A novel scenario for the production of antihyperons in relativistic heavy ion collisions

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We elaborate on our recent suggestion on antihyperon production in relativistic heavy ion collisions by means of multi-mesonic (fusion-type) reactions. It will be shown that the (rare) antihyperons are driven towards chemical equilibrium with pions, nucleons and kaons on a timescale of 1–3 fm/c in a still moderately baryon-dense hadronic environment.

The original idea behind the collective enhancement of strangeness out of a potentially deconfined state of matter, the quark gluon plasma (QGP), is that the strange (and anti-strange) quarks are thought to be produced more easily and hence also more abundantly as compared to the production via highly threshold suppressed inelastic hadronic collisions. In addition, the analysis of measured abundancies of hadronic particles within thermal models supports the idea of having established a (thermodynamically) equilibrated hadronic fireball in some late stage of the reaction (for analyses of Pb+Pb collisions at CERN-SPS see [1,2]). In this respect especially a nearly fully chemically equilibrated yield of strange antibaryons, the antihyperons, had originally been advocated as an appropriate QGP signature [3]. Although intriguing, this may not be the correct (or only) interpretation of the observed antihyperon yields: In the following we will elaborate on our recent idea [4] of rapid antihyperon production by multi-mesonic reactions like \( n_1 \pi + n_2 K \rightarrow \bar{Y} + p \) (see fig. 1 for a particular illustration). As we will demonstrate, this might indeed explain the observed excess of antihyperons.

Before, let us first remind that nonequilibrium inelastic hadronic reactions can explain to a very good extent the overall strangeness production seen experimentally [5]. The major amount of produced strange particles (kaons, antikaons and \( \Lambda \)'s) at SPS-energies can be understood in terms of early and energetic primary, secondary and ternary nonequilibrium interactions. Strange quarks are thought to be produced initially via string excitations. However, applying the usual concept of binary collisions within the transport approaches, it had been the original claim [3] that chemical equilibrium values for the abundancies of antihyperons can not be explained by successive binary (strangeness exchange) reactions. Only by incorporating more exotic descriptions like color-rope formation [6] or high-dense droplet formation [7] in a hadronic transport model a more abundant production of antihyperons can be obtained.

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Figure 1. Schematic picture for the reaction $\Xi + N \leftrightarrow 3\pi + 2K$.

If the hadronic degrees of freedom are in a state of thermodynamical equilibrium, which constitutes the basic concept of thermal model analyses, a dynamically realization to describe such a system has to fulfill the concept of detailed balance in the considered ‘chemical’ reactions. Hence, multi-mesonic (fusion-like) ‘back-reactions’ involving $n_1$ pions and $n_2$ kaons of the type

$$n_1\pi + n_2K \leftrightarrow \bar{Y} + N,$$

(1)

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. In (1) $n_2$ counts the number of anti-strange quarks within the antihyperon $\bar{Y}$. $n_1 + n_2$ is expected to be around $5 - 7$.

Furthermore, the annihilation rate $\Gamma_{\bar{Y}}$ is expected to be large: It is plausible to assume that the annihilation cross sections are approximately similar in magnitude as for $p + \bar{p}$ at the same relative momenta. Hence, with $\sigma_{\bar{Y}N\rightarrow n_1\pi + n_2K} \approx 50$ mb one has $(\Gamma_{\bar{Y}})^{-1} \equiv 1/(\langle \sigma_{\bar{Y}N}\nu_{\bar{Y}N}\rangle \rho_N) \approx 1 - 3$ fm/c, when adopting for the baryon density $\rho_N \approx 1 - 2\rho_0$. The latter value seems reasonable: In Fig. 2 we have depicted the (net) baryon density as a function of time at a space region for particles at midrapidity obtained within the microscopic transport model HSD as employed in [5]. The figure illustrates that a pure hadronic fireball (without any string-like excitations) at a (net) baryon density $\rho_B \approx 2\rho_0$ has started to be established after approximately 5 fm/c after the onset of the collision.

The annihilation together with the multi-mesonic reactions do effectively lead to the following master equation for the yield of a specific antihyperon specie

$$\frac{d}{dt}N_{\bar{Y}} = -\Gamma_{\bar{Y}} \left\{ N_{\bar{Y}} - N_{\bar{Y}}^{eq} \sum_{n_1} p_{n_1} \left( \frac{N_{\pi}}{N_{\pi}^{eq}} \right)^{n_1} \left( \frac{N_K}{N_K^{eq}} \right)^{n_2} \right\}.$$

Here $p_{n_1}$ states the (unknown) relative probability of the reaction (1) to decay into a specific number $n_1$ of pions with $\sum_{n_1} p_{n_1} = 1$. This master equation can be derived from an underlying Boltzmann-type transport equation [8]. The second term describes the gain per unit time in the hyperon yield due to several coalescing pions and kaons. (The microscopic picture of this complicated process is completely hidden; the term is dictated by the principle of detailed balance.) Assuming further that the pions, baryons and kaons
do stay in thermal and chemical equilibrium, the master equation becomes simply

\[ \frac{d}{dt} N_{Y} = -\Gamma_{Y} \left( N_{Y} - N_{Y}^{eq} \right). \]  

(3)

The annihilation rate thus dictates the timescale for (local) chemical equilibration of the antihyperons together with the pions, nucleons and kaons. This scale competes with the expansion timescale of the late hadronic fireball, which is in the same range or larger. In any case these multi-mesonic, hadronic reactions can explain a sufficiently fast equilibration before or at the (so called) chemical freeze-out (with parameters given by the thermal model analyses, where the (net) baryon density has dropped to around 0.5 - 1 \( \rho_{0} \) [1,2]). This interpretation does rest on the (conservative) view that before the chemical freeze-out already a hadronic system has established.

To be more quantitative we show in fig. 3 the number of one particular specie of antihyperons (normalized to the net baryon number) as a function of time when solving the above master equation. The initial abundancy is set to zero. The pions, kaons and nucleons are assumed to stay in thermodynamical equilibrium throughout a (late-stage) isentropic expansion with parameters characteristic for SPS energies. The net baryon density \( \rho_B(t) \) as a function of time has been effectively parametrized from fig. 2. Further details and scenarios will be given in [8]. In addition, the instantaneous equilibrium abundancy of antihyperons, \( N_{Y}^{eq}(T(t), \mu_B(t), \mu_\pi(t))/N_B \), is also depicted. This equilibrium number strongly decreases as a function of time (or decreasing temperature). At a time of 8-10 fm/c (3-5 fm/c after the onset of the description) the antihyperons effectively do ‘freeze’ out roughly at their particular equilibrium value (at a temperature around 150 – 160 MeV) at that given time interval. Refering to fig. 2 this happens at a baryon density \( \rho_B(t_0 = 5 \text{ fm/c}) \) is set to zero.
density of around 0.5 - 1 $\rho_0$ and which coincides with the parameters of the thermal model analyses. Beyond that ‘point’ at moderately low baryon densities the multi-mesonic creation processes becomes more and more ineffective because of the rapid expansion. This might then also explain the ‘position’ of the chemical freeze-out point for the antihyperons [8]. In this respect it would also be very interesting to adopt the reasoning in the recent work by Rapp and Shuryak [9] (which, in part, had actually triggered our work), that the pions and also now the kaons might in fact go out of perfect chemical equilibrium below chemical freeze-out, as their total abundancies effectively have to stay constant.

To summarize, multi-mesonic production of antihyperons is a consequence of detailed balance and, as the rate $\Gamma_F$ is indeed very large, seems to be the by far most dominant source in a hadronic gas. This is a remarkable observation, as it clearly demonstrates the importance of hadronical multi-particle channels. At the moment such ‘back-reactions’ are not included in the present transport codes and some new strategy has to be invented [10] in order to be more competitive for a direct comparison with various experimental findings. Also, our argument should perfectly apply at AGS energies. Indeed a large ratio of $\Lambda/\bar{p} \approx 2 - 3$ for some central rapidity window has been observed by various collaborations, which might indeed also favor a scenario of nearly chemically saturated strange and nonstrange antibaryon populations. More precise experimental data as well as a theoretical analysis along the line of thermal models would be most welcome. Measurements of antihyperon production could also be done at possible future heavy-ion facilities at GSI. This would be a very interesting opportunity to unfold the mechanism here proposed.

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