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Anti-Baryon Production in Heavy-Ion Collisions

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ABSTRACT

We consider baryon and antibaryon production in heavy-ion collisions in the context of the Skyrme model of nucleons as topological solitons. In this model the abundances of baryons and antibaryons are not controlled by thermodynamic Boltzmann factors, but by the sizes of coherence domains for the low-temperature quark condensate. Strong violations of naive chemical equilibrium by the formation process are thus possible. The $B\bar{B}$ production rate is bounded from above by energy and entropy conservation, but may be much larger than the naive Boltzmann expectation. The maximal production rate corresponds to a physically plausible domain size for the chiral domains. We stress the importance of measuring $\bar{B}$ production in heavy-ion collisions as a probe of nonperturbative QCD.

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There are two alternative approaches to baryon structure and dynamics. One is the naive quark model (NQM) [1], according to which baryons are made out of 3 nonrelativistic constituent quarks: $m_p \simeq 3m_q$, $m_q \simeq 300$ MeV. The other is the Skyrme model [2], based on approximate chiral symmetry with current quark masses $m_{u,d} \ll \Lambda_{QCD}$, which views baryons as topological solitons in an effective low-energy theory of pseudoscalar mesons. The NQM is very successful for calculating the static properties and spectrum of hadrons, and has inspired most models of baryon production. Its philosophy was implicit in the suggestion several years ago [3] to study antibaryon and antinuclei production in heavy-ion collisions as a signature for quark-gluon plasma (QGP) formation. However, the NQM has never been derived from QCD for light quarks, and it does not explain naturally the spin content of the proton [4] as revealed by the EMC [5]. The Skyrme model has had some successes with the spectrum and static properties of baryons [6], provides a good description of their internal structure [7], explains naturally the spin content of the proton [8], and has the cardinal merit of being justified in QCD for light quarks [2]. Two of us [9] have recently proposed a qualitative model of baryon production inspired by the Skyrme model, in analogy with the Kibble mechanism [10] for monopole or string formation in the Early Universe.

The basic idea is to view the hadronization of an initial quark-gluon state like a phase transition, with the formation of independent domains in which local order parameters adopt vacuum expectation values independently. One of these order parameters, the quark condensate $\langle \bar{q}q \rangle$, can take a topologically non-trivial set of values, and defects may form when orientations in adjacent domains have a topological mismatch. We interpret these topological defects as baryons, and topologically trivial inhomogeneities may correspond to pseudoscalar mesons (cf. spin waves in ferromagnets). This picture has been applied previously [9] to jet fragmentation in high energy collisions, where the domains were assumed to correspond to "cool" near-mass-shell partons resulting from a perturbative QCD shower. A more natural context for applying this approach might be the hadronization of a thermalized quark-gluon plasma (QGP), as in the Early Universe or in relativistic heavy-ion collisions. We study the latter in this paper, concentrating for simplicity on the initially baryon-free central rapidity region.

The most attractive feature of this approach, compared with previous models for QGP hadronization [1,12,3], is that it in principle allows for a strong violation of chemical equilibrium during the hadronization process, i.e. (anti)baryon production might exceed the limits set by a thermally and chemically equilibrated hadron resonance gas [3,12]. All existing models are based on the notion that (anti)baryons arise via coalescence of 3 (anti)quarks and are thus more or less directly sensitive to the thermal

(anti)quark distributions and chemically equilibrated (anti)quark abundances in the initial QGP state. The optimistic original suggestions, based on the combinatoric recombination model [1,13], that the high antiquark densities in the QGP might lead to antibaryon [3,13] and antinucleus [3] abundances greatly exceeding the values in a chemically equilibrated hadron gas, had to be corrected when it was realized [13,14] that, due to conservation of entropy (in particular the large entropy fraction carried by the QGP gluons), additional quark-antiquark pairs are produced. For entropy reasons these tend to mostly hadronize as light mesons, thus diluting interesting particle ratios like K/π , p/π , Λ/π , etc. to a level very close to chemical equilibrium in a hadron resonance gas [14-16]. Entropy conservation also dictates an enormous growth in volume of the system in the transition from the high-entropy-density QGP to the low-entropy-density hadron gas state, implying that any large (anti)baryon densities calculated from the large (anti)quark densities in the initial QGP are strongly affected by dilution. A proper normalization of their abundances to a conserved quantity (e.g. entropy) again leads to the conclusion within these models that after complete hadronization the resulting hadron gas is very close to chemical equilibrium [15,16].

In contrast, the topological baryons of the Skyrme model do not "count" quarks, and since all partons (quarks, antiquarks and gluons) are equally effective as seeds for the development of the chiral $\bar{q}q$ condensate [9], the number of created topological defects is essentially independent of the chemical composition of the QGP. The only constraints on baryon-antibaryon formation are of global or topological nature (i.e. that the chiral condensate outside the collision zone has a topological winding number corresponding to the total baryon number contained inside, and that the total energy of the collision zone is conserved while its entropy can only increase), or arise from the explicit breaking of $SU(3)$ chiral symmetry by the finite (~ 150 MeV) strange quark mass, which will affect the ratio of strange to nonstrange baryons subject to the constraints imposed by the strange to light quark ratio in the original QGP phase. In this paper we show that these features may lead to a breaking of chemical equilibrium between (anti)baryons and mesons by the hadronization process itself, and argue that an experimental study of the systematics of antibaryon production in nuclear collisions can provide important information on the validity of our topological approach to QGP hadronization.

To set the scene, let us perform a first rough estimate of the baryon production rate disregarding any energy and entropy constraints as well as quark mass effects. We follow the QGP to the beginning of the confinement phase transition (i.e. down to a temperature T_c somewhere between 160 and 200 MeV [17]) and consider the thermally

distributed quarks, antiquarks and gluons there as seeds for a developing chiral condensate. Due to the assumed complete equilibration of the QGP we consider as a first hypothesis the possibility that the orientation in flavor space of $\langle \bar{q}q \rangle$ around each seed is completely random. Of course, we do not know a priori the coherence length for the chiral order parameter in this system, and if the plasma at T_c is still too dense, the assumption of independence of $\langle \bar{q}q \rangle$ around each parton may be overly optimistic. We will check the consistency of this picture at the end of the calculation.

Since at T_c the density of partons is large ($\sim 2-4$ partons/fm³ for a free quark-gluon gas), already for a collision between medium-sized nuclei the total number of partons in the fireball is several hundreds. In this limit the geometrical algorithm [9] to calculate the combinatorial probability for topological defects in the developing chiral condensate simplifies considerably. To identify pointlike defects, one constructs from the partons a network of 1 dimensional simplices [18], which for random orientations of $\langle \bar{q}q \rangle$ at the corners are known [9] in the case of $SU_f(2)$ to have a probability $1/16$ of containing a topological point defect, with a similar number expected in the case of $SU_f(3)$ [9]. In the limit of an infinitely large system, on average a given parton belongs to $\frac{24\pi^2}{36} \approx 6.8$ different simplices [18] and thus generates $6.8/16 \approx 0.12$ topological point defects with unit winding number. It was checked by a Monte Carlo simulation [9] that this asymptotic limit is reached for systems with $\gtrsim 100$ partons. In contrast to the case of jet fragmentation, where the volume containing the partons is of cylindrical shape with a narrow transverse dimension, and thus has a comparatively large surface where the chiral condensate has to be hooked up to the homogeneous value of the outside vacuum, the transverse dimensions of a QGP produced in nuclear collisions are much larger, and surface effects can be neglected. In the case of jet fragmentation these were shown [9] to give a strong phase space correlation between baryon-antibaryon pairs as observed experimentally [19], which we expect to be absent in nuclear collisions.

To normalize properly the rate in a way which does not depend on the actual fireball size we use an entropy gauge. It is known from hydrodynamic simulations including degradation shocks [20] due to a first order hadronization phase transition, as well as from kinetic simulations of the hadronization mechanism [16,21], that cooling and hadronization of a QGP occurs approximately isentropically, with entropy production throughout the expansion stage being bounded near the 10% level. Normalization to the initial QGP entropy thus gives us a measure for the baryon production rate which is hardly affected by the strong expansion during the transition and allows for a sensible comparison with the alternative scenario of a much more dilute equilibrated hadron gas resulting from most other approaches. Of course, in both scenarios BB pair annihilation

in the hadron gas stage is a matter of concern and will be discussed at the end of the paper. Since the QGP partons can be taken as massless (even for the strange quarks with $m_s \simeq T_c$ the error is less than 10%), each one of them carries $\simeq 4$ units of entropy. Our first naive estimate thus yields a baryon antibaryon production rate of

$$\alpha \equiv \frac{B+B}{S} = \frac{0.42}{1} \simeq 0.1, \quad (1)$$

i.e. 0.1 topological defects per unit of entropy.

This should be contrasted with the corresponding ratio in a chemically equilibrated hadron resonance gas with vanishing baryon chemical potential: Using relativistic Boltzmann distributions for the baryons and kaons,

$$\rho_i = \frac{d_i}{2\pi^2} \left(\frac{T}{hc} \right)^3 \left(\frac{m_i}{T} \right)^2 K_2 \left(\frac{m_i}{T} \right), \quad s_i = \frac{d_i}{2\pi^2} \left(\frac{m_i c^2}{hc} \right)^3 K_3 \left(\frac{m_i}{T} \right), \quad (2)$$

where the $K_{2,3}$ are modified Bessel functions and the d_i are the spin-isospin degeneracies, and approximating the pions as massless bosons:

$$\rho_\pi = \frac{3\zeta(3)}{\pi^2} \left(\frac{T}{hc} \right)^3, \quad s_\pi = \frac{2\pi^2}{15} \left(\frac{T}{hc} \right)^3 \quad (3)$$

(with $\zeta(3) = 1.202 \dots$), we find

$$\begin{aligned} \alpha &\equiv \frac{B+B}{S} = \frac{\rho_{N+N} + \rho_{\Lambda+\Lambda} + \rho_{\Sigma+\Sigma}}{s_{N+N} + s_{\Lambda+\Lambda} + s_{\Sigma+\Sigma} + s_{K+K} + s_\pi} \\ &= \frac{0.070 + 0.018 + 0.010}{0.528 + 0.150 + 0.318 + 0.890 + 1.370} = 0.039 \quad \text{for } T = 200 \text{ MeV}; \\ &= \frac{0.011 + 0.003 + 0.006}{0.121 + 0.029 + 0.062 + 0.338 + 0.701} = 0.018 \quad \text{for } T = 160 \text{ MeV}. \end{aligned} \quad (4)$$

Thus, depending on one's preferred value for the critical temperature, the topological baryon production mechanism would appear to be able to generate a factor 2.5 to 6 more baryons than would be present in chemical equilibrium at T_c . For a plasma with the size of a sulphur nucleus (~ 130 fm³) at hadronization a total of about $130 \text{ fm}^3 \times (2-4 \text{ partons/fm}^3) \times (\frac{0.42}{2} \text{ antibaryons/parton}) = 50-100$ antibaryons might thus be created

(compared to only ~ 8 in an equilibrium hadron gas at $T=160$ MeV). Reviving the ideas of ref. [3], one might thus speculate that this would open reasonable chances for creating small antineutrons by antibaryon coalescence at freeze-out. In this process the enhancement factor above hadronic chemical equilibrium would enter with a power 4 (i.e. the mass number of the antinucleus formed), and already for $\bar{n}$ nuclei it could be of the order 40–1000.

These numbers clearly motivate a more thorough analysis of this model, which we will now present. One basic problem with the above analysis is that it completely neglects the constraints of energy and entropy conservation. The original QGP has a certain well-defined energy and entropy content. Since entropy cannot decrease during hadronization, it has to reappear in the hadronic phase, mostly in terms of pions which are light and thus carry away the entropy most economically. Nevertheless, a large fraction of the available thermal energy (which can only decrease, e.g. if the system begins to expand by converting thermal into collective kinetic energy) is already spent this way, and the question arises whether there is enough fireball energy left to also create the large amount of massive baryon-antibaryon pairs estimated above. Indeed, starting from an ideal gas model for the QGP phase, and using a noninteracting hadron resonance gas with the usual free masses for the hadrons, one finds that even if no additional entropy is produced and no thermal energy is lost to collective expansion, energy conservation limits the BB enhancement factor to values between 1.4 ($T_c=200$ MeV) and 2.5 ($T_c=160$ MeV).

Fortunately, this is largely an artifact of the oversimplified equation of state employed. QCD lattice calculations show [22] that above the phase transition strong nonperturbative effects appear which, although not very prominent in the energy density, lead to severe deviations for the pressure and entropy density from the ideal gas behaviour. From the numerical results shown in Ref. [22] for pure $SU_c(2)$ and $SU_c(3)$ gauge theories one sees that already at several times T_c the entropy density begins to drop below the ideal gas curve, with only 30% of the ideal gas value left at T_c . On the other hand, the energy density is hardly affected until $T < 1.2 T_c$, and at T_c is only suppressed to $\sim 45\%$ of the ideal gas value. This raises the ratio of e/s , i.e. the energy available to spend when transforming the entropy into hadronic degrees of freedom, by a factor 45%/30% ≈ 1.5 above the ideal gas estimate used above. Although this analysis refers to Monte Carlo data for the pure gauge theory, it is clear from the few available results for full QCD (see again the review [22]) that things look at least qualitatively similar if quarks are included. We will thus base our analysis on the figure of merit

$$\left(\frac{e}{s}\right)_Q(T_c) = \frac{3}{2} \left(\frac{e}{s}\right)_{ideal} \quad (5)$$

Since for massless particles

$$\left(\frac{e}{s}\right)_{ideal}(T) = \frac{3}{4} T, \quad (6)$$

we thus obtain as a constraint below the phase transition

$$\left(\frac{e}{s}\right)_H \leq \left(\frac{e}{s}\right)_Q(T_c) = \frac{9}{8} T_c, \quad (7)$$

i.e. for a transition at $T_c=200$ MeV (160 MeV) we may spend in the hadron phase at most 225 MeV (180 MeV) per unit of entropy. This defines the limit for the fraction of energy that can be spent on creating massive baryons which carry little entropy.

The effect of this limit is further softened by another consequence of the topological baryon model which has not been mentioned yet: baryon masses are reduced as T approaches the chiral restoration phase transition, as a consequence of a decreasing chiral condensate [23]. Within pure chiral dynamics, the phase transition is of second order, and for small T the chiral condensate has been shown [23] to behave as

$$\frac{\langle \bar{q}q \rangle_T}{\langle \bar{q}q \rangle_0} \approx 1 - \left(\frac{T}{T_h} \right)^2, \quad (8)$$

with $T_h = F\sqrt{12N/(N^2-1)} \approx 186$ MeV in the limit of massless quarks. (Here $N=3$ massless flavors have been assumed, and for the zero temperature pion decay constant $F=88$ MeV was taken, corresponding to the zero quark mass limit [2].) Terms of $\mathcal{O}(T^4)$ and higher have been shown [23] to be small. Similar low temperature expansions were derived for the pion mass (which slowly increases as $\langle \bar{q}q \rangle$ decreases, i.e. chiral symmetry is getting restored) and the pion decay constant F_π (which decreases along with $\langle \bar{q}q \rangle$). Although for m_π and F_π the higher order corrections $\sim T^4$ have not been checked, they are presumably large for $T > F_\pi$. While the expansions [23] are consistent with the PCAC relation

$$m_\pi^2 F_\pi^2 = -2m_q \langle \bar{q}q \rangle \quad (9)$$

up to the terms of order T^2 , they extrapolate to different zero crossings for the chiral condensate and F_π which would violate the relation (9) near T_h . A much more natural interpretation of the results in [23] appears to be that eq. (9) continues to hold near

T_A , i.e. F_π vanishes when $\langle qq \rangle$ does, and the different T^2 coefficients in the low-temperature expansion only indicate a different approach to zero for the two quantities. The parametrizations

$$\begin{aligned} F_\pi(T) &\sim \left(\langle qq \rangle_T \right)^{\frac{2}{2(N^2-1)}} = \left(\langle qq \rangle_T \right)^{9/16}, \\ m_\pi(T) &\sim \left(\langle qq \rangle_T \right)^{-\frac{2}{2(N^2-1)}} = \left(\langle qq \rangle_T \right)^{-1/16}, \end{aligned} \quad (10)$$

are consistent with eq. (9) at all temperatures and agree in the low-temperature limit with the expansions given in [23].

Lattice simulations [22,25] and effective low-energy models [26] incorporating the scale-breaking effects of the trace anomaly in QCD, caused by the vacuum gluon condensate, indicate that the chiral phase transition is actually of (weakly) first order. From the low energy effective Lagrangian point of view this appears to be caused by the way the gluon and quark condensates are coupled to each other, which allows the occurrence of a chiral condensate only in the presence of a gluon condensate [28]. If the gluon condensate evaporates before T has reached T_A , the chiral condensate is forced to evaporate “prematurely”, too, leading to a “fluctuation-induced” first order behaviour. (In the model of ref. [28], gluon condensation is always a first order effect.) This is supported by QCD lattice calculations [25]: an analysis of the behaviour of the chiral condensate for $SU(3)$ with $N_f = 3$ massless flavors in the quenched approximation (which enhances the first order nature of the transition) shows a discrete jump at T_c , followed by an increase by another factor of 2 between T_c and $0.82T_c$. Extrapolating to $T = 0$ according to the prediction eq. (11) of the effective low-energy model we find that the measured value of $\langle qq \rangle$ at T_c corresponds to a little less than 1/4 of its $T = 0$ limit. Thus chiral restoration appears to be a rather weak first order phase transition, with strong precursor effects even far below T_c .

One of these effects is a strong temperature dependence of the baryon mass [27]. While, according to eq. (10), the pseudoscalar mesons show only a very slight ($< 10\%$) mass increase with T , the baryon mass scale (in the limit $m_q \rightarrow 0$) is entirely determined by the single scale parameter in the theory, F_π , which drops quite rapidly. At $T = T_c$ the parametrization (10) predicts an effective baryon mass of order

$$m_B^*(T_c) = m_B \left(\frac{\langle qq \rangle_{T_c}}{\langle qq \rangle_0} \right)^{9/16} \simeq 0.24^{9/16} m_B = 0.45 m_B, \quad (11)$$

where we used for the chiral condensate the above approximate value obtained from the lattice simulations [25].

This implies that the constraint of energy conservation is less stringent, because we do not have to spend immediately the energy of a full baryon rest mass when creating a topological defect. Let us ask which is the maximum rate $\alpha \equiv \frac{p_{B\pm}}{s}$ compatible with the constraint (7). We can write

$$\begin{aligned} \frac{\epsilon}{s} &= \frac{\epsilon_{B\pm B} + \epsilon_{K\pm K} + \epsilon_\pi}{s} = \frac{\epsilon_{B\pm B}}{s} \frac{p_{B\pm B}}{p_{B\pm B}} + \frac{\epsilon_{K\pm K} + \epsilon_\pi}{s} \\ &= \alpha \frac{\epsilon_{B\pm B}}{p_{B\pm B}} + \frac{\epsilon_{K\pm K} + \epsilon_\pi}{s}, \end{aligned} \quad (12)$$

As long as $m_B^* = 0.45 m_B \sim 400 - 500$ MeV is larger than $\frac{3}{2}T \leq 300$ MeV, the nonrelativistic expression for the energy per baryon

$$\frac{\epsilon_{B\pm B}}{p_{B\pm B}} = m_B^* + \frac{3}{2}T, \quad (13)$$

is a good approximation. We will use $m_B^* = 0.45 m_B = 520$ MeV where $m_B = (2m_N + m_A + 3m_\Sigma + 2m_\Xi)/8 = 1150$ MeV is the isospin-weighted average of the ground state baryon octet masses. In the second term in (12) we write the denominator as $s = \gamma(s_{K\pm K} + s_\pi)$, with γ denoting the entropy fraction contributed by the baryons. By inspection of eqs. (1) and allowing for a modest increase in γ due to the reduced baryon masses, we may take (very conservatively, see eq. (16)) $\gamma \geq \frac{4}{3}(\frac{2}{3})$ for $T = 160$ (200) MeV. For $(\epsilon/s)_{K,K,\pi}$ we may use eq. (6), the error due to the kaon mass remaining less than a few %. Inserting all this into eq. (7) we find the constraint

$$\alpha < \frac{\frac{2}{3}T_c + \frac{3}{2}T}{m_B^* + \frac{3}{2}T} \quad (14)$$

which, if evaluated at the critical temperature with the above values for γ and m_B^* , yields

$$\alpha < 0.15 \quad (0.12) \quad \text{for } T_c = 200 \text{ (160) MeV.} \quad (15)$$

We see that our geometrical estimate (1) for the maximum BB rate respects this constraint, and that in this refined analysis energy and entropy conservation turn out to

be no longer a matter of concern. We have checked that no problems occur at later times either, since, as the system cools down and more energy is required by the increasing baryon masses, the mesons give off sufficient thermal energy that the energy conservation limit is never exceeded.

Thus, as far as entropy and energy conservation are concerned, the naive estimate (1) seems to be perfectly valid. However, the equilibrium hadron gas calculation which was done for comparison should be revised, in the light of the occurrence of rather small effective baryon masses. Indeed, we find with effective baryon masses $m_B^* = 0.45 m_B$ that the equilibrium ratios (1) are modified to

$$\begin{aligned} \alpha &\equiv \frac{B+B}{S} = \frac{\rho_{N+N} + \rho_{\Lambda+\Lambda} + \rho_{\Sigma+\Sigma} + \rho_{\Xi+\Xi}}{s_{N+N} + s_{\Lambda+\Lambda} + s_{\Sigma+\Sigma} + s_{\Xi+\Xi} + s_{K+K} + s_{\pi}} \quad (16) \\ &= \frac{0.106 + 0.160 + 0.130 + 0.242}{2.101 + 0.881 + 2.140 + 1.530 + 0.890 + 1.370} = 0.131 \quad (T=200 \text{ MeV}); \\ &= \frac{0.152 + 0.056 + 0.142 + 0.076}{0.856 + 0.338 + 0.890 + 0.191 + 0.338 + 0.701} = 0.118 \quad (T=160 \text{ MeV}). \end{aligned}$$

This means that once the prediction of the Skyrme model of strongly decreasing baryon masses at finite temperature is included into a chemical equilibrium estimate, almost equally strong BB enhancements result! Thus chemical equilibrium is not drastically broken in the topological baryon production model, but a strong baryon-antibaryon enhancement would already be a consequence of the strong effective mass effect for the baryons, which can be viewed as a precursor of chiral symmetry restoration at the deconfinement transition.

Irrespective of the question whether it could be taken as evidence for our topological hadronization model, the observation of enhanced BB production in the central region of relativistic nuclear collisions would be most exciting, because it would lend in one way or the other support to the picture of baryons as topological solitons in a chiral condensate. However, similar to the case of strangeness, it would directly demonstrate only that (i) baryons have a small effective mass at high T and that (ii) a system of such low-mass baryons close to chemical equilibrium had been formed. While this would clearly be a new effect of highly excited nuclear matter, this would not constitute a direct proof of a QGP origin of these baryons.

We will close this paper with two comments on the internal consistency of our approach, and one related to effects from the finite strange quark mass. The first

comment refers to the question of the coherence length of the chiral condensate at the phase transition point. As pointed out in [22], the reduction of entropy density below the ideal gas limit observed in QCD lattice calculations can be attributed to a quenching of quark-gluon states with lower-than-average thermal momenta, $p < (2 - 3)T_c$. This leads to a reduction of the parton density near T_c by about a factor 3 below the ideal gas limit. Hence at $T_c = 200$ MeV we have about 1.7 partons/fm³, leading to $1.7 \times 0.42 = 0.7$ topological defects per fm³. Since the size of the topological baryons is inversely proportional to F_π (again on dimensional grounds), the typical size of a baryon at T_c will be $1/0.45 = 2.2$ times its size at $T = 0$. Using the mean square radius of the topological charge (baryon density) distribution of a $(T=0)$ Skyrme, $r_B = (0.4-0.5)$ fm, we find for the typical volume of a baryon near T_c a value of 4 fm³, which decreases very fast ($\sim F_\pi^{-3}$) as T drops below T_c . Thus the product of baryon density times baryon volume near T_c is of order 1, with some tendency for overlap right at the phase transition. This indicates that our basic assumption of using the QGP partons as seeds for chiral condensates with random orientation is qualitatively alright, and the numbers are consistent with the interpretation of T_c as the (de)confinement transition.

Our second comment refers to the question of BB annihilation during the hadronic expansion stage, before particle freeze-out. This process has been simulated by kinetic calculations in which the rate equations for inelastic hadrochemical reactions are solved using (thermally averaged) free space cross-sections [13, 16]. The result is [28] that there is only very little annihilation before freeze-out, due to the rather small annihilation cross section of $10 - 15$ mb. These calculations now have to be modified, since the (anti-)baryon density is about a factor 5 larger than used before (when normal nucleon masses and chemical equilibrium were assumed). The total annihilation cross section does not change, since effects from the growth in baryon size are exactly cancelled by their reduced internal baryon density. With 0.7 topological defects per fm³, i.e. 0.35 baryons/fm³, at $T_c = 200$ MeV one finds an antibaryon mean free path of ~ 3 fm, while at $T_c = 160$ MeV the baryon density is about a factor of 2 smaller and the mean free path is twice as big. This is of comparable size as the fireball radius, and thus, if helped by a strong dynamical expansion leading to rapid cooling and early dynamical freeze-out [29], antibaryons are not expected to be strongly affected by annihilation, and some of the initial BB enhancement should survive. We defer a more quantitative study of this question to a future publication.

Let us finally also comment on the effects of the finite strange quark mass on our hadronization scenario. Since $T_c \geq m_s$, in the equilibrated quark-gluon plasma strange

quarks are nearly as abundant as up and down quarks ($s/u \geq 0.8$). Since baryon formation is here considered as a topological process which is not sensitive to the mass of the topological defect created, we thus expect to generate defects with the isospin quantum numbers of all the ground state octet baryons in roughly equal numbers (hyperons being suppressed by a factor $s/q \geq 0.8$, cascades being suppressed by $(s/q)^2 \geq 0.65$ per individual isospin state). This is quite different from the usual hadronic equilibrium estimates, where the mass differences between strange and non-strange baryons lead to a much stronger strange baryon suppression. Thus the topological production process discussed here predicts more strange baryons (in particular Ξ and Ξ) than conventional chemical equilibrium, even if the latter is evaluated with reduced effective baryon masses [see eq. (16)]. This means that the hadronic system originates with strange baryon abundances above the chemical equilibrium values (far above if normal baryon masses are assumed, slightly above if the smaller effective baryon masses are considered), and this is only possible if they come from a hadronizing QCD. In any purely hadronic environment, strangeness equilibrium is approached from below, since the initial conditions set by the primary nucleon-nucleon collisions are known to correspond to strangeness abundances far below saturation. Of course, there exists again the possibility that this strange baryon enhancement is diluted by final state interactions, in particular strangeness exchange processes with the multitude of pions in the fireball. How much of the initial enhancement can survive depends on the time-scale in which freeze-out is approached and has again to be investigated more quantitatively by a future kinetic calculation.

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