

## Evidence for a Phase with High Specific Entropy in Nuclear Collisions

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We determine the entropy-per-baryon content of the central reaction region in terms of the charged particle multiplicity. We study the consistency of our findings with recent data on strange antibaryon production at 200A GeV in S-A collisions ( $A \sim 200$ ) assuming formation of a central fireball. Hadron gas models which do not invoke strong medium modifications of hadron masses do not provide enough entropy and are inconsistent with the combined experimental results. In contrast the quark-gluon plasma hypothesis explains them naturally.

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One of the fundamental differences between the two phases of dense hadronic matter often referred to as hadronic gas (HG) and quark-gluon plasma (QGP) is the entropy content per baryon which can be observed in the final particle multiplicity. At fixed temperature  $T$  (as, for example, given by the observed slope of the momentum spectra of the emitted particles) the QGP is the phase with the higher entropy; this difference occurs because of the liberation of the color degrees of freedom in the color deconfined QGP phase. In the domain of temperatures and flavor chemical potentials explored in the recent experiments with 200A GeV sulphur-ion collisions this difference is larger than a factor 2 [1].

Here we note (for more details see [2]) that it is possible to relate the observed strange particle data with multiplicity data and obtain a specific measurement of the entropy content of the central rapidity source of strange baryons and antibaryons. We show that this leads to a clear incompatibility of the hadronic gas reaction model with the observations which require a considerably larger specific entropy in the source. On the other hand we observe that the required entropy content is in agreement with the QGP hypothesis. This assertion supplements the earlier finding [3] that the strange particle source has, in spite of its sizable baryon chemical potential, a symmetric strangeness phase space (as is generally true for a QGP), which is at the same time nearly fully saturated [4], properties difficult to understand in normal hadronic matter.

We note that in 200A GeV sulphur reactions involving heavy nuclear targets the observed particle spectra, after correcting for resonance decay effects [5], resemble thermal distributions possibly including a collective flow component [6]. An interpretation in terms of a generalized thermal model, which assumes local thermal equilibrium of all components and chemical equilibrium of the gluon and light quark abundances, and allows for incomplete chemical equilibrium for the strange quark abundance,

appears to be consistent with the observed particle ratios [2, 3].

The central fireball from which the particles emerge is described by its temperature  $T$  and by the chemical potentials  $\mu_i$  of the different conserved quark flavors  $u, d, s$  [or by the corresponding fugacities  $\lambda_i = \exp(\mu_i/T)$ ]. The hadronic chemical potentials are given as the sum of constituent quark chemical potentials. The strong and electromagnetic interactions do not mix quark flavors, and the net numbers of  $u, d,$  and  $s$  quarks are separately conserved on the time scale of hadronic collisions. For the strange flavor we also introduce the phase space saturation factor  $\gamma_s$  [1, 3]. In that framework an analysis of the strange particle momentum spectra within the fireball model [7] found consistency of all strange particle measurements in S-A collisions (with  $A \sim 200$ ) at 200A GeV with an "apparent temperature" (inverse slope parameter) of  $T_{\text{apparent}} = 210 \pm 10$  MeV. This value comprises in principle the effects of thermal motion and collective expansion flow, and it is still a matter of debate [5, 6] how these two effects superimpose each other in the heavy-ion data.

Two extreme and sometimes complementary pictures of the dynamics can be imagined. In the first one assumes thermal evaporation or sudden disintegration without collective flow, such that the inverse slope reflects the true temperature,  $T \simeq 210$  MeV. In the second approach one assumes  $T = 150$  MeV combined with a transverse flow velocity  $\beta_f = 0.32$  at freeze-out, leading to the same apparent temperature via the blueshift effect. It has already been pointed out [1] that only the former scenario ( $T > 200$  MeV) can be consistent with a conventional *hadronic gas* constrained by the principle of strangeness conservation and the observed strange-antistrange phase space symmetry  $\mu_s \simeq 0$ , unless a strong modification of the hadron gas equation of state is performed (see also [2, 8]). In the conventional HG picture, at a temperature  $T = 150$  MeV the strangeness constraint at  $\mu_s = 0$  re-

quires a very large value of the baryon chemical potential,  $\mu_B \sim 900$  MeV. This value is entirely incompatible with the experimental yield of strange antibaryons as it implies for example a ratio  $\bar{\Lambda}/\Lambda \simeq \exp[-\frac{4}{3}\mu_B/T] \simeq 0.0003$ . This should be compared to the reported [9] central rapidity result for S-W collisions triggered on high multiplicity which, after correction for the contamination from cascade decays, is  $\bar{\Lambda}/\Lambda = 0.13 \pm 0.03$ . Similarly, the ratio  $\bar{\Xi}/\Xi \simeq \exp[-\frac{2}{3}\mu_B/T]$  would yield  $\simeq 0.02$  instead of  $\sim 0.4$  reported. Thus, if confirmed, the observation of  $\mu_s = 0$  excludes the flow interpretation of the observed spectra within a conventional equilibrium HG picture [6], and within such a picture the measured slope of  $\simeq 210$  MeV must be taken as a serious indicator of the true temperature of the source. However, at  $T > 200$  MeV the notion of a hadron resonance gas develops numerous internal inconsistencies which alone raise doubts about the validity of such a hadron gas interpretation. In the context of a QGP true temperatures of 200–220 MeV are, of course, entirely possible, but in this case the observation  $\mu_s \simeq 0$  does not force us to accept the apparent slope directly as a temperature, since this value of  $\mu_s$  is assumed by a strangeness-neutral QGP at any temperature.

As a further argument against the interpretation of the data in terms of a HG state at  $T \simeq 210$  MeV we show here that the corresponding entropy content of such a state is inconsistent with the available data on charged particle multiplicity, while no such problem exists if one instead assumes the formation of a high entropy quark-gluon phase. A first indication for a grave inconsistency in the HG interpretation is contained in the results discussed in Ref. [10]; a combined chemical analysis of the NA35 [11] and WA85 [9] data led these authors to assume an equilibrated HG at  $T = 170$  MeV and  $\mu_B = 257$  MeV as the source for the emitted strange particles. With these parameters the observed  $\pi/K$  ratio is underpredicted by nearly a factor 2, indicating an overabundance of pions and thus excess entropy in the data which are not compatible with the thermal HG model.

To quantify this argument and allow for a phenomenological discussion of the entropy balance, we introduce the following easily measurable quantity:

$$D_Q \equiv \frac{N^+ - N^-}{N^+ + N^-}. \quad (1)$$

$D_Q$  is the ratio of net charge multiplicity to the total charged multiplicity. It can be determined (without identifying particles) with any tracking device within a magnetic field. As long as the experimental acceptance and efficiency is similar for particles with both signs of the electric charge, this ratio is insensitive to acceptance corrections. A simple and well-known estimate of this ratio in which only pions and nucleons are counted, assuming  $N_{\pi^+} = N_{\pi^-} = N_{\pi^0} = N_{\pi}/3$ , is given by

$$D_Q^{\text{nonstrange}} \approx \frac{B}{N_{\pi}} \frac{0.75}{1 + 0.75(B/N_{\pi})}, \quad (2)$$

where  $B$  is the number of baryons in the fireball. As we see,  $D_Q$  is a measure of the baryon to pion ratio. We note that the estimate Eq. (2) is wrong by two partially compensating factors of order 2: both higher mass non-strange resonances as well as charged strange particles must be included at their observed level, and therefore we will study  $D_Q$  and its relation to the entropy content of the source numerically.

We constrain in our calculations [2] the domain of thermodynamic parameters such that the net strangeness of the gas is  $\langle s \rangle - \langle \bar{s} \rangle \simeq 0$ . Imposing the phase space symmetry between strange and antistrange particles by setting the strange quark fugacity  $\lambda_s = 1 \pm 0.05$ , as required by the observed strange baryon and antibaryon ratios [2, 3], we can eliminate the temperature as a free parameter. We thus obtain a relation between the computable quantity  $D_Q$  and the baryon chemical potential (baryon density) of the hadronic gas which we show in Fig. 1. Up to  $\mu_B \leq 600$  MeV we observe a nearly linear behavior  $D_Q \approx \mu_B/1.3$  GeV. The vertical line in Fig. 1 indicates the intercept with  $\mu_B = 340$  MeV, the preferred value obtained in the analysis of strange baryon multiplicities [2, 3].  $D_Q$  for the hadronic gas, as indicated by the horizontal line, is thus of the order 0.25.

Experiment EMU05 [12] has determined the ratio (1) as a function of pseudorapidity in a sample of 15 high multiplicity ( $>300$ ) events of 200A GeV S-Pb collisions which were obtained by placing a 200  $\mu\text{m}$  Pb foil in front of the emulsion track detector. In the central (pseudo)rapidity region they measure  $D_Q(y \simeq 2.5 \pm 0.5) = 0.088 \pm 0.007$ , which differs considerably from the HG based theoretical expectation above. Similar values for  $D_Q$  can be extracted from the results reported by the NA5 collaboration [13] for  $p$ - $p$  and  $p$ - $A$  reactions (for a comparison with  $A$ - $A$  collisions, see also [14]); however, in this case the projectile contains no neutrons [which do

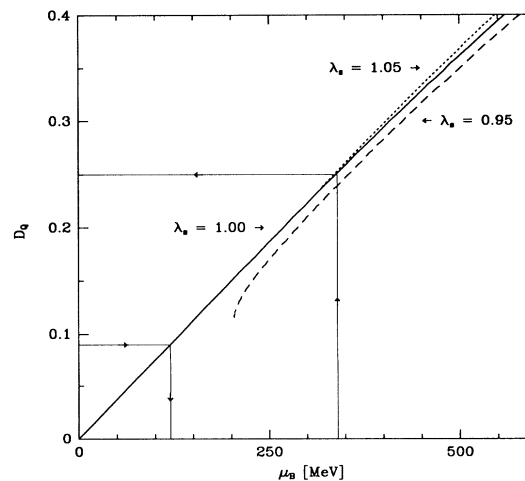


FIG. 1.  $D_Q$  as a function of  $\mu_B$  for fixed  $\lambda_s = 1 \pm 0.05$  in a HG fireball with zero conserved strangeness.

not contribute to the numerator in Eq. (1) but produce particles which contribute to the denominator]. A similar value for  $D_Q$  in  $p$ - $p$  and  $A$ - $A$  collisions thus is an indicator for additional stopping of baryons at central rapidity. It is also worth pointing out that, although the global features represented by  $D_Q$  appear at first sight to be rather similar in  $p$ - $p$ ,  $p$ - $A$ , and  $A$ - $A$  collisions, there are striking differences in certain particle ratios, in particular of strange particles, which show that  $D_Q$  alone is not sufficient to characterize the collision mechanisms.

From Fig. 1 we see that within the thermal HG model the EMU05 value of  $D_Q$  requires a baryon chemical potential of  $\mu_B \simeq 120$  MeV. Note that for  $\lambda_s \simeq 1$  this value of  $\mu_B$  translates into  $\bar{\Lambda}/\Lambda \simeq \exp[-\frac{4}{3}\mu_B/T] \simeq 0.47$  instead of the measured value  $0.13 \pm 0.03$  for  $m_\perp > 1.7$  GeV [9]. We thus conclude that the hypothesis of a hadronic gas fireball for 200A GeV S-W collisions is glaringly inconsistent with the combined EMU05 and WA85 data on  $D_Q$  and the  $\bar{\Lambda}/\Lambda$  ratio.

We will now relate the observable  $D_Q$  to the entropy content of the fireball. If we assume that hadronization of some primordial hadronic phase results in hadrons with thermal momentum distributions (as the data seem to indicate), i.e., that at most chemical equilibrium but not thermal equilibrium is broken by the hadronization process, then we are allowed to relate the specific entropy per baryon  $S/B$  of the primordial phase with the value  $D_Q$  for the resulting hadrons using the hadronic gas model for the fireball. Note that  $S/B$  can only increase during evolution of the primordial phase into hadrons; it is a nearly conserved quantity in all existing hadronization models (see, for example, Ref. [15]). It is easy to check [2] that  $S/B(D_Q)$  is nearly independent of the thermodynamic state of the hadron-emitting source: the product of  $D_Q$  with  $S/B$  is essentially proportional to the entropy per emitted pion; cf. Eq. (2). Therefore  $D_Q$  is a direct measure of the specific entropy of the system.

In Fig. 2 we show  $S/B(D_Q)$  computed with the observed value  $\lambda_s = 1$  and for vanishing net strangeness. (The long-dashed line in this figure is the result *without* strange particles, showing that the strange particle corrections are large: at fixed  $D_Q$ , almost half of the entropy is contained in strange particles.) We see in particular that the measured value  $D_Q \simeq 0.09$  implies a specific entropy  $S/B \simeq 50$ . This has to be contrasted to a value of about 21 units per baryon which we would expect from the hadron gas value  $D_Q = 0.25$  (see Fig. 1). Thus the entropy extracted from the multiplicity measurements is by more than a factor 2 larger than the value provided by the hadron gas interpretation of the particle ratios. We can further strengthen our arguments for a high entropy phase by considering the temperature dependence of the relationship between  $S/B$  and the observable  $D_Q$ . In order to reintroduce  $T$  as a parameter we relax the requirement  $\lambda_s = 1$  ( $\mu_s = 0$ ) but continue in this calculation to request zero strangeness content of the fireball. For the entire range of temperatures between 150 and 300 MeV

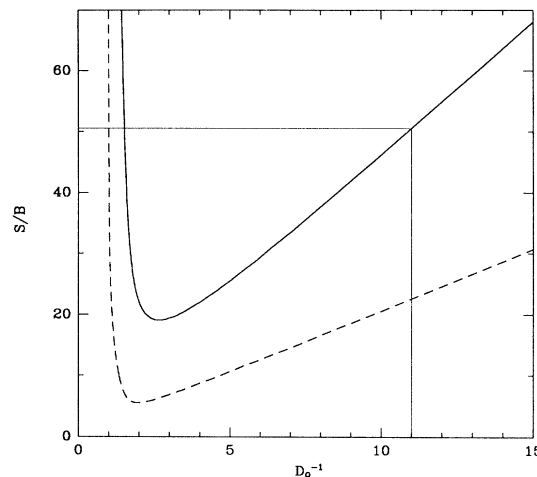


FIG. 2. Entropy per baryon  $S/B$  as a function of  $D_Q^{-1}$  for fixed  $\lambda_s = 1$  and conserved zero strangeness. Dashed: same without strange particles.

the value  $D_Q \simeq 0.09$  implies  $S/B = 50 \pm 4$ . We verified that this observation remains in essence valid even if the strangeness conservation requirement is slightly relaxed also, as may be required if the fireball emits strange flavor asymmetrically. A complete description of these results will be presented in Ref. [2].

Having shown that the measured value of  $D_Q$  points to the formation of a high entropy state, we proceed to further discuss its interpretation in terms of a QGP fireball. We use the perturbative equation of state where the presence of  $\alpha_s$  reduces the light quark and gluon effective degrees of freedom according to the first order perturbative formula. Along with most other work we leave the contributions of the massive strange quarks to entropy, energy, etc., unaffected by these perturbative QCD interactions. In the QGP phase a fireball with zero strangeness always possesses  $\mu_s = 0$ . With  $\mu_d/T = 0.54$ ,  $\mu_u/T = 0.51$  (allowing for the asymmetry between the  $u$  and  $d$  quarks; see [2]) we find for  $T = 210$  MeV and a value of  $\alpha_s = 0.6$  that the QGP energy density is  $2.2$  GeV/fm<sup>3</sup>, the baryon density  $0.27$ /fm<sup>3</sup> (nearly twice normal nuclear density), and the fully saturated strange quark density would be  $0.64$ /fm<sup>3</sup>. A non-negligible portion of the energy is contained in the strange quark pair density. A further small component is in the latent energy density of the vacuum which we took here to be  $(170 \text{ MeV})^4$ . While all these quantities depend rather strongly on the actual value of  $T$ , the entropy per baryon depends only on the ratio  $\mu_B/T$  (up to small corrections from the strange quark mass). Thus it is determined by the  $\bar{\Lambda}/\Lambda$  and  $\bar{\Xi}/\Xi$  data [9], independent of how the  $m_\perp$  spectra are interpreted in terms of temperature and flow, including the influence of resonance decays [2, 4]. We obtain  $S^{\text{QGP}}/B = 47$  for  $T/\mu_B = 210/340 = 0.62$ . Changing  $\alpha_s$  from 0.6 to 0.4 changes  $S^{\text{QGP}}/B$  to 51; for

$\alpha_s = 0.8$  we find  $\mathcal{S}^{\text{QGP}}/\mathcal{B} = 41$ . A further uncertainty in the value of  $\mathcal{S}^{\text{QGP}}/\mathcal{B}$  of the order of 10% arises from the dependence of the strange quark component of the entropy on the ratio  $m_s/T$ .

Although the thermal picture becomes less reliable for smaller collision systems, let us shortly consider a similar analysis for the results obtained by the NA35 collaboration [11, 16] in S-S interactions at 200A GeV. In this case we can base our discussion only on the reported charged particle rapidity densities [16] and the measured  $\bar{\Lambda}/\Lambda$  ratio [11]. S-S interactions show at central rapidity visibly less baryon number stopping than S-W collisions; from the data on  $d(N^+ - N^-)/dy$  and  $dN^-/dy$  in [16] we read off a central rapidity value of  $D_Q^{\text{S-S}}(y=3) = 0.065$  with a probable error of order 25%. According to Fig. 1 this implies a specific entropy  $\mathcal{S}/\mathcal{B} = 65-75$ . The large magnitude of this number is due to the considerable degree of transparency in this small collision system, resulting in a low central baryon density. The raw  $\bar{\Lambda}/\Lambda$  ratio (uncorrected for  $\Xi$  decays) is strongly peaked at central rapidity and rises there to a value  $\bar{\Lambda}/\Lambda = 0.34$  (with an error of order 50%) [11]. This implies a nonzero combination of chemical potentials,  $\mu_B + 1.5\mu_s = (0.8 \pm 0.4)T$ . Unfortunately, the large error in this number and the fact that no information on cascade production is available, prevents us from separating the strange and baryon chemical potentials and to proceed quantitatively with the analysis. Still, it is clear that  $\mu_B$  should be smaller than in S-W collisions, reducing the sensitivity of our method which works better for baryon-rich environments. On the other hand, forthcoming results from recent measurements in the S-Pb collision system by the NA36 collaboration [17], which cover a larger rapidity window, promise to provide the possibility of verification of the picture developed here.

The above discussion of the entropy content of the fireball and its relation to the particle ratios demonstrates that the existing S-W data are not only inconsistent with a fireball consisting of a HG with  $\mathcal{S}/\mathcal{B} \sim 20$ , but suggest strongly a QGP interpretation of the high entropy phase: we saw that the EMU05 data [12] imply a source with specific entropy of order 50, showing a remarkable coincidence with the value computed for a QGP state with the thermal parameters determined for the WA85 strange particle multiplicities [9]. The necessity of a high entropy phase as the source of the abundant strange particles observed by WA85 [9], NA35 [11], and NA36 [17] provides a strong indication for the formation of a hot baryon-rich quark-gluon plasma in 200A GeV S-A collisions. If true this should provide a very interesting physics environment for the upcoming experiments with Au and Pb beams.

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