Do chemically saturated antihyperon abundancies signal the quark gluon plasma?

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Abstract. We first review the production and the possible chemical equilibration of strange particles at CERN-SPS energies within a microscopic hadronic transport calculation. It is shown in particular that the strange quarks are produced initially via string excitations in the primary, secondary and ternary interactions. We then further elaborate on a recent idea of antihyperon production by multi-mesonic reactions like \( n_1 \pi + n_2 K \rightarrow \bar{Y} + p \) corresponding to the inverse of the strong binary baryon-antibaryon annihilation process. It is argued that by these reactions the (rare) antihyperons are driven towards local chemical equilibrium with pions, nucleons and kaons on a timescale of 1–3 fm/c in the still moderately baryon-dense initial hadronic environment after the termination of the prehadronic string phase. Accordingly this mechanism can provide a convenient explanation for the antihyperon yields at CERN-SPS energies without any need of a deconfined quark gluon plasma phase.

Keywords: relativistic heavy ion collisions, quark gluon plasma, (multi-)strange particles

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1. Introduction and Motivation

The prime intention for present and future ultrarelativistic heavy ion collisions lies in the possible experimental identification of the quark gluon plasma (QGP). The QGP represents a theoretically hypothesized and from QCD lattice calculations convincingly established new phase of matter, where quarks and gluons are deliberated from the hadronic particles and move freely over an extended, macroscopically large region. Moreover, considering several different observations within the Lead Beam Programme at the CERN-SPS, strong ‘circumstantial evidence’ for the temporal formation of the QGP has been conjectured [1] very recently. As one particular
example, strangeness enhancement has been predicted already a long time ago as one of the much favored diagnostic probes for the short-time existence of a QGP [2]: The main idea is that the strange (and antistrange) quarks are thought to be produced more easily and hence also more abundantly in such a deconfined state as compared to the production via highly threshold suppressed inelastic hadronic collisions. In this respect, especially the antihyperons and also the multistrange baryons were advocated as the appropriate candidates [2].

In Fig. 1 we depict the intriguing observation from the seminal report article of Koch, Müller and Rafelski: It shows the approach to chemical equilibrium of the various population densities of strange hadronic particles containing at least one antistrange quark as a function of time 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 within a thermalized fireball environment of hadronic particles the strange antibaryons are dominantly be produced by subsequent binary strangeness exchange reactions with the (maybe) chemically equilibrated kaons like

$$K + \bar{p} \rightarrow \pi + \bar{\Lambda}, \Sigma; \quad K + \bar{\Lambda} \rightarrow \pi + \Xi$$

(1)

Fig. 1. Part (b) of Fig. 5.5 taken from the report article by Koch, Müller and Rafelski [2]. Clearly the antihyperons do not approach chemical equilibrium even after 1000 fm/c, whereas the kaons have equilibrated much earlier.
with very low cross sections. On the other hand, assuming the existence of a temporarily present phase of QGP and following simple coalescence estimates the abundant (anti)-strange quarks can easily combine with the light (anti-)quarks to form the strange hadrons [2], which do then, in return, come close to their chemical equilibrium values. (Of course, these predictions can only be regarded as qualitative, yet plausible: A satisfactory theoretical understanding of the dynamics and of the hadronisation of a hypothetical deconfined phase as well as the production of strangeness in this state is at present not really given.)

Indeed, an enhancement of strangeness has been reported, calibrated in relation to p+p or p+A collisions [3]. This is in particular true for the antihyperons (and to a little lesser extent for multistrange baryons). Such an enhancement can certainly not be explained by the above mentioned binary strangeness exchange reactions. On the theoretical side the analysis of measured abundancies of hadronic particles with simple thermal models [4-6] strongly supports the idea of having established an equilibrated fireball in some late stage of the reaction, where all hadrons with light and/or strange quark content do exist in number nearly according to their chemical equilibrium values. (The thermodynamical properties found by the various groups can phenomenologically easily be explained in fact by a rapidly hadronizing and disintegrating QGP phase [7]. This has very recently been pursued in trying to extract the critical energy density [6].) (Nearly perfect) Chemical equilibration is found to be true for the antihyperons. Alas, this all then gives strong support for some new exotic mechanism like, most plausible, the temporary formation of a deconfined and strangeness saturated new state of matter.

Although intriguing, after all this may not be the correct interpretation of the observed antihyperon yields: In the following we elaborate on our recent idea of antihyperon production by multi-mesonic reactions like

\[ n_1\pi + n_2K \rightarrow \bar{Y} + p \]

corresponding to the inverse of the strong binary baryon-antibaryon annihilation process [8]. The latter process, on the other hand, dictates the timescale of how fast the antihyperon densities do approach local chemical equilibrium with the pions, nucleons and kaons. This timescale is thus to a good approximation proportional to the inverse of the baryon density. Adopting an initial baryon density of approximately 1–2 times normal nuclear matter density \( \rho_0 \) for the initial and thermalized hadronic fireball, the antihyperons will equilibrate on a timescale of 1–3 fm/c! This timescale competes with the expansion timescale of the late hadronic fireball, which is in the same range or larger. In any case it becomes plausible that these multimesonic, hadronic reactions, contrary to the binary reactions (1), can explain most conveniently a sufficiently fast equilibration before the (so called) chemical freeze-out occurs at the parameters given by the thermal model analyses (, and where the baryon density has dropped to around 0.5 - 0.75 \( \rho_0 \)). One can always argue that before this point in time a new state of matter might have occurred as the energy density becomes close to or above 1 GeV/fm\(^3\) [9]. (This is the value what lattice QCD at present estimates for the critical energy density, where at equilibrium and zero net baryon density the transition to a deconfined state should occur.) Our interpretation does rest on the (conservative) view that before the chemical freeze-
out already a hadronic system has established. Whether even before this stage a
deconfined state or a non-equilibrium stage of hadronic string-like excitations had
existed is then still a matter of debate, but it is not the present issue for explaining
the chemical saturation of the antihyperons at chemical freeze-out.

Before we detail this mechanism of antihyperon production and also comment
on a few of the necessary assumptions (and potential reservations [9]), we first want
to briefly sketch in the next section a couple of interesting conclusions on overall
strangeness production (i.e. the most dominant kaons and Λs) and equilibration
obtained within a microscopic hadronic transport model [10,11].

2. Strangeness production and equilibration

![Graph](image)

**Fig. 2.** Calculated $K^+/\pi^+$-ratio around midrapidity for central Au+Au reactions
(open squares) from SIS to RHIC energies in comparison to experimental data.
For visualization of the the collective strangeness enhancement the corresponding
ratio for elementary p+p collisions (open circles) is also depicted. This plot has
been taken from [15,16].

As outlined in the introduction the possible strangeness enhancement in heavy
ion collisions has been one of the driving motivation for the experimental study
of strange particle production. Since a relative enhancement is observed already
in hadron-hadron collisions for increasing energy (see Fig. 2), which is certainly
not due to any macroscopic or bulk effects, the to be measured strangeness should be compared relative to p+p collisions at the same energy. The arguments for enhanced strangeness production via the QGP should generally apply already for the most dominant strange particles, the kaons, as their chemical equilibration time in a hadronic fireball has been estimated to be \( \approx 100 \text{ fm/c} \) [2] (see also fig. 1 and fig. 3). On the other hand, it was also argued 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 [12]. Moreover, as we will now summarize, nonequilibrium inelastic hadronic reactions can explain to a very good extent the overall strangeness production seen experimentally [10,13].

In a recent systematic study we had investigated the properties of \( K^+ \), \( K^- \) and \( \Lambda \) particles in nuclear reactions from SIS to CERN-SPS energies [10] within the microscopic hadron-string transport approach HSD (for details describing the transport algorithm see [14]). An important ingredient has been the implementation of the elementary cross sections for strangeness production in baryon-baryon, baryon-meson and meson-meson channels. An enhancement of the scaled kaon yield due to hadronic rescattering both with increasing system size and energy was found. This is expected within any hadronic model if the kaons and other particles do not feel any attractive potentials. 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 \( \approx 6 \sim 8\% \) at AGS to SPS energies before the hadronic rescattering starts. 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. The outcome for the most dominant strange particles, the \( K^+ \)-mesons, is summarized in fig. 2. We want to emphasize that the secondary (meson-baryon) and ternary (meson-meson) induced string-like interactions do contribute significantly to the total 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 explains the factor 1.75 as the relative enhancement compared to p+p (compare fig. 2). 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. On the other hand, at the lower AGS energies, the relative enhancement factor of \( \approx 3 \) can not be fully explained within the cascade type calculations [10]. This might indicate some new physics involved for the primary \( s\bar{s} \) production mechanism: Including meson potentials can help to reasonably understand the production of \( K^+ \) and especially \( K^- \) mesons at lower SIS energies, yet some smaller, but still significant underestimation at AGS energies does persist [14,16].

Only for a system close to thermal equilibrium, as was assumed in the early calculations [2], the overall strangeness production rates (for kaons and \( \Lambda \)s) are substantially suppressed due to the high thresholds. As pointed out above and also in a very recent study [11] this is due to the oversimplified initial conditions. In [11]
Fig. 3. Time evolution towards stationary equilibrium values for various particle ratios in an ‘infinite matter’ calculation [11]. The box is prepared with a baryon density $\rho_B = \rho_0$ and an energy density of $\epsilon = 0.52 \text{ GeV/fm}^3$. The $K^+ / \pi^+$ ratio needs about 50-100 fm/c to approach its stationary equilibrium value. The left panel shows the time scale up to 1000 fm/c, whereas the right panel demonstrates the initial stage. For the initialized non-equilibrium situation the $K^+ / \pi^+$-ratio starts via the decay of the early (primary, secondary and ternary) string excitations already at a large value moderately close to its later equilibrium value.

‘infinite’ hadronic matter is simulated within a cubic box, starting with a nonequilibrium initial configuration in momentum space which does somehow resemble the initial or early intermediate situation in a true heavy ion collision. One particular microscopic simulation towards equilibrium is depicted in fig. 3. As one can see really chemical equilibrium for the kaons and antikaons is approached only at $\approx 50 \text{ fm/c}$ at the given energy and baryon density (which both are higher than the ones calculated from the chemical freeze-out point [4]). This is in accordance with the early calculations [2]. On the other hand one also sees that eg the $K^+ / \pi^+$-ratio $\approx 0.15$ starts via the decay of the early string excitations already at a quite large value and then stays rather constant in time. As elaborated above, in a simulation of a true heavy ion collision strangeness is produced in the very early stage and these early produced strange/antistrange quarks then suffice to explain the majority of strange particles (kaons, antikaons and $\Lambda$s) at SPS energies.

In addition, it was also shown in [11] that local kinetic equilibrium is reached on a sufficient fast timescale by the multiple processes of subsequent string fragmentation. The string excitations do provide a very efficient mechanism to produce
Do $\bar{Y}$ signal the QGP?  

Do $\bar{Y}$ signal the QGP?  

transversal energy. In summary, the microscopic transport calculations do support qualitatively the idea that there exists a regime in time during the heavy ion collision where thermal and chemical equilibrium among the various hadronic particles should be (locally) realised.

3. Antihyperon production by kaons and pions

We now repeat and detail on our previous idea on antihyperon production [8]: Not subsequent binary hadronic reactions of type (1) but in fact multi-pionic and kaonic interactions in a thermalized hadronic gas lead to a very fast chemical equilibration of the antihyperon degrees of freedom. For this one has to look first on the following annihilation reactions similar to the standard baryon annihilation $\bar{p} + p \rightarrow n \pi$, but now involving one antihyperon and then do apply rigorously the concept of detailed balance:

$$
\bar{\Lambda} + N \leftrightarrow n\bar{\Lambda} \pi + K
$$

$$
\bar{\Xi} + N \leftrightarrow n\bar{\Xi} \pi + 2K
$$

$$
\bar{\Omega} + N \leftrightarrow n\bar{\Omega} \pi + 3K
$$

or, in shorthand notation,

$$
\bar{Y} + N \leftrightarrow n\pi + n\bar{Y}K .
$$

$n_Y$ counts the number of anti-strange quarks within the antihyperon $\bar{Y}$. $n + n_Y$ is expected to be around $\approx 5 - 7$. The reactions (2) are all exothermic. It is also plausible to assume that the annihilation cross sections are approximately the same like for $N\bar{p}$ at the same relative momenta. Hence, in the relevant regime of a thermal hadronic gas with temperatures of $T \approx 120 - 200$ MeV one has $\sigma_{p\bar{Y} \rightarrow n\pi + n\bar{Y}K} \approx 50$ mb, which is indeed a large cross section.

The above reactions (2) do effectively lead to the following master equation for the respectively considered antihyperon density within a hadronic gas:

$$
\frac{d}{dt}\rho_{\bar{Y}} = -\langle \sigma_{\bar{Y}N}v_{\bar{Y}N} \rangle \left\{ \rho_{\bar{Y}}\rho_{N} - \sum_{n} R_{(n,n\bar{Y})}(T,\mu_B,\mu_s)(\rho_{\pi})^{n}(\rho_{K})^{n\bar{Y}} \right\} .
$$

The ‘back-reactions’ of several effectively coalescing pions and kaons are incorporated by the ‘mass-law’ factor

$$
R_{(n,n\bar{Y})}(T,\mu_B,\mu_s) = \frac{\rho_{\bar{Y}}^{eq.}\rho_{N}^{eq.}}{(\rho_{\pi}^{eq.})^{n}(\rho_{K}^{eq.})^{n\bar{Y}}} p_n .
$$

Here $p_n$ states the (unknown) relative probability of the reaction (2) to decay into a specific number $n$ of pions with $\sum_n p_n = 1$. $R$ has a clear physical origin as it
Fig. 4. Time evolution of the (average) net baryon density for midrapidity $|\Delta Y| \leq 1$ and central Pb+Pb-collision. Here the amount of baryon number residing still in string-like excitations is explicitly discarded. String-like excitations have disappeared after 4.7 fm/c, so that from this time on a pure hadronic fireball develops and expands. Its initial net baryon-density starts slightly above $\rho_B = 2\rho_0$.

is responsible to assure detailed balance in the competition between the annihilation process and the various contributing multi-mesonic 'back reactions'. $\mathcal{R}$ then depends only on the temperature and the baryon and strange quark chemical potentials. $\langle \sigma_{\bar{Y} N} v_{\bar{Y} N} \rangle$ denotes the thermally averaged cross section. We take $N$ as synonym for any baryonic particle, most dominantly the nucleons and $\Delta$-excitations. Furthermore, $\Gamma_{\bar{Y}} \equiv \langle \sigma_{\bar{Y} N} v_{\bar{Y} N} \rangle \rho_B$ gives the effective annihilation rate of the respective antihyperon specie on a baryon. Assuming that the pions, baryons and kaons stay in thermal and chemical equilibrium, the master equation then becomes simply

$$\frac{d}{dt} \rho_{\bar{Y}} = -\Gamma_{\bar{Y}} \left( \rho_{\bar{Y}} - \rho_{\bar{Y}}^{eq} \right). \quad (5)$$

It should become clear by now that indeed the mean annihilation rate yields the characteristic inverse time to drive the antihyperon densities to their chemical equilibrium values, i.e. it corresponds to the inverse of the characteristic chemical equilibration time. So how large is it?

At the onset of thermalization and chemical equilibration for all other degrees of freedom in the hadronic fireball the baryon density might still be rather large and could exceed two times normal nuclear matter density [17, 18]. In fig. 4 we have depicted the net baryon density as a function of time at a space region for particles
at midrapidity obtained within a microscopic transport model [18]. The figure illustrates that a pure hadronic fireball (without any string-like excitations) at two times baryon density has established during the ongoing (longitudinal) expansion. It is interesting to note that the chemical freeze-out ‘point’ with the parameters calculated in [4–6] takes place at a value of $0.5 - 0.75 \rho_0$. This would correspond to a time of 8-10 fm/c in fig. 4. Taking now for the average baryon density evolving shortly before the chemical freeze-out point $\langle \rho_B \rangle \approx 1 - 2 \rho_0$ and employing the above estimate for the antihyperon annihilation cross section, i.e. $\sigma_{pY \rightarrow n\pi + nY K} \approx 50$ mb, one has for the chemical equilibration time of antihyperonic particles the striking number

$$\langle \Gamma_{pY} \rangle^{-1} = \frac{1}{\langle \sigma_{pY \rightarrow n\pi + nY K} \psi_{pY} \psi_{n} \rangle \rho_B} \approx 1 - 3 \text{ fm/c} .$$

(6)

This is a very fast process (!) and lies below the typical fireball lifetime of 10 fm/c. Indeed, microscopic calculations within (U)RQMD have shown that antibaryon annihilation takes place with considerable rate and that the overall anti-baryon yield can be hardly described within the standard transport approaches exactly because of the large annihilation cross section [19]. Antihyperons are forced rather immediately to local chemical equilibrium together with the pions, kaons and nucleons by the ‘back reactions’! One has to be a little bit more precise [9]: What actually has to be compared is the timescale of how fast the fireball does expand or, referring to the rate (6), of how fast the baryon density does drop. From fig. 4 one finds that this timescale is 3-4 fm/c. This is a reasonable expectation. Hence, there is no need for any ‘exotic’ explanation (like eg the temporal existence of a potential QGP saturated in strangeness) to account for the thermally and chemically equilibrated particle number of antihyperons observed at the chemical freeze-out point. In fact, beyond that ‘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 would then also explain the clearer ‘position’ of the chemical freeze-out point for the antihyperons.

To be more quantitative some explicit coupled master equations for an expanding system have to be considered. Such work is in progress [20]. In addition one can also study at which point on average the antihyperon degrees of freedom kinetically do decouple (thermal freeze-out). The decoupling does depend probably and most simply on the explicit (and unknown) parametrisation of the elastic cross section of the antihyperons with the pions. This has been pointed out already by Hecke et al [21] when addressing the fact that the experimentally deduced effective inverse slopes $'T'_Y$ of the (anti-)hyperon spectra and especially of the multi-strange $\Omega$-spectrum do not follow the linear increasing trend in mass.
4. Summary, conclusions and outlook

To summarize, the multi-mesonic source of production of antihyperons is a consequence of detailed balance and, as the rate $\Gamma_Y$ is indeed very large, this is the by far most dominant source compared to any binary production channel (1). This, as we believe, is a remarkable observation as it clearly demonstrates the importance of hadronic multi-particle channels. At the moment such ‘back-reactions’ cannot be handled within the present transport codes and some clever strategy has to be invented. This could be a nice exercise for the future. Nonetheless, as we have shown, there exists a simple non-exotic mechanism for explaining the $\bar{Y}$ abundancies in a purely hadronic scenario.

One might be tempted to ask whether a similar reasoning also applies for the multi-strange hyperons (the $\Xi$ and the $\Omega$) for which also some 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. It might be that only more exotic microscopic processes (or potentially only the celebrated deconfined state of matter) can explain the enhancement [23].

The mechanism to work out for the antihyperonic degrees of freedom is based on two rather moderate assumptions: (I) The thermally averaged annihilation cross section for antihyperons colliding with a nucleon, i.e. $\bar{Y} + N$, is roughly as large as the measured one for $\bar{p} + p$ or $\bar{p} + n$. (II) At the onset for the equilibration of the antihyperons one has to assume a hadronic fireball with still a moderate baryonic density and where the pions together with the nucleons and the kaons are assumed to be nearly in chemical equilibrium. As discussed in the second section, the abundant and early production of kaons and antikaons can reasonably be accounted for by hadronic transport models. If, as presented in some of the thermal models, a strangeness suppression factor $\gamma_s$ for each unit of strangeness is introduced [5], one then finds for the stationary point of the master equation [8]

$$\rho_Y^{eq} \rightarrow \rho_Y = (\gamma_s)^n \rho_Y^{eq},$$

which is consistent with the employed phenomenological prescription [5].

There is also a clear hint at AGS energies of enhanced anti-$\Lambda$ production: On the one hand the E859 Collaboration has measured the $\bar{\Lambda}/\bar{p}$ ratio in Si+Au at 14.6 AGeV and had reported a large value $\bar{\Lambda}/\bar{p} = 2.9 \pm 0.9 \pm 0.5$ for some central rapidity window. On the other hand such a value has also been discovered, albeit for low transverse momentum, by the E864 Collaboration for the most central collisions [24]. According to the thermal models the deduced temperatures at the AGS-energies are lower and the obtained baryon densities are even higher. Our argument should thus perfectly apply. Measurements of antihyperon production could also be done at possible future heavy ion facilities at GSI working then at much higher bombarding energies comparable or exceeding AGS energies. This would be a very interesting opportunity to unravel the here proposed mechanism.
Do $\bar{Y}$ signal the QGP?

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Notes

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c. Our idea has been triggered by a recent work [22] (but see also next footnote $d$) which dealt with the question of how antiprotons might maintain nearly perfect chemical equilibrium until so called thermal freezeout at temperatures $T \approx 110$ MeV much lower than at chemical freeze-out. However, the baryon densities are typically much lower between these two stages of chemical freeze-out to thermal freeze-out ($\rho_B \sim 0.5 - 0.05 \rho_0$, compare also fig. 4), so that the multipionic reactions $n\pi \leftrightarrow N + \bar{p}$ becomes less effective while competing against the rather rapid expansion and dilution. Our intention, on the other hand, has been to explain qualitatively via the addressed multihadronic channels the production of antihyperons before and at the so called point of chemical freeze-out.
d. The here discussed multi-mesonic channels for producing antihyperons are not considered for the first time: In fact they had been taken into account in the set of master equations for the strange hadronic particle densities by Koch et al [2]. The now mysterious question is then why the authors had not come at that time to our present conclusion? Much to the contrary they put forward the agenda for the antihyperons as a clear signature of a QGP. Looking at Fig. B3 in [2] they have only considered the annihilation cross section $\sigma_{\bar{p}p \rightarrow 5\pi} \approx 10$ mb, which is a factor of 5 or so smaller than the total annihilation cross section. Still, inspecting fig. 1, their equilibration rate of the antihyperons is even then still two to three orders of magnitude too small!

References

20. C. Greiner and S. Leupold, work in progress.