smooth and continuous enhancement is expected in a hadronic description by these effects. Experimentally, at AGS energies and also at the lower, new SPS data, a different behaviour for the excitation $K^+/\pi^+$ is seen. The relative enhancement factor here is $\approx 3$ and can not be fully explained within the cascade type calculations [35]. Strangeness production is underestimated by $\approx 30\%$ compared to explicit kaon data [35] whereas the pion population is in addition slightly overestimated. This discrepancy in strangeness production at AGS energies indicates either hadronic physics not taken into account or some new nonhadronic physics involved for the primary $s\bar{s}$ production. Including kaon potentials does help to some extent to raise somewhat the production of $K^+$ and especially $K^-$ mesons at highest AGS energies, still a significant underestimation at AGS energies does persist [36, 37]. The above HSD results do agree more or less with older RQMD results [38] (version 1.7) and ARC results [39], whereas newer RQMD calculations (version 2.3) are more in line with data. (Unpublished) URQMD calculations, as reported in [34], do find agreement for the lower AGS energies, but otherwise appreciably do underestimate the ratio. In the here reported HSD calculations only established baryon resonances up to $N^*(1535)$ are included, whereas at least in the newer version of RQMD [33] resonances of much higher mass have been implemented. As for the AGS energies and the lower SPS energies the baryon densities achieved are the highest, especially then the baryonic resonances could be of crucial importance and thus could be the possible reason for the significant differences in the various numerical simulations. At the full
SPS energies, where the secondary interactions are meson dominated, the possible influence of baryonic resonances is diminished and this then could explain why at this much higher energy the various model predictions do not differ as much as compared to the various AGS energies. (The changing role and importance of either baryonic or mesonic contributions to the $K^+ / \pi^+$ excitation function when going from AGS to SPS energies has recently also been observed within a thermal model analysis [4].) Clearly, a unified description would be desirable, however, different physical interpretations for the various model inputs can hardly be justified by a theoretical ab initio derivation at present.

Closing the discussion on the outcome of strangeness production at AGS and SPS energies within transport simulations, I do mention once more that the overall strangeness is produced by the very first highly non-equilibrium collisions. The amount of strange quarks in the system is then roughly conserved when the energetic and non-equilibrium reactions have ceased and the system has started to equilibrate locally in its particle momentum distributions. This observation is indeed the continuation to much higher bombarding energies of the early statement raised by Randrup and Ko for Bevalac energies. Refering again to our recent investigation [24], summarized in fig. 3, the chemical saturation timescale of kaons in a hadronic transport description is larger than 40 fm/c for all equilibrium energy densities up to 2-3 GeV/fm$^3$, and thus exceeds considerably the lifetime of the fireball in the center of mass frame.

What do we know about predictions on strangeness production in a QGP or on the strangeness content of a fully saturated QGP? The basic answer is ‘not much more’ than in the days when the first pQCD estimate [5] was made. This is a personal, and provocative statement. The old and simple estimate for the saturation rate of strangeness was based on the elementary cross section $\sigma_{gg \to s\bar{s}} \approx \pi \alpha_s^2 \ln \frac{v}{m_s}$ of two free gluons fusing to a strange-antistrange quark pair folded with thermal distributions for the gluons. The cross section depends logarithmically on the value of the strange quark mass. Instead of using the current mass of $m_s \approx 150$ MeV one might consider the typical value of $m_s^{NJL} \approx 400 - 500$ MeV obtained within a Nambu-Jona-Lasinio approach at and slightly above chiral restoration temperature [41], yielding roughly a factor of 2-3 smaller cross section in the kinemtical region of interest. The powerful tool of ‘hard thermal loop’ resummed techniques, in order to deal with the dynamically generated masses in a thermal field theoretical, infrared safe and consistent framework, for calculating strangeness production in the QGP has not been carried out with full success and a lot of uncertainties do remain [42]. Lattice gauge calculations so far have not contributed at all to the question of how much strangeness is inside a saturated QGP or inside a hadronic system close to the critical temperature. The strangeness content is again based solely on simple, perturbative estimates. Furthermore, hadronization is a nonperturbative phenomena and it is not known whether strangeness can be produced or not when hadrons are created out of a deconfined QGP state.

As mentioned in the introduction, a factor of 2-3 enhancement in the $K/\pi$-ratio relative to the one obtained in p+p collisions was not really considered as an unambiguous signal for QGP creation. Strangeness enhancement relative to p+p is seen from SIS energies up to nowadays RHIC energies. With particular respect to the experimental findings at SIS and AGS it is valid to say that strangeness enhancement does not require deconfinement. In view of our discussion above, strangeness production can be understood in terms of hadronic physics, although
Figure 5. Schematic picture for the multi-mesonic fusion-like reaction $3\pi + 2K \leftrightarrow \Xi + N$.

this does not disprove a temporary creation of a QGP.

The true proposed and advocated candidates have been the multistrange baryons, and, even more strikingly, all antihyperon species [7]. The analysis of abundancies of hadronic particles and especially strange particles, measured by NA49 and WA97, within thermal models does strikingly support the idea of having established a (thermodynamically) equilibrated and chemically saturated hadronic fireball in some particular late stage of the reaction, dubbed ‘point’ of chemical freeze-out (for analyses of Pb+Pb collisions at CERN-SPS see [8, 9]). In this respect especially a nearly fully saturated yield of antihyperons is found. In the following I will now report on our recent idea [10] of rapid antihyperon production by multi-mesonic reactions of the type (4) (see also the schematic illustration fig. 5) and provide new calculations considerably supporting this new insight. This idea does rest on the (conservative) view that before chemical freeze-out already a hadronic system has been established.

A few detailed, yet purely phenomenological attempts to explain a more abundant production of antihyperons within a hadronic transport description do exist like the color rope formation by Sorge et al [43, 33] or the high-dense cluster formation of Werner and Aichelin within the VENUS transport approach [44]. The underlying mechanisms, however, have to be considered as exotic: Sorge (as well as other studies like e.g. [45]) point out in detail the dramatic role of antibaryon annihilation, which he more then counterbalances by initial formation via color ropes. He also finds that the binary exchange channel (3) is actually not as small as advertised originally in [7], but helps rather quickly to repopulate the various strange antibaryon populations, if enough antibaryons are present (compare also the above discussion at SIS energies for the dominance and importance of the complete similar (T-conjugated) reaction (6)). The high-dense cluster formation, on the other hand, resembles in its philosophy the idea that in a very dense hadronic system potential multi-particle interactions could be modelled by a simple statistical treatment.

What are the new arguments? If the hadronic degrees of freedom are in a state of thermodynamical equilibrium, which constitutes the basic concept of any thermal model analyses, a dynamically realization to describe such a system has to fulfill the concept of detailed balance in the considered chemical reactions. As the annihilation of antihyperons on baryons is of dramatic relevance, the multi-mesonic (fusion-like) ‘back-reactions’ involving $n_1$ pions and $n_2$ kaons, corresponding to the inverse of the strong binary baryon-antihyperon annihilation process (similar to the standard baryon annihilation $\bar{p} + p \rightarrow n + \pi$), have, in principle, to be taken care of in a dynamical
simulation. \( n_2 \) counts the number of anti-strange quarks within the antihyperon \( \bar{Y} \). \( n_1 + n_2 \) is expected to be around 5 – 7. This reasoning has first been raised recently by Rapp and Shuryak concerning the production of anti-protons [47].

\[ n_1 + n_2 \approx 5 - 7. \]

Figure 6. The antihyperon to baryon number ratio \( N_{\bar{Y}}/N_B(T) \) and \( N_{\bar{Y}}^{eq.}/N_B(T) \) as a function of the decreasing temperature. For the evolving system an isentropic, Bjorken-like (including transversal) expansion \( V(t) \) has been assumed with an entropy per baryon of \( S/A = 30 \) yielding the explicit dependence \( T(t) \) for the temperature and similarly for the chemical potentials as functions of time. \( N_{\bar{Y}}(t_0 = 3 \text{ fm/c}) \) is set to zero.

The annihilation rate \( \Gamma_{\bar{Y}} \), as implemented in the various codes, is large and it should be approximately similar in magnitude as for \( p + \bar{p} \) at the same relative momenta. Hence, with \( \sigma_{p\bar{Y} \to n_1\pi + n_2K} \approx 50 \text{ mb} \) one has

\[
(\Gamma_{\bar{Y}})^{-1} = 1/(\langle \sigma_{\bar{Y}Nv_{\bar{Y}N}} \rangle \rho_N) \approx 1 - 3 \text{ fm/c},
\]

when adopting for the baryon density a typical value \( \rho_N \approx 1 - 2 \rho_0 \) when the system is still more dense than at the chemical freeze-out ‘point’ with \( \rho_N \approx 0.5 - 1 \rho_0 \) [8, 46]. It is this rapid annihilation process which also does dictate the timescale of how fast the antihyperon densities do approach local chemical equilibrium with the pions, nucleons and kaons. This follows rigorously from the concepts of kinetic theory [10, 48]. In principle, one can start from a kinetic Boltzmann-type equation taken into account these multi-mesonic fusion-type reactions as the production term being the necessary counterpart to the annihilatin term. From the microscopic Boltzmann description master equations, as presented in [14], can be obtained in a direct way [48]. Assuming further (for simplicity) that throughout the later expansion of the fireball the pions, baryons and kaons do stay in thermal and chemical equilibrium, a simplified master equation for the number of antihyperons as a function of time can be written in the most simple, but yet direct and illustrative form

\[
\frac{d}{dt} \rho_{\bar{Y}} = -\Gamma_{\bar{Y}} \left\{ \rho_{\bar{Y}} - \rho_{\bar{Y}}^{eq.} \right\},
\]
where production due to the multi-mesonic ‘back-reactions’ is hidden in the second term \( \Gamma_{Y} \rho_{G}^{eq} \).

The annihilation (= chemical saturation) timescale of the antihyperons is indeed small, and, according to \( [5] \), it is roughly proportional to the inverse of the baryon density. Still it has to compete with the expansion timescale of the late hadronic fireball, which is in the same range or larger. It becomes clear that these multimesonic, hadronic reactions, contrary to binary reactions, can explain most conveniently a sufficiently fast chemical equilibration of the antihyperons. A redistribution of some strange antiquarks out of the reservoir of the most abundant strange particles, the kaons, and of light antiquarks out of the huge reservoir of pions occurs to populate the much rarer antihyperon degrees of freedom to its equilibrium value. Beyond a certain ‘point’ (which, of course, is actually some continuous regime where inelastic decoupling occurs) with already a moderately low baryon density (and correspondingly low pion and kaon densities) it will be that the multi-mesonic creation process becomes more and more ineffective. This can explain, as will be demonstrated now, the clear ‘position’ of the chemical freeze-out for the antihyperons.

![Figure 7](image-url)

**Figure 7.** The anti-Λ to baryon number ratio \( N_{Y}/N_{B} \) \( (t) \) as a function of time for an assumed isentropic, Bjorken-like (including transversal) expansion \( V(t) \) and for various entropy content described via the entropy per baryon ratio \( (S/A = 20 – 40) \).

To be quantitative, two results of a recent study [48] will be briefly explained. The global late-time evolution of the system is assumed to be an isentropic expansion of the hadronic resonance gas with fixed total entropy content being specified via the entropy per baryon ratio \( S/A \). The effective volume \( V(t) \) is parametrized as function of time by longitudinal Bjorken expansion and including also an accelerating radial expansion. At starting time \( t_0 \) an initial temperature \( T_0 \) is chosen. (In the following two figures \( T_0 \) is set to 190 MeV. For the various entropy per baryon ratios \( S/A = 20 – 40 \) this corresponds to an initial baryon density of \( \rho_{B}(T_0; S/A) = 2.5 - 1\rho_0 \) and to an initial energy density of about 1 GeV/fm\(^3\).) From this ansatz the temperature and the chemical potentials do follow as function of time. The initial abundance of
antihyperons is set to zero (as a minimal assumption). A set of master equations of the principal structure as (10) are solved. In fig. 6 the number of antihyperons of each specie (normalized to the conserved net baryon number) as a function of the decreasing temperature is depicted. For a direct comparison the instantaneous equilibrium abundance of antihyperons, \( N_{eq}^Y(T(t), \mu_B(t), \mu_s(t))/N_B \), is also shown. The entropy per baryon is chosen as \( S/A = 30 \) being characteristic to global SPS results [13, 14, 15]. The equilibrium number strongly decreases as a function of time (or decreasing temperature). The typical characteristic of the depicted results is that first the antihyperons are dramatically being populated, then their individual yield does overshoot its respective equilibrium number and then does finally saturate at some slightly smaller value because of some final reabsorption. From fig. 6 one sees that the antihyperons effectively do saturate at a number which can be compared to an equivalent equilibrium number at a temperature parameter around \( T_{eff} \approx 150 - 160 \) MeV. This value for the temperature is strikingly close to the ones obtained within the various thermal analyses [8, 9, 46, 49]. (For the baryochemical potential a similar finding holds [15].)

In fig. 7 the number of anti-Λs as a function of time is given for various entropy per baryon ratios. One notices that the final value in the yield significantly depends on the entropy content, or, in other words, on the baryochemical potential. Especially the results at midrapidity from WA97 can best be reproduced by employing an entropy to baryon ratio \( S/A = 40 \) [48].

Summarizing, multi-mesonic fusion-type reactions are a consequence of detailed balance and as the rate \( \Gamma_Y \) is indeed very large for a dense hadronic system chemical equilibrium is approached very quickly. This is a remarkable observation as it clearly demonstrates the importance of hadronic multi-particle channels. In this respect I would like to mention the recent proposal by Karliner and Ellis, that an intermediate multi-pion-state can actually explain the so called \( e^+e^- \rightarrow \bar{N}N \) puzzle at threshold energies [50].

As the basic assumptions, i.e. (I) the annihilation cross section for antihyperons colliding with a nucleon is roughly as large as the measured one for \( \bar{p} + p \) and (II) at the onset for the equilibration of the antihyperons one has to assume a somehow equilibrated hadronic fireball with still a moderate baryonic density, are quite modest and not of any exotics, the enhancement of antihyperon production is not a true QGP signature. One can always argue that (1) the hadronic gas can only exist as a dilute system with an energy density to be considerable below 1 GeV/fm\(^3\), otherwise the system would be in a deconfined QGP state, and/or (2) the expansion goes dramatically rapid so that any inelastic interactions in the late hadronic system are non-effective [51, 49]. But these are just other model assumptions.

One could be tempted to ask whether a similar reasoning also applies for the multi-strange hyperons (the Ξ and the Ω) for which also experimentally a significant enhancement has been reported. The answer is ‘no’. The equilibration rate here would be governed by the density of antibaryons and is thus too low, or putting it differently, the equilibrium density of multi-strange hyperons is much higher than the one of antihyperons. Especially the Ω could be the potential loop-hole as QGP signal, as it is very difficult to obtain its dramatically large yield (compared to p+p) by pure binary final state hadronic interactions without invoking additional pre-hadronic mechanisms [52, 53]; see, however, also [54, 55].

Cassing made a significant step forward very recently in trying to implement such ‘back-reactions’ within a present transport code. First results concerning the
production of anti-protons at AGS and SPS energies are quite impressive \[56\]. There is also a clear hint at AGS energies of enhanced anti-Λ production: E917 \[57\] had reported very recently a large value for the $\bar{\Lambda}/\bar{p}$ ratio of $3.6^{+4.7}_{-1.8}$ for central Au+Au collisions, which confirms earlier, but indirect measurements by E864 and E878, and by E859 for the lighter Si+Au collision at 14.6 AGeV. Here it is mandatory to first understand the $\bar{p}$-production as reported by e.g. E802 and to see whether the multipionic channel is dominant. This seems to be indeed the case \[56\]. The enhanced production of anti-As compared to anti-protons at AGS energies one can understand in a way that one assumes that their annihilation cross section on baryons is just slightly smaller \[18\]. But this is speculation at present. Unfortunately, there is no data for $\Xi$ at AGS. A clean and detailed measurement of all antihyperons represents an excellent opportunity for future heavy ion facilities at an energy upgraded GSI.

4. Conclusions: ‘Where are we ...?’

I have tried to review three of the early great ideas of why strange particles can probe interesting, collective physics of strong interactions in a macroscopic system. For the theoretical guide of the discussion I had tried to review and to give insight in the present and very detailed knowledge of hadronic transport approaches. They do serve as an excellent benchmark to understand the complete nonequilibrium evolution, to test and implement, if possible, various ideas and, if necessary, to really unravel new exciting physics beyond standard transport.

Do we see a strongly reduced effective energy for the antikaons, and a slightly enhanced one for the kaons at SIS energies? All groups do need the potentials in one or the other way. None of the many transport approaches can describe the various data without invoking some sort of in-medium modifications. So there is a good indication. However, there still remains some important cross sections to be addressed and compared in detail among the transport competitors in order to converge to a consistent picture.

Do we have learned the nuclear EoS from kaon measurement? There is a moderate indication that indeed one can extract a soft and momentum dependent EoS from comparison with data. Still, because of the various ambiguities in the cross sections, which have to be addressed, I think the claim might be premature. In any case cross correlations with other potential good observables on the nuclear EoS should be consistently addressed with each individual model if to come for a final consensus.

Last not least the historically intriguing question whether we do see the QGP from abundant strange particle production and, in particular, from antihyperons? As elaborated, I believe that the overall strangeness discussed is produced at the very early nonequilibrium stage. As this seems to be true for all energies this does not prove deconfinement. How does then strange flavor redistribution to rare particles happen. At SIS energies the rare antikaons are not produced directly but stem from secondary flavor exchange reaction of a hyperon on a pion. An alternative reasoning could be true for making the rare antihyperons at SPS and AGS energies: Intriguing, novel, multi-mesonic collapses to form baryon-antibaryon pairs could efficiently do the job. Hence, antihyperons can be produced by more collective and complicated, yet hadronic kinetic reactions.
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