Antihyperon-Production in Relativistic Heavy Ion Collisions

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Recently it has been shown that the observed antiproton yield in heavy-ion collisions at CERN-SpS energies can be understood by multi-pionic interactions like \( \pi\pi\pi\pi \leftrightarrow p\bar{p} \) which enforce local chemical equilibrium of the antiprotons with the nucleons and pions. Here we show that antihyperons are driven towards local chemical equilibrium with pions, nucleons and kaons on a timescale of less than 3 fm/c when applying a similar argument for the antihyperons by considering the inverse channel of annihilation reactions like \( \bar{Y} + p \leftrightarrow n_1\pi + n_2K \). These multi-mesonic reactions easily explain the antihyperon yields at CERN-SpS energies as advertised in pure thermal, hadronic models without the need of a quark gluon plasma phase. In addition, the argument also applies for AGS energies.

\[ \pi + \bar{p} \rightarrow \bar{K} + \bar{\Lambda}, \bar{\Sigma} \]  
\[ \pi + \bar{\Lambda} \rightarrow \bar{K} + \bar{\Xi} \]  

or, successively, by further binary strangeness exchange reactions with the (to be produced) kaons like e.g.

\[ K + \bar{p} \rightarrow \pi + \bar{\Lambda}, \bar{\Sigma} \]  
\[ K + \bar{\Lambda} \rightarrow \pi + \bar{\Xi} \]  

with rather low cross sections. Antihyperons should indeed be very rare and exotic probes. On the other hand, assuming the existence of a temporarily present phase of QGP, the rather light strange quarks, following simple kinetic arguments, can be produced much more abundantly by strangeness suppression factor \( \gamma_s \) for each unit of strangeness contained in a specific hadronic particle is introduced to slightly better account...
for a common overall fitting to the ratios \[ [7, 10, 12] \]; this factor typically varies around \( \gamma_s \approx 0.7 - 0.9 \) and is thus close to unity.

Although the arguments at hand seem rather plausible, it has been shown by means of sophisticated hadronic transport algorithm like RQMD \[ 3 \] or HSD \[ 4 \] that at least the major amount of produced strange particles, kaons, antikaons and Lambdas can be understood in terms of still energetic and non-equilibrium secondary and ternary interactions among nucleons and already produced mesons. This is especially true at SpS-energies \[ 4 \], whereas at lower AGS-energies some smaller deficiency still persists. Only for a system close to thermal equilibrium, as was assumed in the early calculations \[ 3 \], the strangeness production rates are substantially suppressed due to the high thresholds when considering such oversimplified initial conditions \[ 15 \]. The conclusion that a QGP is needed to explain the overall strangeness production seems to be considerably weakened and thus premature if it is not to explain for the enhanced production of the rare antihyperons and multistrange baryons! A few phenomenological attempts to explain the more abundant production within a hadronic transport description do exist like the color rope formation by Sorge et al \[ 16 \] or the high-dense cluster formation of Werner and Aichelin within the VENUS code \[ 17 \]. The underlying mechanisms, however, have to be considered as exotic (like also the ad hoc dynamical formation of the QGP). In addition, the agreement with data is quantitatively not completely satisfying \[ 18 \].

In the following we present and elaborate on a convincing argument that not binary hadronic reactions, as considered above, 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. Our argument will be 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 we assume a hadronic fireball (with thermodynamic parameters as obtained e.g. in \[ 6–11 \]), where the pions together with the nucleons and the kaons are assumed to be nearly in chemical equilibrium. As discussed above, the abundant and early production of kaons and antikaons can reasonably be accounted for by sophisticated hadronic transport models without the need for a QGP.

Indeed the idea was triggered by a recent work of Rapp and Shuryak who described the maintenance of nearly perfect chemical equilibrium of antiprotons together with pions and nucleons during the late stage of the expanding hadronic fireball until thermal freezeout at rather low temperatures of \( T \approx 120 \text{ MeV} \) \[ 14 \]. They argued that the balance between the inverse multi-pionic channel of the reaction

\[
\bar{p} + N \leftrightarrow n\pi , \tag{3}
\]

where \( n \approx 5 - 7 \) denotes the typical number of pions, together with the strong annihilation rate \( (\Gamma_{\bar{p}})^{-1} = \tau_{\bar{p}} \approx 3 \text{ fm/c} \) leads to an effective chemical potential for the antiprotons

\[
\mu_{\bar{p}} \approx -\mu_p + n\mu_\pi = -\mu_B + n\mu_\pi , \tag{4}
\]

which can account for the antiproton yield also with parameters at thermal freeze-out. The pions are assumed here to acquire a nonvanishing chemical potential \( \mu_\pi \neq 0 \) as the inelastic annihilation of pions cannot be sustained at lower temperatures \[ 21 \]. In any case this is a remarkable observation as it clearly demonstrates for special observables - like the considered abundance of antiprotons - the importance of kinetic multi-particle channels. It is rather well-known that the overall \( \bar{p} \) yield can be hardly described within standard transport approaches due to the large annihilation cross section without invoking new ad hoc assumptions or scenarios \[ 21 \]. This circumstance is then exactly due to the violation of detailed balance when not considering the multi-particle ‘back-reaction’ as the most dominant source of production. Naively one might argue that the probability of \( 5 - 7 \) pions to come close in space is very low and therefore irrelevant. This however is misleading. In fact concerning e.g. possible changes in the total pion number the reaction \( (3) \) might be neglected. For \( \bar{p}s \) (and for anti-strange baryons), however, the situation is different since their abundance is very low. Therefore also less likely reactions may become important.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Fig1.png}
\caption{Schematic picture for \( \bar{\Xi} + N \rightarrow 3\pi + 2K \). See main text for details.}
\end{figure}

Let us consider the analogous annihilation reactions involving one antihyperon

\[
\begin{align*}
\Lambda + N &\leftrightarrow n_\Lambda \pi + K \\
\bar{\Xi} + N &\leftrightarrow n_{\bar{\Xi}} \pi + 2K \\
\bar{\Omega} + N &\leftrightarrow n_{\bar{\Omega}} \pi + 3K
\end{align*} \tag{5}
\]
or, in shorthand notation,

\[
\bar{Y} + N \leftrightarrow n_\pi + n_\gamma K , \tag{6}
\]

where \( n_\gamma \) counts the number of anti-strange quarks within the antihyperon \( \bar{Y} \), and, in direct analogy to reaction \( (3) \), \( n + n_\gamma \) is expected to be around \( 5 - 7 \).
A typical annihilation reaction is schematically depicted in Fig. 1. The reactions [1] are exothermic as the reaction (3). As an educated guess it is plausible to assume that the annihilation cross sections are approximately the same as for \( N\bar{p} \) for the same relative momenta. In the relevant regime of a thermal hadronic gas with temperatures of \( T \approx 150 – 200 \) MeV one has \( \sigma_{pY \rightarrow n\pi + n\bar{Y}} \approx \sigma_{p\bar{p} \rightarrow n\pi} \approx 50 \) mb in the relevant energy regime \([19, 22]\). (Of course, though, the annihilation cross section of equally charged particles like e.g. \( \Xi^+ + p \) will be Coulomb suppressed at very low relative momenta, but this is not of much importance for the thermally averaged cross section.) At the onset of thermalization and chemical equilibration for all other degrees of freedom in the hadronic fireball the baryon density is still rather large and might exceed two times normal nuclear matter density. For the following estimate we use \( \rho_B \approx 2\rho_0 \) [3]. One then finds for the inverse of the thermal reaction rate which as we shall see equals the chemical equilibration time of the antihyperon particles

\[
(\Gamma_Y)^{-1} = \tau_Y := \frac{1}{\langle \sigma_{p\bar{Y} \rightarrow n\pi + n\bar{Y}} \rangle \rho_B} \approx 1 - 2 \text{ fm/c} ,
\]

which is indeed very small and much below the typical fireball lifetime of \( 5 - 10 \) fm/c. Antihyperons are forced rather immediately to local chemical equilibrium together with the pions, kaons and nucleons! There is no need for any exotic explanation, either hadronic or by coalescence out of a potential QGP, to account for the thermally and chemically equilibrated total particle number of antihyperons.

We have to note that the consideration of the above reactions [3] is not new. In fact, this has been taken into account already in the master equations for the strange hadronic particle densities developed by Koch et al [3]. The obvious question is then why they had not obtained our present conclusion, but much to the contrary put forward the by now famous agenda for the antihyperons as a clear signature of a QGP! Looking at Fig. B3 in [3] they have only considered the annihilation cross section \( \sigma_{p\bar{p} \rightarrow n\pi} \approx 10 \) mb, which is a factor of 5 or so smaller than the total annihilation cross section \( \sigma_{p\bar{p} \rightarrow n\pi} \approx 50 \) mb [23, 19] in the relevant kinematic regime. As the obtained results in [3] do still show a much slower equilibration rate, a definite conclusion cannot be given [23].

To present our argument more definite, let us write down the dominating contribution for the master equation of the antihyperon density in a hadron gas following closely the notation in [3]:

\[
\frac{d}{dt}\rho_Y = -\langle \sigma_{Y \bar{N} + n\pi} \rangle \rho \rho_N - \sum_n \mathcal{R}_{(n,nY)}(T, \mu_B, \mu_s) \rho^n \rho_N^n ,
\]

where \( \rho_i \) is the density of species \( i \) and

\[
\mathcal{R}_{(n,nY)}(T, \mu_B, \mu_s) = \frac{\rho_n^{eq} \rho_N^{eq}}{(\rho_n^{eq})^n \rho_N^{eq}}
\]

denotes the appropriate factor for assuring detailed balance which depends only on the temperature and the chemical potentials. Here we sum over all possible final number \( n \) of pions. \( \langle \sigma_{Y \bar{N} + n\pi} \rangle \) denotes the thermally averaged cross section as defined in [3]. As the nucleons are the most dominant baryonic particles we take \( \rho_N \approx \rho_B \) and employing (3) the master equation (6) can be brought in the more intuitive form

\[
\frac{d}{dt}\rho_Y = -\Gamma_Y \rho_Y + \mathcal{G}_Y ,
\]

where \( \Gamma_Y \approx 0.5 - 1 \) c/fm. If the pions, nucleons and kaons stay in thermal and chemical equilibrium (assumption II), i.e.

\[
\rho_n = \rho_n^{eq} , \quad \rho_N = \rho_N^{eq} , \quad \rho_K = \rho_K^{eq}
\]

(11) simply becomes

\[
\frac{d}{dt}\rho_Y = -\Gamma_Y \{ \rho_Y - \rho_Y^{eq} \} .
\]

Thus the equilibration time is given by \( \Gamma_Y^{-1} \) as advocated above.

From (11) it follows that the multi-mesonic back-reactions, leading to a production term \( \mathcal{G}_Y \), are necessary to achieve and to further maintain chemical equilibrium of antihyperons with pions, kaons and nucleons. This 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 the binary production channels (1) and (2). Note that as \( \mathcal{G}_Y = \Gamma_Y \cdot \rho_Y^{eq} \), the overall production rate \( \mathcal{G}_Y \) is still a very small number. On the other hand, these multi-particle reactions cannot be handled within the present transport codes and are thus completely neglected (- sometimes with the ‘excuse’ that \( \mathcal{G}_p \) or \( \mathcal{G}_Y \) would be overwhelming largely suppressed by multi-particle phase space). From our discussion it is obvious that the production of antiprotons \( \bar{p} \) and antihyperons cannot be addressed by these approaches. Nonetheless as we have shown there is a simple non-exotic explanation for the \( \bar{Y} \) abundances in a purely hadronic scenario.

If, as presented in some of the thermal and chemical models, a strangeness suppression factor \( \gamma_s \) for each unit of strangeness is introduced \([4, 11, 15]\), we only have to replace in (11) and accordingly in (12)

\[
\rho_K^{eq} \rightarrow \rho_K = \gamma_s \rho_K^{eq} \rightarrow \rho_Y = (\gamma_s)^{n_Y} \rho_Y^{eq} .
\]

Accordingly, the antihyperon density would acquire an additional factor \( (\gamma_s)^{n_Y} \) compared to chemical equilibrium.
value from the stationary limit of the master equation, if the kaon number is not fully saturated. This is consistent with the employed phenomenological prescription in [15].

As a final comment we briefly consider the situation of antihyperon production in relativistic nucleus-nucleus-collisions at the AGS and at RHIC: According to the thermal models the deduced temperatures at the AGS-energies are lower and the obtained baryon densities are higher [7,9,10]. The latter would imply that according to [7] the antihyperon chemical equilibration time \( \tau_Y \) becomes even smaller. As the pions and to some good extent also the kaons are found to be in chemical equilibrium [8,10], our argument should perfectly apply! In this case, if the fireball does not stay too long in the late stage hadronic phase, chemical equilibrium of the antihyperons in a baryon dilute hadron gas should be much larger. In this case, if the pions and to some good extent also the kaons are found to be in chemical equilibrium [8,10], our argument should perfectly apply! In this case, if the fireball does not stay too long in the late stage hadronic phase, chemical equilibrium of the antihyperons cannot be reached or maintained, if there is no other source of their production.

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