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Chemical equilibration due to heavy Hagedorn states

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Abstract. A scenario of heavy resonances, called massive Hagedorn states, is proposed which exhibits a fast ($t \approx 1$ fm/c) chemical equilibration of (strange) baryons and anti-baryons at the QCD critical temperature T_c. For relativistic heavy ion collisions this scenario predicts that hadronization is followed by a brief expansion phase during which the equilibration rate is higher than the expansion rate, so that baryons and antibaryons reach chemical equilibrium before chemical freeze-out occurs.

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1. Introduction

The enhancement of (multi-)strange (anti-)baryons has been predicted as a potential proof for the existence of the quark gluon plasma (QGP) in relativistic heavy ion collisions [1]. Hadro-chemically saturated multiplicities of (anti-)hyperons have been experimentally discovered in central collisions in Pb+Pb experiments at CERN-SPS and in Au+Au experiments at Brookhaven, see Ref. [2].

At SPS energies, the strong increase in the yield of antiprotons [3] and antihyperons [4, 5] has been explained by a "clustering" of mesons of the following type:

$$n_1\pi + n_2 K \leftrightarrow \bar{Y} + p\,. \tag{1}$$

This channel is very efficient to chemically equilibrate (strange) antibaryons in a baryon-dense fireball as is expected at the SPS energies. The equilibration time scale is

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inversely proportional to the density of baryons and to the annihilation cross-section, i.e., $(\Gamma_{\bar{Y}})^{(-1)} \sim 1/(\sigma_{B\bar{Y}} v_{B\bar{Y}} n_B)$. Assuming that various cross-sections are related as given roughly by the additive quark model, $\sigma_{B\bar{Y}\to n\pi+n_Y K} \approx \sigma_{N\bar{p}\to n\pi}$, (for a theoretical model, see Ref. [6]) and that the density is about 1 to 2 times larger than the normal nuclear matter density ρ_0, one finds equilibration times for antibaryons $t_{\rm eq} \approx$ 1–3 fm/c [4]. This leads to microscopically calculated antihyperon yields which are consistent with the fitted chemical freeze-out parameters [5].

The multi-meson reactions at RHIC cannot account for an efficient, direct baryon-antibaryon pair production within the standard hadron resonance gas model. The observed "chemically saturated" (strange) (anti-)baryon yields [3, 4, 6] cannot be obtained from hadron cascades. Antibaryons are much more abundant at RHIC than at SPS, and equilibration times are $\sim$ 10 fm/c at a temperature of about 170 MeV [4, 6, 7]. Nevertheless, the RHIC hadron multiplicities suggest that chemical equilibrium is reached at about 170 MeV $\approx T_c$. Thus, it has been suggested that various hadron species are "born in equilibrium" [8].

Here, a scenario of dynamical equilibration is developed, overcoming some shortcomings (see Sec. 2) of Ref. [9] (hereafter referred to as BSW). According to BSW, the reactions in Eq. (1) alone lead to chemical equilibration at RHIC. Sec. 3 presents a sufficiently fast ($\approx$ 1 fm/c) chemical equilibration mechanism for both of (strange) baryons and anti-baryons. It relies on abundant (at T_c) massive resonances, called Hagedorn states (HS), which are short lived. (Strange) baryon and antibaryon production proceeds along the reaction

$$\left(n_1\pi + n_2 K + n_3 \bar{K} \leftrightarrow\right) HS \leftrightarrow \bar{B} + B + X\,. \tag{2}$$

Here X represents all possible multi-hadron states. Such reactions are an important generalization of Eq. (1). The equilibration time can be estimated by the branching ratios of HS decays into $B + \bar{B} + X$ using a microcanonical statistical model. We then address the production of strange (anti-)baryons, especially the rare Ω (sss) state. The role of HS for chemical equilibration at nonzero net baryon density (e.g., at SPS and AGS energies) is briefly discussed.

2. Overpopulated hadron densities

Typical equilibrium baryon/antibaryon densities in a net baryon-free hadronic system at $T \approx 170 - 180$ MeV are $n_B^{eq} = n_{\bar{B}}^{eq} \approx 0.04$ fm^{-3} (neglecting eigenvolume effects). With annihilation cross sections $\langle\sigma v\rangle \approx 30$ mb, the equilibration time due to reactions as in Eq. (1) is $t_{\rm eq} \approx 10$ fm/c. This cannot explain the apparent chemical equilibration of baryon and antibaryons [4, 6, 7]. It was suggested in Ref. [9] that such multi-meson collisions can still lead to quick chemical equilibration, in close vicinity to the phase transition: by comparing a hadron gas model equation of state with the lattice results, it was speculated that there exists a state of extra-large particle density around T_c, which is effectively overpopulated with pions and kaons. This overpopulation then could drive the baryon and antibaryon pair production on a very short time scale. In essence, the total production of a specific type of baryon (e.g., the Ω as the most exotic one) is attributed [9] to the gain term in the following master equation [4, 5, 6, 7]:

$$\frac{d}{dt}n_\Omega = -\text{“loss”} + \text{“gain”} \equiv -\langle \sigma_{\Omega\bar{B}} v_{\Omega\bar{B}} \rangle \times \left(n_{\bar{B}} n_\Omega - \sum_{n_1,n_2} \hat{M}_{(n_1,n_2)} (n_\pi)^{n_1} (n_K)^{n_2} \right) . \quad (3)$$

Here the mass-action factor reads $\hat{M}_{(n_1,n_2)} = n_{\bar{B}}^{(eq)} n_\Omega^{(eq)} / (n_\pi^{(eq)})^{n_1} (n_K^{(eq)})^{n_2}$. Notice that, in accord with Eq. (3), the density of Ωs tends to approach $n_\Omega^{(eq)}$ during chemical equilibration. If the equilibrium is maintained, i.e., when the “loss” and “gain” reactions have equal rates, saturation does not change. In this case, the production (as well as the annihilation) rate are given by $\Gamma_\Omega \simeq \langle \sigma_{\Omega\bar{B}} v_{\Omega\bar{B}} \rangle n_{\bar{B}}$, and the corresponding chemical equilibration time is $\tau_\Omega^0 \simeq 1/\Gamma_\Omega$. This gives $\tau_\Omega^0 \geq 10$ fm/c.

The master equation (3) is valid even if the particle yields are initially not in full chemical equilibrium. It then dictates how the population changes with time. The BSW idea can now be formulated as follows: the overpopulation of meson states by a factor α, $n_{\pi,K} \rightarrow \alpha \cdot n_{\pi,K}^{eq}$, as compared to the standard equilibrium value in the hadron resonance gas model at T_c should result in rates rescaled by α^5, i.e., $\Gamma_\Omega^{prod} = \alpha^5 \cdot \Gamma_{2\pi 3K \rightarrow \Omega\bar{B}}^{eq}$. If $\alpha = 2$, the production rate for Ωs (as well as for other baryons and antibaryons) increases by a factor 32! One concludes, therefore, that baryons and antibaryons are readily produced by multi-meson reactions in an overpopulated bath of pions and kaons, and the equilibration should happen on timescales $t_{\rm eq} \lesssim 1$ fm/c [9]. The rapid ($\sim T^{60}$) fall-off [9] of the multi-particle reaction rates with temperature suggests that the “chemical freeze-out temperature” is also a measure of the phase transition temperature.

However, there is a serious consequence of this argument: literally, it predicts that baryons and antibaryons are tremendously overpopulated as compared to their equilibrium values. Once produced, there is no way to get rid of them any more in the later stages, because the annihilation reactions are then suppressed dynamically. This is not seen in experiment. Inspect once again the master equation (3): its (quasi-)stationary fixed point is reached when the expression in parentheses vanishes, i.e., when the annihilation rate is equal to the production rate. This corresponds to (anti-)baryon densities, rescaled by a factor β, i.e., $n_{\Omega,\bar{B}} \rightarrow \beta \cdot n_{\Omega,\bar{B}}^{eq}$, where $\beta = (\alpha)^{5/2}$. This may slightly change when other multi-meson channels are taken into account. For $\alpha = 2$, $\beta = 5.6$, which predicts way too many (anti-)baryons in the system. In fact, the state with overpopulated (anti-)baryons is reached on a timescale of $\tau = \tau_\Omega^0/\beta$. This is short enough to compensate the rapid fireball expansion. However, once a large number of (anti-)baryons is produced, it is difficult to get rid of them quickly enough in order to reach standard hadron equilibrium values before the chemical freeze-out. The fraction of (anti-)baryons which annihilates is too small, because the corresponding annihilation rates are then not sufficiently large in an ordinary hadron resonance gas.

3. Fast equilibration due to Hagedorn States

We propose to circumvent this drawbacks of the BSW scenario by postulating that the needed additional degrees of freedom close to T_c are not light mesons ("pions" and "kaons"), as proposed in Ref. [9], but that they consist of heavy mesonic and baryonic resonances, called Hagedorn states. The conjectured unstable Hagedorn states can produce sufficiently many baryon-antibaryon pairs, on a sufficiently short time scale. HS efficiently and effectively can account for various multi-particle collisions ("interactions") in a consistent way:

$$HS \leftrightarrow n_1 \cdot \pi + n_2 \cdot K + n_3 \cdot \bar{K} \,, \tag{4}$$

$$HS \leftrightarrow B + \bar{B} \,, \tag{5}$$

$$HS \leftrightarrow B + \bar{B} + \bar{n}_1 \cdot \pi + \bar{n}_2 \cdot K + \bar{n}_3 \cdot \bar{K} \;\equiv\; B + \bar{B} + X \;. \tag{6}$$

This is akin to the Hagedorn's original idea [10], that the strong interactions of low mass hadrons can be attributed to an exponentially increasing mass spectrum as $T \to T_c$. This old idea has severe consequences for the time-scales of chemical equilibration — from the phase space arguments, one intuitively expects that multi-particle decays in (6) dominate the $B\bar{B}$ production.

Some comments to the Hagedorn picture are in order. Close to the crossover (critical) temperature, T_c, the conventional description of QCD in terms of the known set of PDG hadron degrees of freedom can indeed not be sufficient (PDG: all known resonances from the particle data group booklet). In fact, one should insist that this set is not sufficient in order to understand the lattice results on the equation of state of QCD [9, 11, 12]. The PDG-hadron resonance gas model falls short when estimating the pressure of lattice QCD as the crossover temperature is approached. This is not surprising, if one recalls the role of the highly lying massive states in the Hagedorn model. In the absence of a clear phase transition, it is easy to imagine that (additional, unknown) hadronic degrees of freedom can be used in the description of hot matter, in fact, even for temperatures above the crossover temperature [13]. Of course, the further one goes away from "T_c", the less convenient such descriptions should become. Physically, this could be due to the increasing width of resonances [12]. In the standard Hagedorn model, the density of states increases exponentially with their mass. Eventually, this leads to a divergence of the pressure, as the value of the temperature approaches the Hagedorn temperature from below. Is the Hagedorn model ruled out, therefore? We believe this is not necessarily the case. As pointed out in Ref. [12, 14], the model can be modified in a natural way that cures the problem with the pressure. In addition, quite recently the philosophy of Hagedorn behaviour has also become popular with regard to the equation of state of large N gauge theories [15] and Super-Yang-Mills theories [16].

3.1. Estimate of the baryon/antibaryon production

The number density of HS states in the vicinity of the critical temperature is estimated as in Ref. [9]: additional degrees of freedom to the PDG hadron resonance gas are needed in order to understand the energy density of a thermal system around T_c, obtained in lattice QCD calculations. The additional energy density of order $\Delta\epsilon_c \approx 0.3 - 0.5$ GeV/fm^3 is needed. Let us identify this with the energy density of the HS, $\Delta\epsilon_c \equiv \epsilon_{HS}$. Than, a typical HS mass is $M_{HS} \approx 3$–6 GeV. The total number density of these HS is

$$n_{HS} \approx \frac{\Delta\epsilon_c}{\langle M_{HS}\rangle} \approx 0.05 - 0.15\,\mathrm{fm}^{-3}\ . \tag{7}$$

We now proceed to estimate the baryon-antibaryon production rate due to $HS \to B\bar{B} + X$, where X stands for any possible number of additional hadrons. HS must be highly unstable: the phase space for multi-particle decays becomes immense with increasing mass. Extrapolating the width from the known meson resonances at 2 GeV (widths of 0.3–0.5 GeV) linearly (as suggested by the string model, e.g., in the last paper of Ref. [15]), we find that the total width of such high mass mesonic states is $\Gamma^{tot}_{HS} \gtrsim 0.5-1$ GeV. In the next subsection, we estimate the average baryon number $\langle B\rangle$ per unit decay of a HS within a microcanonical approach. Here we quote only the result: $\langle B\rangle \approx 0.2 - 0.4$. Hence, the relative decay width is given by $\Gamma_{B\bar{B}X} \approx \langle B\rangle \cdot \Gamma^{tot}_{HS} \approx 100$–300 MeV. Take the lower value in the following. Then, the production rate for baryon-antibaryon pairs is estimated

$$\frac{dN_{B\bar{B}}}{d^4x} = \Gamma^{prod}_{B\bar{B}} = n_{HS}\cdot\Gamma_{HS\to B\bar{B}+X} \approx 0.05\,\mathrm{fm}^{-4}\,. \tag{8}$$

With $n^{eq}_{\bar{B}} \approx n^{eq}_{B} \approx 0.04\,\mathrm{fm}^{-3}$ at chemical freeze-out, at RHIC, for all baryons and anti-baryons, their chemical equilibration rate is given via $\Gamma^{prod}_{B\bar{B}}/n^{eq}_{\bar{B}} \approx 1.25\,\mathrm{fm}^{-1}$: the chemical equilibration time is very small, $\tau^{chem}_{B\bar{B}} \approx 0.8$ fm/c.

A large fraction of all possible reactions (6) also generates chemical equilibration among the "lighter" hadrons. For example, these distinct reaction channels easily alter the number of pions (or kaons) in the system (e.g., $7\pi \leftrightarrow 4\pi$), so that in turn the light degrees of freedom become fully equilibrated chemically.

The population of HS should die out very rapidly when the temperature is decreased within a narrow interval around the critical point. Thus, our scenario predicts that the chemical decoupling should happen naturally very close to T_c, similarly as it was anticipated in the BSW scenario [9]. In contrast to the BSW mechanism, however, the approach proposed here does *not* lead to the BSW-oversaturation of baryons and antibaryons from decaying HS. Indeed, one might worry that such decays could produce too many $B\bar{B}$ pairs during the expansion and cooling of fireball. This is no problem as soon as the cooling proceeds smoothly, the densities of baryons and antibaryons stay close to their equilibrium values. However, in the extreme case of ultrafast cooling and decoupling, the number of additionally produced pairs (via the decay of all HS states) can be estimated to be $\delta n_{B\bar{B}} \lesssim (\Gamma_{B\bar{B}+X}/\Gamma^{tot}_{HS})\cdot n_{HS} \approx 0.2\,n_{HS}$. Thus, relative overpopulation is $\delta n_{B\bar{B}}/n^{eq}_{B} \lesssim 0.2$–0.4. As this is the most extreme case, the actual overpopulation will certainly be much smaller.

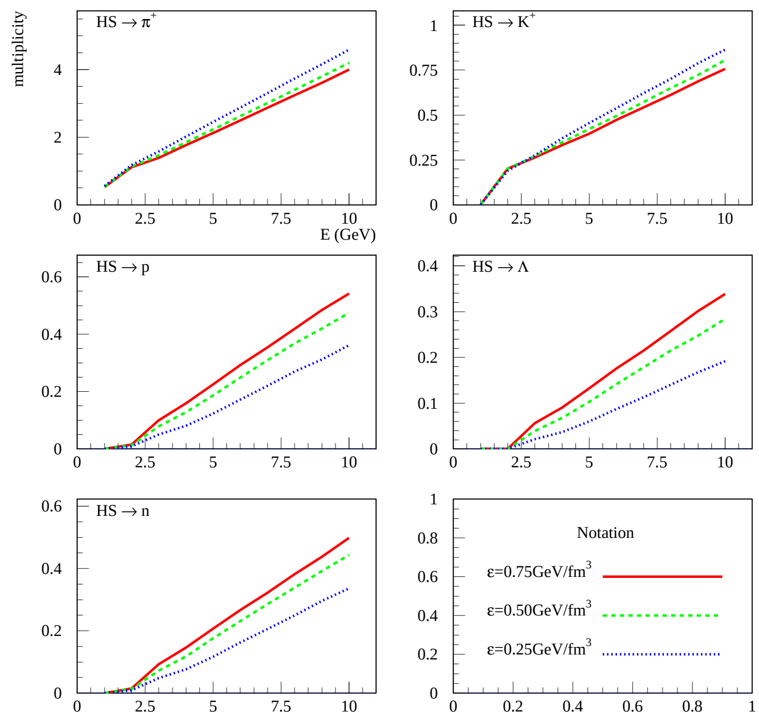

Figure 1. Multiplicity of individual hadrons coming per unit decay of a mesonic, nonstrange HS as a function of the mass $E = M_{HS}$.

3.2. Microcanonical decay of a Hagedorn state

We now provide an estimate for the individual branching ratios of the decay of a HS state into baryon-antibaryon pairs. The $B\bar{B}$ annihilation reactions at LEAR have been understood well within a statistical description [17]. Without any further information, we assume that the HS decay also with a statistical, microcanonical branching.

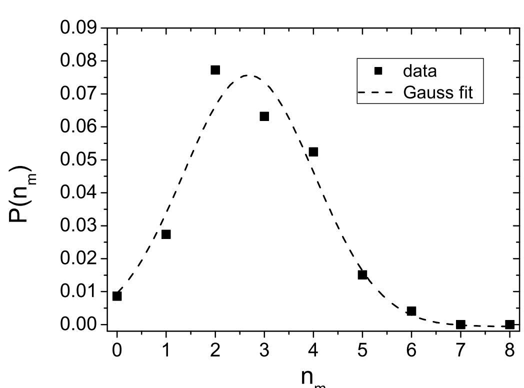

Figure 2. Branching probability distribution of additionally produced mesons $HS \to B + \bar{B} + n_m \cdot M$ as a function of the meson number per unit decay of a $M_{HS} = 4$ GeV Hagedorn state.

The microcanonical description of hadron reactions (e.g., pp or $p\bar{p}$) developed in Ref. [18] is used here. A state is described solely by its mass $m \equiv M_{HS}$, by its (reaction) volume $V \equiv V_{HS} = M_{HS}/\epsilon$, where ϵ denotes the mean energy density of a HS state, and by quantum numbers such as the net baryon number and the net strangeness.

In Fig. 1 we depict the various numbers of hadrons h in the distinct decay channels $HS \rightarrow h+X$ per unit decay. The HS states are purely mesonic, with no net strangeness. The energy density ϵ of the HS states is varied in the range 0.25–0.75 GeV/fm^3. The mass of the HS is varied continuously from $M_{HS} = 0$ GeV to 10 GeV. For example, in a single decay of a state with mass $m_{HS} = 4$ GeV, there are about 2 π^+, 0.075–0.15 protons and neutrons each, 0.35 K^+ and 0.025–0.075 Λ's produced. For the mean baryon number, one finds $\langle B \rangle = 0.2$–0.4. This was the input value used in the estimate of the partial decay width in the previous subsection.

Fig. 2 shows the branching distribution $p(n_m)$ of the associated mesons as a function of the meson number per unit decay of a $M_{HS} = 4$ GeV Hagedorn state. They are produced in $HS \rightarrow B + \bar{B} + n_m \cdot M$. The HS energy density is $\epsilon = 0.5$ GeV/fm^3. The sum of the branching probabilities adds up to $\langle B \rangle \approx 0.3$, as noted above. On average 3 (stable) mesons accompany a HS decay into a baryon-antibaryon pair. Moreover, the direct decay, $HS \rightarrow B + \bar{B}$, is *not* likely.

3.3. Strange baryons and antibaryons

The Λ particle has a sizeable production probability in the decay of nonstrange mesonic HS. One can estimate similarly that the Λ and the $\bar{\Lambda}$ can be quickly populated and reach their chemical equilibrium value by the interplay between the decay and the production of the HS. What about the most exotic baryonic state, the Ω, with three units of strangeness?

First, one might think that the Ω can also be produced directly from nonstrange HS, i.e., via $HS_{\text{nonstrange}} \leftrightarrow \Omega + \bar{B} + X$. For a $M_{HS} = 4$ GeV HS, the average branching into Ωs per unit decay is calculated to be $\langle \Omega \rangle \approx 2 \cdot 10^{-4}$, so $\Gamma_\Omega^{prod} \approx 0.1 - 0.2$ MeV. At $T = 170$ MeV, the density of Ωs in a PDG hadron gas is $n_\Omega^{eq} \approx 4 \cdot 10^{-4}$ fm^{-3}. The chemical equilibration rate is

$$\Gamma_\Omega^{chem} = \Gamma_\Omega^{prod} \frac{n_{HS}}{n_\Omega^{eq}} \approx 25 - 50\,\text{MeV} \Rightarrow \tau_\Omega \approx 4 - 8\,\text{fm/c}\,. \tag{9}$$

This timescale is too long to (fully) explain a chemically saturated abundance.

As a next step, consider *(multi-)strange* mesonic HS, for which the reaction $HS(sss\bar{q}\bar{q}\bar{q}) \leftrightarrow \Omega + \bar{B} + X$ might be sufficient. It turns out that $\langle \Omega \rangle \approx 0.05$ for a $m_{HS} = 4$ GeV and thus $\Gamma_\Omega^{prod} \approx 25 - 50$ MeV. For the chemical equilibration rate one has

$$\Gamma_\Omega^{chem} = \Gamma_\Omega^{prod} \frac{n_{HS}(sss\bar{q}\bar{q}\bar{q})}{n_\Omega^{eq}} \approx 50 - 100\,MeV \quad \Rightarrow \tau_\Omega \approx 2 - 4\,\text{fm/c}\ . \tag{10}$$

Here we have assumed that $n_{HS}(sss\bar{q}\bar{q}\bar{q})/n_\Omega \approx n_{HS\,\text{nonstrange}}/n_B \approx 2.5$. Altogether, strange Hagedorn states can explain the population of Ω.

3.4. Importance of baryonic HS: from the Hagedorn temperature to the Hagedorn line?

So far, we have only considered the role of mesonic HS. Now we discuss the role of baryonic HS. Until now, we have concentrated on the mid-rapidity region at RHIC, where $\mu_B \approx 0$. Here, the fraction of baryonic to mesonic states can be estimated by comparison with that for normal hadrons: $n_{BHS}/n_{MHS} \approx n_B/n_M \approx 0.04/0.3 = 0.13$. One thus would conclude that these states do not carry a major fraction of the energy density. This can change, though, at finite μ_B at AGS or SPS regime, where the baryonic HS achieve an extra enhancement factor $e^{\mu_B/T}$. Such states could show up along a narrow $\mu{-}T$ band below a critical "Hagedorn" line $T_H(\mu_B)$ [19]. This conjecture requires further development that is beyond the scope of this paper.

Baryonic HS can also help to produce strange baryons. Consider the Ω and any Ω-like HS, respectively. The latter can decay and can be produced by the following two reactions:

$$(a) \quad \Omega HS \leftrightarrow B\,(\neq \Omega) + X \tag{11}$$

$$(b) \quad \Omega HS \leftrightarrow \Omega + X \tag{12}$$

Here $B \neq \Omega$ denotes baryon states with net strangeness less than three. The HS with higher net strangeness are populated by multi-hadronic fusion of baryons (resonances) with lesser strangeness and with other mesons, but with at least one kaon. On the other hand, the Ωs then stem from the decay of these ΩHS. If such a scenario is to work, the ΩHS have to be produced sufficiently fastly. We now estimate the chemical equilibration times, both for saturating the ΩHS and for saturating the Ωs. To do this one needs the relative branching probability separately for the decays happening via (a) and via (b). By employing the microcanonical model, one obtains for a $M_{\Omega HS} = 4$ GeV Hagedorn state $p_{(a)} = 0.9$ and $p_{(b)} = 0.1$. The ΩHS predominantly decays into baryons with lesser strangeness. The chemical equilibration time for the ΩHS can be written

$$\left(\tau^{chem}_{\Omega HS}\right)^{-1} = \Gamma_{\Omega HS \leftrightarrow B+X} \approx p_{(a)} \cdot \Gamma^{tot} = 0.4 - 0.8\, GeV\,. \tag{13}$$

Hence, such states do equilibrate very fast. For the Ω we have

$$\left(\tau^{chem}_{\Omega}\right)^{-1} = \Gamma_{\Omega HS \leftrightarrow \Omega+X}\,\frac{n_{\Omega HS}}{n^{eq}_{\Omega}} = p_{(b)} \cdot \Gamma^{tot}\,\frac{n_{\Omega HS}}{n^{eq}_{\Omega}}\,. \tag{14}$$

The ratio of Ω-like resonances to Ω in the vicinity of T_c is probably $O(1)$. We estimate $n_B/(n_p + n_n) \approx 4$ at T=170 MeV. For $n_{\Omega HS}/n^{eq}_{\Omega} = 1$, one has $\tau_\Omega \sim 2 - 4$ fm/c. Hence, exotic ΩHS can also be a key for explaining the chemical saturation of the Ω. This would also be true, in particular, at SPS energies. Such a mechanism can work at finite μ_B, as the ratio $n_{\Omega HS}/n^{eq}_{\Omega}$ does not depend on μ_B in Boltzmann approximation.

4. Summary and Conclusions

We have elaborated the special role of Hagedorn states for chemical equilibration of (strange) baryons and antibaryons. The chain of reactions (2) or (6) catalyzes rapid equilibration of antibaryons and baryons in the vicinity of the deconfinement transition.

The production and the decays of HS are governed by detailed balance, where both the continuous repopulation of HS as well as the annihilation of baryon-antibaryon pairs in the back reactions drives their chemical saturation. Three assumptions are necessary: (i) $\Delta\epsilon_{HS} \approx 0.3-0.5$ GeV/fm^3 at $T \approx T_c$; (ii) $\Gamma_{HS}^{tot} \gtrsim 0.5-1$ GeV; (iii) a microcanonical, statistical estimate of individual branching ratios.

The Hagedorn states are additional degrees of freedom which represent complicated many-particle (hadronic or partonic) plasma correlations in hot dense matter. Close to the critical temperature this plasma is a strongly interacting phase, which contains such states. A clear cut proof, however, within the lattice QCD is not available at present [20].

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