STRANGE ANTI-BARYONS
QGP VERSUS HG

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Abstract
We study quark-gluon plasma (QGP) and hadronic gas (HG) models of the central fireball presumed to be the source of abundantly produced strange (anti-)baryons in \( S \rightarrow W \) collisions at 200 GeV A. We consider how multi-strange (anti-)baryon multiplicities depend on strangeness conservation and compare the HG and QGP fireball scenarios. We argue that the total particle multiplicity emerging from the central rapidity region as well as the variation of production rates with changes in the beam energy allows to distinguish between the two reaction scenarios.

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1 INTRODUCTION

Kinetic strange particle production models [1] show that abundant strangeness is suggestive of QGP formation in relativistic nuclear collisions. Even more specific information about the nature of the dense matter can be derived studying strange quark and anti-quark clusters, which are more sensitive to the environment from which they emerge [2], here in particular particle density. Therefore the relative production abundances of strange and multi-strange baryons and anti-baryons where studied experimentally [3]. They turned out to be particularly sensitive probes of the thermal conditions of their source [4]. It has already been demonstrated that the observed particle abundances are in agreement with a picture of explosively disintegrating QGP fireball [5].

It can be also argued [6, 7] that these results are compatible with the scenario of an equilibrium HG fireball, though here one lacks an accepted mechanism for strangeness production. But perhaps more importantly, it is hard to imagine a hadronic gas at temperature well above the pion mass, viz. $T = 215$ MeV which is the required temperature for the hadronic gas interpretation of the strange anti-baryon data to work [6].

The problem we address here is how one can eliminate experimentally the unnatural for the circumstances possibility of a hadronic gas fireball as the underlying strange particle source. We suggested [7] that a simple distinction of these two phases derives from the inherent difference with regard to their entropy content $S$ given a fixed and conserved property, such as baryon number content $B$ which can be determined experimentally. $B$ is seen as being well understood in terms of the nucleon number of the combined system of the projectile nucleus and the target tube of nuclear matter cut out in the collision from the much larger target nucleus. Baryon number of the fireball can decrease only by particle radiation in the final disintegration of the fireball, beyond which we assume that the scattering between the different components have ceased and the relative abundances carry the information about the property of the source.

On the other hand, once the pre-equilibrium reactions have been terminated, and the particle momentum distributions have reached their thermal form, entropy production effectively has ceased, even if a phase transition occurs from a primordial phase to the final HG state. Hence both baryon number and entropy content of the isolated fireball remain constant and their ratio in a theoretical description is rather model independent. Therefore a supplementary measurement, which will permit to define the properties of this source is the multiplicity per participating baryon in the fireball which is directly related to entropy. While the hadronization of the entropy rich QGP fireball is presently not understood, we take advantage here of the fact that in any case a substantially enhanced particle multiplicity must result, as compared to the HG scenario. This can e.g. arise if the QGP fireball were to evaporate emitting hadronic particles sequentially. For $T \sim 215$ MeV [8], HG leads to about 40% of the particle multiplicity expected for QGP scenario [7].

Alternatively, one may be able to distinguish the two cases considering the response of the measured parameters to changes in energy or/and size of the colliding nuclei [4]. We note that the hadronic gas particle abundances are certain functions of the three thermal parameters, $T$ the temperature, $\mu_B$ the baryo-chemical potential, and $\mu_s$ the strange-chemical potential. The constraint to a fixed strangeness fixes in HG a relation between $\mu_B$ and $\mu_s$. Ideally, the number of strange and antistrange quarks are equal, but pre-equilibrium emission can introduce a small asymmetry. The strange-chemical potential $\mu_s$ will in case of QGP formation always remain independent of $\mu_B$, and near to the value $\mu_s = 0$, while the saturation of the phase space described by a factor $\gamma$ (see below) will approach unity for increasing size of the hot fireball. Neither result is generally correct for the case of HG, and values of $\mu_B$ and $\gamma$ have considerable impact on the strange particle abundances.
To be able to forecast both for QGP and HG scenarios the behavior of strange particle abundances as the nuclear collision energy changes we study here how the strange-chemical potential $\mu_s$ relates to the baryo-chemical potential $\mu_B$, for several choices of energy density (temperature). We consider three benchmark temperatures: aside of $T \simeq 200$ MeV appropriate for the CERN–SPS energy range we also include in our discussion $T \simeq 150$ appropriate for the lowest conditions with probable QGP formation and $T \simeq 300$ MeV, which we judge appropriate for the BNL–RHIC facility under construction.

Our work [7, 9] is in detail very different from the parallel effort of Cleymans and Satz [6, 10]. We study particle ratios at fixed transverse mass $m_T > 1.5$ GeV. We allow for the strangeness phase space to be only partially saturated, and we consider the degree of saturation to be experimentally measurable with the result to be compared to the kinetic theory of strangeness production. We allow the strangeness to be unbalanced (up to 10%). We compare the entropy contents for the different scenarios and confront the findings with the observed particle multiplicity. We consider S–S experimental results not to be in the same class as the S–W results (at 200 GeV A) due to the different stopping, and do not combine the data in our analysis of the experimental results. We do not use kaon data, as kaons, unlike strange anti-baryons can arise from peripheral, spectator related processes and are therefore not necessarily witnesses of the same stages of the collision.

2 THERMAL FIREBALL MODEL

We assume the formation in the collision of a region of space containing much of the energy and baryon number available, with the hadronic particles sharing the accessible energy — this we call a central (rapidity) fireball. Our discussion is unaffected by the presence of a collective flow, and the thermal parameters of the fireball are deduced from the experimental results. In this analysis we imply that a rapid disintegration of the fireball ensues its initial formation. Therefore it is possible to use a simple average value of the thermal parameters for the entire fireball neglecting the influence of flow on the spectra [11]. Recent studies of the dynamics of QGP to HG transition [12] find that such a scenario is not impossible for the hot and dense fireball we consider here.

For a hadronic fireball created in central S→W collisions one has about 108 baryons in the geometric interaction tube at small impact parameter. In the HG fireball scenario we find that the strange pair abundance is about 0.4 per baryon, given the thermal parameters determined earlier [6], corresponding to about 40 strange particle pairs. In QGP fireball scenario the strangeness pair abundance per baryon at $\gamma = 0.7$ is about one, i.e., there is a strange particle yield enhancement by about factor 2.5 as compared to hadronic gas interactions.

2.1 u–d asymmetry

The ratio of the net number of down and up quarks in the fireball

$$R_f = \frac{\langle d - \bar{d} \rangle}{\langle u - \bar{u} \rangle},$$

arising in a S→W-tube collisions is $R_f^{S→W} \simeq 1.08$ and in Pb–Pb collisions it is $R_f^{Pb→Pb} \simeq 1.15$. Taking this into account we denote: $\mu_q = (\mu_d + \mu_u)/2$ and the asymmetry is related to $\delta \mu = \mu_d - \mu_u$. The value of $\delta \mu$ is at each fixed $T$ given by the value of $R_f$, in dependence on the assumed structure of the source, i.e., the equation of state. In the region of $T, \mu_B$ of interest to us we find that $\delta \mu/\mu_q \sim R_f - 1$; though small, the difference between the chemical potentials of $u$ and $d$ quarks is not negligible.
2.2 Partition function

We have distinguished between the $u,d$ quarks in our calculations and had computed the HG partition function distinguishing the flavor content of strange and non-strange hadrons. We have summed explicitly the contributions of hadronic particles with the mesons included up to mass 1690 MeV, nucleons up to 1675 MeV and Δ’s up to 1900 MeV. Our procedure will be evident when we discuss the strange particle sector explicitly below. We note that higher hadronic resonances would matter only if their number were divergent as is the case in the Boots trap approach of Hagedorn [13] and the HG was sufficiently long lived to populate all high mass resonances. Our simple minded approach to describe the HG phase is not sufficiently precise as soon as we ask questions which are dependent either on the ever increasing mass spectrum of particles or on the proper volume occupied by the particles [14]. However, quantities such as condition of zero strangeness, fixed entropy per baryon are independent of the absolute normalization of the volume and of the renormalization introduced by the diverging spectrum and hence can be considered in the approach we take.

In order to simplify the comparison between our work and Ref. [6] that while we always use $\mu_s$ the strange (quark) chemical potential, these authors use instead the chemical potential $\mu_S$ of the kaons ($q\bar{s}$). The relation is: $\mu_s = \mu_q - \mu_S = \mu_B/3 - \mu_S$. Here we employed the relation between the baryo-chemical potential and quark chemical potential $\mu_B = 3\mu_q$ as follows from the baryon number carried by quarks. In general it is not necessary to introduce different chemical potentials (or fugacities) for the hadronic gas phase, as the chemical potential of each HG species is simply the sum of the potentials of the constituent quarks, *viz.* for a proton $\mu_p = 2\mu_u + \mu_d$, etc. Frequently, instead of chemical potentials the fugacities $\lambda_i = \exp(\mu_i/T)$ are used.

In the Boltzmann approximation the partition function for the strange particle fraction of the hadronic gas, $Z_s$ in the notation of Ref. [15] is

$$\ln Z_s = \frac{V T^3}{2\pi^2} \left\{ (\lambda_s \lambda_q^{-1} + \lambda_q^{-1} \lambda_s) \gamma F_K 
+ (\lambda_s \lambda_q^2 + \lambda_q^{-1} \lambda_s^2) \gamma F_Y 
+ (\lambda_s^2 \lambda_q + \lambda_q^{-2} \lambda_s) \gamma^2 F_\Xi 
+ (\lambda_s^3 + \lambda_q^{-3}) \gamma^3 F_\Omega \right\}, \tag{2}$$

where the kaon ($K$), hyperon ($Y$), cascade ($\Xi$) and omega ($\Omega$) degrees of freedom in the hadronic gas are included successively. Given the recently measured values of the thermal parameters we are obliged to sum over some more strange hadronic particles than was done in Eq. 4 of Ref. [15]. The phase space factors $F_i$ of the strange particles are:

$$F_K = \sum_j g_{K_j} W(m_{K_j}/T),$$
$$F_Y = \sum_j g_{Y_j} W(m_{Y_j}/T),$$
$$F_\Xi = \sum_j g_{\Xi_j} W(m_{\Xi_j}/T),$$
$$F_\Omega = \sum_j g_{\Omega_j} W(m_{\Omega_j}/T). \tag{3}$$

We have included kaons up to 1650 MeV, hyperons up to 1750 MeV, cascades up to 1820 MeV and also omegas up to 2250 MeV. We use the notation $W(x) = x^2 K_2(x)$, and $K_2$ is the modified Bessel function. The factor $\gamma$ in Eq. 2 allows us to consider the strange particle gas away from absolute...
chemical equilibrium which corresponds to the value $\gamma = 1$. In general, if there is not sufficient time to make strangeness (but sufficient time to exchange strange quarks between the carriers, which we implicitly assumed above) the partition function applies with $\gamma < 1$. The value of the factor $\gamma$ is determined by the dynamics of strangeness production. Its measurement is only possible in the comparison of abundances of hadrons comprising different numbers of strange (or antistrange) quarks. The value $\gamma = 0.7 \pm 0.1$ arising from the WA 85 results [3] is suggestive of QGP based strangeness production mechanisms.

### 2.3 Strangeness balance

We consider a HG fireball in which the number of $s$ and $\bar{s}$ quarks is (nearly) equal. The condition that the total strangeness vanishes takes the form

$$0 = \langle s \rangle - \langle \bar{s} \rangle = \lambda_s \frac{\partial}{\partial \lambda_s} \ln Z_s.$$  \hspace{1cm} (4)

This is an implicit equation relating $\lambda_s$ with $\lambda_q$ for each given $T$. A slight generalization is obtained allowing that a small fraction imbalance in strange quark numbers arising from pre-equilibrium emission [9] and effects of up to 10% were considered.

### 3 CONSTRAINT BETWEEN $\mu_s$ AND $\mu_B$

In order to better understand the numerical results we first study an aspect of the condition (4) analytically. We seek for $\mu_s = 0$, viz. $\lambda_s = 1$, non trivial values of $\mu_B^0$ (different from the trivial solution $\mu_B^0 = 0$) for which strangeness balances out. We find the exact answer to be:

$$\mu_B^0 = 3 \text{cosh}^{-1} \left( \frac{F_K}{2 F_Y} - \frac{\gamma F_\Xi}{F_Y} \right).$$  \hspace{1cm} (5)

There is a real solution only when the argument on the right hand side is greater than unity. It turns out that this condition is a sensitive function of the temperature $T$ and of the hadronic resonances included in Eq. [3]. For any given spectrum used to compute the phase space factors $F_i$ there is a temperature $T_0$ beyond which no such solution is possible — this occurs since $F_K/F_Y$ is a monotonically decreasing function of $T$ (see Fig. 1, Ref. [15]).

In consequence of the above observations we expect that there is a domain of temperatures for which even a considerable change of $\mu_B$ does not induce a significant change of $\mu_s$. For the complete set of resonances we have included in the phase space factor, this quite peculiar behavior occurs just at the temperature $T \simeq 215 \text{ MeV}$. In Fig. [3] we present the constraint between $\mu_s$ and $\mu_B$ at fixed $T = 200 \text{ MeV}$ (solid curves), 150 MeV (long-dashed curves), 300 MeV (short-dashed curves) and 1,000 ($\simeq \infty$) MeV (dotted curves) for $\gamma = 0.7$ (the choice $\gamma = 1$ influences this result insignificantly). The solid lines corresponding to $T = 200 \text{ MeV}$ is indeed leading to quite small values of $\mu_s$ for all $\mu_B < 500 \text{ MeV}$.

### 3.1 Strange baryon ratios

This behavior explains why in the vicinity of $T = 215 \pm 15 \text{ MeV}$ the QGP and HG are leading to the same particle abundances: the constrain to zero strangeness in HG is consistent with $\mu_s$ characteristic of QGP phase. We also find as Fig [3] clearly shows, that this ambiguity does not
Figure 1. Strange-chemical potential $\mu_s$ versus baryo-chemical potential $\mu_B$ for zero strangeness fireball. Long-dashed line corresponds to $T = 150$ MeV, solid line to $T = 200$ MeV, and dashed line to $T = 300$ MeV. The dotted line is the limiting curve for large $T$.

persist at higher or lower temperature. To make this point more quantitative, we now study strange baryon ratios arising from a thermal fireball constrained to vanishing strangeness.

Comparing spectra of particles with their antiparticles within overlapping regions of $m_\perp$, the Boltzmann and all other statistical factors cancel, and their respective abundances are only functions of fugacities \[2\]. In Fig. 3.1 we show for the case of exactly vanishing strangeness the resulting relation of $R_\Xi = \Xi^-/\Xi^-$ with $R_\Lambda = \Lambda/\Lambda$. In addition to the HG results for temperatures $T = 200$ MeV (solid line), $T = 150$ MeV (dashed line) and $T = 300$ MeV (dotted line) we show the case $\mu_s = 0$ corresponding to QGP source (dashed-dotted line). The cross corresponds to the result reported by the WA85 experiment \[3\]. As can be seen, the QGP curve will nearly coincide with the $T = 215$ MeV curve in the HG case, as we noted before \[7\].

In addition to the baryon ratios one can also consider the ratio of kaons to hyperons, again at fixed $m_\perp$. Because of the experimental procedures used, which rely on the observation of the disintegration of neutral strange particles into two charged products a comparison of the $K_s$ (here $s$ stands for short) with the $\Lambda$ (which includes the $\Sigma^0$ abundance) is available. Considering $R_K = K_s/(\Lambda + \Sigma^0)$ as function of $R_\Lambda$ we find that there is poor sensitivity of the result to the nature of the fireball, $R_K$ is a good measure of the baryo-chemical potential \[1\] of the source of these particles, which may be in part the fragmentation region of the heavy target nucleus.

### 3.2 Measurement of $\gamma$

We have introduced the factor $\gamma$ which characterizes the approach to saturation density of the strange quark abundance. It can be experimentally measured by determining the product:

$$\frac{\Xi \cdot \Xi}{\Lambda \cdot \Lambda} = \gamma^2.$$ \[6\]

It is easy to see that all spectral and chemical factors cancel in this combination of particle abundances, and the only unbalanced factor is the phase space density of strangeness. We refer to reference \[8\] for further details.
Strange anti-baryons — QGP versus HG

Figure 2. $R_A$ versus $R_\Xi$. Long-dashed line corresponds to $T = 150$ MeV, solid line to $T = 200$ MeV, and dashed line to $T = 300$ MeV in HG. The dashed-dotted line corresponds to QGP.

4 DISCUSSION

In the $\mu_B$–$T$ plane the condition of zero strangeness combined with the condition $\lambda_s = 1$ leads to the curve shown in Fig. 4 by the solid line. Dashed line is the case $\lambda_s = 0.95$ and dotted line $\lambda_s = 1.02$. The upper and lower boundary of hatched area arise from $\mu_B/T = 3 \cdot 0.52 \pm 0.01$ and from the constraint obtained from the $K^-/\Lambda$ ratio reported [3]. We find that if we are willing to accept a hadronic gas at temperature of $T \simeq 200 - 210$ MeV, it could indeed be the source of strange particles — a puzzle in such an interpretation is the condition of $\lambda_s \simeq 1$ which is natural for QGP, and does not have at present any special founding for the HG state.

5 Particle Multiplicity

The properties of the HG and QGP fireballs are considerably different in particular with regard to the entropy content. Both states are easily distinguishable in the regime of values $\mu_B$, $T$ shown in Fig. 4. We find for the entropy per baryon $S_{HG}/B = 21.5 \pm 1.5$. Consequently, the pion multiplicity which can be expected from such a HG fireball is $4 \pm 0.5$. This is less than half of the QGP based expectations we found in [7], and clearly the difference is considerable in terms of experimental sensitivity. Checking the theoretical sensitivity we find that the point at which the entropy of HG and QGP coincide and strangeness vanishes and $\lambda_s \simeq 1$ is at $T \simeq 135$ MeV, $\mu_B \simeq 950$ MeV, quite different from the region of interest here. We note that charged particle multiplicity above 600 in the central region has been seen [16] in heavy ion collisions corresponding possibly to a total particle multiplicity of about 1,000, as required in the QGP scenario for the central fireball we described above.

Some of these emulsion particle multiplicity data are shown as function of rapidity in Fig. 5. Here we draw $D_Q$, the difference in the number of positively and negatively charged particles normalized by their sum. All up to date scanned (15) events of 200 GeV A S-Ag interactions with the “central” trigger being the requirement for the total charged multiplicity $> 300$. Reaction spectators (target fragments) are not observed in this experiment. In absence of strange particles
we find assuming pion symmetry $\pi^+ = \pi^- = \pi^0 = \pi/3$:

$$D_Q \equiv \frac{N^+ - N^-}{N^+ + N^-} \to \frac{B}{\pi} \frac{1.5}{1 + R_t} + 1.5 \frac{B}{\pi}$$  \hspace{1cm} (7)$$

At central rapidity a value of 0.08–0.09 is found. For a hadronic gas with small strange particle component we would have expected based on the entropy argument a value more than twice as large. In a numeric calculation in which we take $\lambda_s = 1 \pm 0.05$ and fix the temperature for each $\mu_B$ such that strangeness is conserved, we find:

$$D_Q = \frac{\mu_B}{1.3 \text{ GeV}} \text{ for } \mu_B < 0.6 \text{ GeV}. \hspace{1cm} (8)$$

This HG result is extremely simple, considering the complexity of the calculation. We thus see that in the HG scenario for the strangeness source which has to have $\mu_B \sim 0.35 \text{ GeV}$, see Fig. 4, Eq. 8 implies $D_Q \sim 0.27$, which is incompatible with the EMU 05 data [16], as is seen in Fig. 5. Along with this observation that HG is incompatible with the combined EMU 05 and WA85 data goes the fact we discussed here at length that the characteristic property of QGP is the persistence of the fireball parameters $\mu_s = 0$, $\gamma \sim 1$ irrespective of the temperature reached.

### 5.1 Dependence on Temperature

Only for a temperature in the vicinity of 200–215 MeV the HG scenario also leads to the value $\mu_s = 0$, while there is no ready explanation how $\gamma \sim 1$ is reached. We have identified the reason for this coincidence to be the peculiar behavior of $\mu_s$ as function of $\mu_B$ when the constrain on the total fireball strangeness is imposed. Thus it is quite natural to expect that at the lower energy accessible to CERN–SPS (60 GeV S–beam and about 50 GeV Pb–beam) a lower value of temperature accompanied by higher value of $\mu_B$ will be reached. We stress that if the strange

![Figure 3](image-url)
Strange anti-baryons — QGP versus HG

Figure 4. Emulsion data for charged particle multiplicity as function of pseudo-rapidity: difference of positively and negatively charged particles normalized by sum of both polarities. (Courtesy of CERN-EMU 05 collaboration, Y. Takahashi et al. [16]).

Particles emerge from nearly zero strangeness fireball formed at a given temperature (150, 200, 300 MeV) it is imperative that the observed particle ratios fall on the here presented lines of Fig. 3.1.

In conclusion we note that the currently available strange particle spectra, though consistent both with QGP and/or HG at $T > 200$ MeV, are strongly favoring the QGP interpretation (because of $\lambda_s = 1$, $\gamma \simeq 1$). This case is considerably strengthened by the consideration of the emulsion multiplicity data. Our discussion therefore strongly suggests that strange anti-baryon abundances be measured along with non-strange particle multiplicities and that it is desirable to widen the study of strange anti-baryon ratios to higher and lower nuclear beam energies.

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