HOT HADRONIC MATTER AND
STRANGE ANTI-BARYONS

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Abstract

We demonstrate that both quark-gluon plasma (QGP) and hadronic gas (HG) models of the central fireball created in $S \to W$ collisions at 200 GeV $A$ are possible sources of the recently observed strange (anti-) baryons. From the theoretical point of view, the HG interpretation we attempt remains more obscure because of the high fireball temperature required. The thermal properties of the fireball as determined by the particle ratios, are natural for the QGP state. We show that the total particle multiplicity emerging from the central rapidity region allows to distinguish between the two scenarios.

Published in Phys. Lett. B 292 (1992) 417–423.
1 Strange quarks sources

In collisions of relativistic heavy nuclei, there is a substantially enhanced production of strange hadronic particles [1]. Since the time scale in a typical nucleus-nucleus collision is very short, it is necessary to determine kinetically the strange particle production [2]. Theoretical models of kinetic strangeness production suggest that abundant strangeness is either a signature of QGP or of some other new phase, e.g., with partially restored chiral symmetry [3] in which the cross section for strangeness production is considerably enhanced. Enhancement in the total strangeness abundance tells us that we deal with a state of matter which is either dense or relatively long-lived or in which strangeness production cross sections are enhanced or possesses some combination of these three factors. In order to be more specific about the nature of the dense matter, individual strange quark and anti-quark clusters, which may be more sensitive to the environment from which they emerge [4], have to be considered. Recent measurements of the abundance of strange anti-baryons and baryons at 200 GeV A collisions of S-ions with a W-target by the WA85 collaboration [5] constrains the properties of the central rapidity source of these particles and it has already been demonstrated that the particle abundances are well in agreement with a picture of explosively disintegrating QGP fireball [6]. Similarly, it has been already argued that these results are compatible with the scenario of an equilibrium HG fireball [7]. Given that both approaches (HG and QGP fireballs) can account for the presented data, our main objective here will be to identify a difference between QGP and HG scenarios which permits to distinguish the underlying strangeness source despite the limited information available today. We note that on theoretical grounds the QGP interpretation is a more palatable one in view of the domain of the thermal parameters associated with the fireball.

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 [8]. 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 the 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. In contrast to fireball entropy, the thermal fraction of energy of the fireball is decreasing in the course of fireball evolution even though the total energy content is conserved; it can not be therefore used for the study of the properties of the source on a model independent way.

Implicit in the physical picture developed here is the formation of a central and hot matter fireball in the nuclear collisions at 200 GeV A. This reaction picture does not necessarily imply “full stopping” of either baryon number or energy when the smaller projectile collides at small impact parameter with the target, actually effectively with the tube of matter in its path in the target nucleus. All that such a picture presumes is that the energy and flavor content of the central rapidity region is able to scatter several times, leading to thermal particle spectra in $m_\perp$. Support for such source of strange particles comes from the remarkably central production of strange particles as reported by the NA35 collaboration \[9\] even for S–S collisions and more recently by the NA36 experiment \[10\] for S $\rightarrow$ Pb. All these and other data \[11\] can be combined to show that the source of transversely produced particles has a common apparent temperature of $T = 210 \pm 10$ MeV \[12\].

2 Strange particle ratios

The statistical variables of the system are the temperature $T$ and the chemical potentials $\mu_i$ of the different conserved quark flavors $u, d, s$. It is convenient to denote:

$$\mu_q = (\mu_d + \mu_u)/2, \quad \delta \mu = \mu_d - \mu_u, \quad \mu_B = 3\mu_q;$$

(1)

here, $\mu_q$ is “quark” chemical potential, $\mu_B$ is the baryo-chemical potential and $\delta \mu$ describes the (small) asymmetry in the number of up and down quarks due to the neutron excess in heavy ion collisions. It is straightforward to identify that the ratio of the number of down and up quarks in a $S \rightarrow W$-tube collisions is 1.09, and this number will help fix the small value of $\delta \mu$, in dependence on the assumed structure of the source – in any case this asymmetry leads to small corrections in our work and though implemented, will be not discussed at length. We further introduce the fugacities $\lambda_i = \exp(\mu_i/T)$ which are the tools of counting the particles. Finally we note that it is not necessary to introduce different fugacities (and chemical potentials) for the hadronic gas phase, as the fugacity of each HG species is simply the product of the fugacities of the constituent quarks, viz. $\lambda_N = \lambda_q^3$, $\lambda_K = \lambda_q \lambda_s$, etc. The fact that quark flavors $u, d, s$ are separately conserved on the scale of times of the hadronic collisions implies that their number is conserved and the production (or annihilation) can only occur in $X \leftrightarrow q_i \bar{q}_i$. In consequence the chemical potentials for particle and anti-particle flavors are opposite to each other and this implies ($\lambda_{\bar{q}_i} = \lambda_{q_i}^{-1}$).

In any statistical model for the production of particles based on a thermal source the (relative) probability of (formation) emission of a (composite) particle (ignoring correlation effects) is:

$$P \propto \prod_i g_i \gamma_i \lambda_i \gamma_i e^{-E_i/T}.$$  

(2)
For a composite particle at energy $E = \sum_i E_i$, Eq. 2 becomes simply a phase space factor times the Boltzmann exponential $e^{-E/T}$ factor. We recall that $E = m_\bot \cosh(y)$ with $m_\bot = \sqrt{m^2 + p^2_\bot}$ (the transverse direction is with regard to the original collision axis) and $y$ is the particle rapidity. The other factors in Eq. 2 are:

(a) the statistical multiplicity factors $g_i$, referring to the degeneracy of the $i$ ($=u, d, s$) component, and characterizing also the likelihood of finding among randomly assembled quarks, the suitable spin-isospin of the particle;

(b) the product of chemical fugacities $\lambda_i$ for each constituent quark species;

(c) allowance is made for the approach to the absolute chemical equilibrium by strange quarks with a factor $0 \leq \gamma_s \leq 1$, for the strange quark flavor content of the particle.

As the method of measurement distinguishes the flavor content, we keep explicit the product of $\lambda_i$-factors; $\gamma_s$ will enter when one compares particles with different number of strange quarks and/or anti-quarks. The difference between $\gamma_s$ and $\lambda_s$ is that $\gamma_s$ is the same for both $s$ and $\bar{s}$ viz. $\gamma_s = \gamma_{\bar{s}}$, as both particles are produced together and hence their total abundance is equally distant from ‘full’ phase space. We assume that for light flavors the $\gamma_q$-factor is effectively unity considering the collision times and the strength hadronic cross sections. We note that this counting rule allows to describe the relative abundances of strange baryons and anti-baryons at fixed $m_\bot$. All baryons considered here have spin $1/2$, but they include spin $3/2$ resonances which become spin $1/2$ states through hadronic decays. This is implicitly contained in the counting of the particles by taking the product of the quark spin degeneracies; since in all ratios to be considered this factor is the same, we shall not discuss it further. When considering hyperons we must remember that there are two different charge zero states of different isospin $\Lambda$ and $\Sigma^0$: the experimental abundances of $\Lambda$ and $\bar{\Lambda}$ ($I=0$) implicitly include, respectively, the abundance of $\Sigma^0$ and $\Sigma^0$ ($I=1, I_3=0$), arising from the decay $\Sigma^0 \rightarrow \Lambda^0 + \gamma (74 \text{ MeV})$; hence the true abundances must be corrected by a factor $\approx 2$, e.g. $\Xi/\Lambda = 2 \cdot \Xi/(\Lambda + \Sigma^0)$, the latter being the observed quantity.

Comparing spectra of particles within overlapping regions of $m_\bot$, the Boltzmann and many statistical factors cancel, and their respective abundances are only functions of fugacities, e.g.:

$$R_\Xi = \frac{\Xi^-}{\Xi^+} = \frac{\lambda_d^{-1} \lambda_s^{-2}}{\lambda_d \lambda_s^2}, \quad R_\Lambda = \frac{\Lambda}{\bar{\Lambda}} = \frac{\lambda_d^{-1} \lambda_u^{-1} \lambda_s^{-1}}{\lambda_d \lambda_u \lambda_s}. \quad (3)$$

The cascade and lambda ratios can easily be related to each other, in a way which shows explicitly the chemical potential dependence:

$$R_\Lambda = R_\Xi^2 \cdot e^{2(\delta\mu/T) e^{\delta\mu_s/T}}, \quad R_\Xi = R_\Lambda^2 \cdot e^{-\delta\mu/T} e^{\delta\mu_s/T}. \quad (4)$$

Always remember that Eq. 4 is generally valid, irrespective of the state of the system (HG or QGP). Since the asymmetry $\delta\mu$ is small (see below), Eq. 4 determines the value of the baryo-chemical and strange potentials to considerable precision (because of the factor 6 in the exponents). The value emerging from such an analysis will correspond to the conditions prevailing in the source of the strange (anti-) baryons.
In Eq. 3 above the factor $\gamma_s (< 1)$ did not appear because it is the same for both strange quarks and anti-quarks. It enters where particles of differing strangeness content are compared:

$$\mathcal{R}_s \equiv \frac{\Xi^-}{\Lambda} = \frac{\Lambda}{p} = \gamma_s \cdot \frac{\lambda_s - 1}{\lambda_u} ; \quad R_s \equiv \frac{\Xi^-}{\Lambda} = \frac{\Lambda}{p} = \gamma_s \cdot \frac{\lambda_s}{\lambda_u} .$$

(5)

The product of both expressions in Eq. 5 determines the unknown quantity $\gamma_s$:

$$\mathcal{R}_s \cdot R_s \equiv \frac{\Xi^-}{\Lambda} \cdot \frac{\Xi^-}{\Lambda} = \frac{\Lambda}{p} \cdot \frac{\Lambda}{p} = \gamma_s^2 .$$

(6)

The factor $\gamma_s$ accounts for much of our ignorance about the dynamics of strangeness formation and the approach to equilibrium of the strange quark abundance. A value $\gamma_s \simeq 1$ is believed to favor QGP interpretation of the data [1].

3 Strange baryon/anti-baryon source

We now recall the high $m_\perp$, central $y$ strange anti-baryon abundances emerging from high energy nuclear collisions of 200 GeV/AS $\rightarrow W$. The following data is from the CERN experiment WA85 [3], and we have: $R_\Xi := \Xi^-/\Xi^+ = 0.39 \pm 0.07$ for $2.3 < y < 3$ and $p_\perp > 1$ GeV/c. In p-W reactions in the same $(p_\perp, y)$ region, a smaller value $0.27 \pm 0.06$ is found. Furthermore, $R_\Lambda := \Lambda/\Lambda = 0.13 \pm 0.03$ for $2.4 < y < 2.8$ and $p_\perp > 1$ GeV/c. Here corrections were applied to eliminate hyperons from cascading decays. The ratio $R_\Lambda$ for S-W collisions is slightly smaller than for p-W collisions in the same kinematic range. WA85 also determined $\Xi^-/(\Lambda + \Sigma^0) = 0.6 \pm 0.2$ and $\Xi^-/(\Lambda + \Sigma^0) = 0.20 \pm 0.04$ at fixed $m_\perp > 1.72$ GeV. The fact that the more massive and more strange anti-cascade exceeds at fixed $m_\perp$ the abundance of the anti-lambda is most striking, even considering the experimental error. These results are inexplicable presently in terms of particle cascades [3]. The relative yield of $\Xi^-$ appears to be 5 times greater than seen in the $p-p$ ISR experiment [14] at higher energy.

These results imply in view of Eq. 3: $\gamma_s = \sqrt{0.48 \pm 0.17} = 0.7 \pm 0.1$ – the source is near to absolute chemical equilibrium of strangeness. Note that the error which comprises only the experimental measurement error comes out amazingly small for $\gamma_s$, considering how large the error on the individual quantities has been. The values of the chemical potentials are determined by the two forms of the Eq. 4. Neglecting the isospin asymmetry factor, we find: $\mu_q/T = 0.167 \cdot \ln(R_\Xi/R^2_\Lambda) = 0.52 \pm 0.1$, and $\mu_s/T = 0.167 \cdot \ln(R_\Lambda/R^2_\Xi) = -0.03 \pm 0.06$. $\mu_s$ vanishes within the precision of the measurements, which indicates exact symmetry between the produced strange and anti-strange quarks, which can only occur in either:

1. a baryon number free fireball of arbitrary composition – this is clearly excluded by the presence of a finite $\mu_q$;

2. in a QGP phase before hadronization;
3. in a HG at the magic point in $(T, \mu_B)$ parameter space for which the size of the phase space for strange and anti-strange baryons accidentally agree.

4 Interpretation

The QGP interpretation of the conditions determined above is natural: In QGP we always have $\mu_s = 0$ for a fireball with zero strangeness. This implies that we implicitly assume that the loss of strangeness due to pre-equilibrium emission is small and/or symmetric between $s$ and $\bar{s}$-quarks. Furthermore, with $\mu_d/T = 0.54$, $\mu_u/T = 0.51$ (allowing for the asymmetry between the $u$ and $d$ quarks) we find for the value of $\alpha_s = 0.6$ and $T = 210$ MeV that the energy density is 2.2 GeV/fm$^3$, baryon density 0.27/fm$^3$, above normal nuclear density and the strange quark density is 0.45/fm$^3$ (allowing for the factor $\gamma_s = 0.7$ as determined). The entropy per baryon is $S_{QGP}/B = 46.9$ and it rises slowly to 47.1 as temperature is increased by 20 MeV. Naturally, strangeness density scales nearly with $T^3$, while the energy density scales nearly with $T^4$. A non-negligible portion of the energy is contained in the strange quark pair density. A further small component is in the latent energy of the vacuum which we took here to be 170 MeV$^4$. We note that while presence of $\alpha_s$ reduces the light quark and gluon effective degrees of freedom according to the known first order perturbative behavior, we have left the contributions of strange quarks to entropy, energy, etc... unaffected by the perturbative QCD interaction.

When the value of $\alpha_s$ is changed by $\pm 0.2$ there is a small change in the entropy per baryon: for $\alpha_s = 0.4$ we find the value $S_{QGP} = 50.5$, for $\alpha_s = 0.8$ we find $S_{QGP} = 41.4$. As noted before, in principle entropy must increase in the evolution of the QGP fireball, and in practice this increase is small once thermal conditions are reached. The entropy content per baryon is ultimately contained in the particle multiplicity that emerges in the central rapidity region, mostly in form of pions. As each baryon in a non-relativistic nucleon gas has the entropy content

$$\frac{S_B}{B} = 2.5 + \frac{m_B - \mu_B}{T} \approx 5.5$$

the remaining entropy, $S_\pi = S_{QGP} - S_B$ is divided between the pions: in a relativistic pion gas at $T \simeq 1.5m_\pi$ we have entropy content per particle $\simeq 4$. Consequently we find that the thermal parameters of the QGP fireball would lead to a hadronic particle multiplicity per participating baryon which must be above $(46.9 - 5.5)/4 \simeq 10.5$ with the uncertainty in the value of $\alpha_s$ introducing an uncertainty of one unit in this value. As expected, the QGP picture thus leads to a relatively high final state multiplicity.

We now turn to discuss the possibility that the single data point we have for $T, \mu_s, \mu_q$ is associated with a hadronic gas fireball. It is easy to write in the Boltzmann approximation the partition function for the strange particle fraction of the hadronic gas, $Z_s$, as it has been presented in Ref. [15]. However, given the WA85 values of the thermal parameters we are obliged to sum over many more strange hadronic particles than was done in Eq. 4 of Ref. [15].
We have in detail:

$$\ln Z_s = \frac{V_s T^3}{2\pi^2} \left[ (\lambda_s \lambda_q^{-1} + \lambda_s^{-1} \lambda_q) \gamma_s F_K + (\lambda_s \lambda_q^2 + \lambda_s^{-1} \lambda_q^2) \gamma_s F_Y 
+ (\lambda_s^2 \lambda_q + \lambda_s^{-2} \lambda_q^{-1}) \gamma_s^2 F_\Xi + (\lambda_s^3 + \lambda_s^{-3}) \gamma_s^3 F_\Omega \right] \tag{8}$$

where the kaon ($K$), hyperon ($Y$), cascade ($\Xi$) and omega ($\Omega$) degrees of freedom in the hadronic gas are included successively. The phase space factors $F$ of the strange particles are:

$$F_K = \sum_j g_{K_j} W(m_{K_j}/T); \quad K_j = K, K^*, K_2, \ldots m \leq 1650 \text{ MeV},$$

$$F_Y = \sum_j g_{Y_j} W(m_{Y_j}/T); \quad Y_j = \Lambda, \Sigma, \Sigma(1385), \ldots m \leq 1750 \text{ MeV},$$

$$F_\Xi = \sum_j g_{\Xi_j} W(m_{\Xi_j}/T); \quad \Xi_j = \Xi, \Xi(1530), \ldots m \leq 1820 \text{ MeV},$$

$$F_\Omega = \sum_j g_{\Omega_j} W(m_{\Omega_j}/T); \quad \Omega_j = \Omega, \Omega(2250). \tag{9}$$

where $W(x) = x^2 K_2(x)$, and $K_2$ is the modified Bessel function.

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

$$0 = \langle s \rangle - \langle \bar{s} \rangle = \lambda_s \frac{\partial}{\partial \lambda_s} \ln Z_s. \tag{10}$$

This is an implicit equation relating $\lambda_s$ with $\lambda_q$ for each given $T$. In actual calculations we have distinguished the $u, d$ quarks and introduced as required $\lambda_u, \lambda_d$ in lieu of $\lambda_q$, with the ratio of $\lambda_d/\lambda_u$ determined by the requirement that the ratio of down to up flavor is 1.09 (at temperature $T \simeq 210 \text{ MeV}$ this leads to $\delta \mu/\mu_q \simeq 0.09$). In order to implement this requirement we of course had to include in the partition function the non-strange hadrons, which was done in the same way, with the mesons included up to mass 1690 MeV, nucleons up to 1675 MeV and $\Delta$'s up to 1900 MeV. We note that higher resonances would matter only if their number were divergent as is the case in the Bootstrap approach of Hagedorn \[16\] and the HG was sufficiently long lived to populate all high mass resonances. We caution the reader that our empirical approach suffers 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 \[17\]. 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 the $\mu_B - T$ plane the condition of zero strangeness combined with the condition $\lambda_s = 1$ leads to the curve shown in Fig. 1 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. 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 – another 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.

However, we find that 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. 1. We find for \( S_{\text{HG}}/S = 21.5 \pm 1.5 \). 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 above, 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 \( \lambda_s \simeq 1 \) 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 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.

We thus conclude that the different models for the source of the strange particles in \( S \rightarrow W \) 200 GeV collisions can be differentiated with help of the entropy content which corresponds to the final particle multiplicity. Particle multiplicity per baryon of about 10 indicates pure QGP fireball, around 4 suggests pure HG, and an intermediate value may be taken to be indicative of a mixed and/or pre-critical phase. We recall that the number of baryons in a zero impact parameter collision is about 110, and that in the above discussion multiplicity of strange particles is included – strangeness being a non-negligible component in the particle flow. While we can not distinguish alone in terms of strange particle high \( m_\perp \) spectra the QGP and HG hypothesis for the case \( T = 200 - 220 \) MeV, we have shown assuming that the fireball has net strangeness zero, that in the extreme conditions considered here both hypothesis are falsifiable when studying the associated particle multiplicities.

Acknowledgement: J. R. would like to thank U. Heinz for stimulating discussion of these results, and his co-authors and members of Collège de France – WA85 collaboration for their kind hospitality in Paris.

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Figure 1. The solid line shows in the $\mu_B$–$T$ plane the condition of zero strangeness in HG fireball assuming the QGP-like condition $\lambda_s = 1$; dashed line $\lambda_s = 0.95$; dotted line $\lambda_s = 1.02$. Hatched is the region compatible with the experimental WA85 data. The $\oplus$ corresponds to $T = 220$ MeV, $\mu_B = 340$ MeV, the central point for QGP fireball.