BNL-36620
CONF-8504152--1

CAN ANTIBARYONS SIGNAL THE FORMATION OF A QUARK-GLUON PLASMA?*

Ulrich Heinz, BNL

and

P.R. Subramanian† and W. Greiner

Institut für Theoretische Physik der J. W. Goethe-Universität
Postfach 11 19 32, D-6000 Frankfurt a.M. 11, West Germany

BNL--36620

DE85 012262

ABSTRACT

We report on recent work which indicates that an enhancement of antibaryons produced in the hadronization phase transition can signal the existence of a transient quark-gluon plasma phase formed in a heavy-ion collision. The basis of the enhancement mechanism is the realization that antiquark densities are typically a factor 3 higher in the quark-gluon plasma phase than in hadronic matter at the same temperature and baryon density. The signal is improved by studying larger clusters of antimatter, i.e. light antinuclei like $\bar{\alpha}$, in the central rapidity region. The effects of the transition dynamics and of the first order nature of the phase transition on the hadronization process are discussed.

Although there is widespread agreement that high energy collisions ($E_{lab} \gg 10$ GeV/A) between very heavy nuclei ($A \gtrsim 200$) will provide the conditions to form a quark-gluon plasma[1-3], the question how one would experimentally verify that this plasma had been formed has up to now not been answered satisfactorily. Various signatures have been suggested[3]: direct photons[4] and lepton pairs[5] as electromagnetic probes for the initial hot phase of the plasma, strange particles as a signature for the presence of many gluons in the plasma[6,7], and rapidity fluctuations as a signature

---

*Contributed paper for the "Workshop on Experiments for RHIC", held at Brookhaven National Laboratory, April 15-19, 1985

†On leave of absence from the Department of Nuclear Physics, University of Madras, Madras 600 025, India.

for an (effectively) first order hadronization phase transition in the final stage of the collision[8] are the more specific ones, but other features of the particle emission spectra (like $p_\perp$ distribution and multiplicity) may also contain information. Unfortunately, all of these signatures are affected by an hadronic background from the initial and final phases of the collision, are sensitive to the degree of local thermalization reached during the collision or, like the K^+/π^+ ratio, may be affected by the nature of the phase transition (entropy production)[9]. It is highly unlikely that the existence of the quark-gluon plasma will be proven through one of the above signals by itself; corroborating evidence from as many different channels as possible will be needed to make a convincing case for this new state of matter.

In this paper we investigate the possibility of forming clusters of antimatter (antinuclei) from the antiquark content of the plasma phase in the hadronization phase transition. This is motivated by realizing that, due to restoration of chiral symmetry and their approximate masslessness, light quarks are much more abundant in the quark-gluon plasma than in a hadronic gas of the same temperature and baryon density. Therefore one is tempted to conclude that the chance to coalesce several antiquarks to form a (color-singlet) piece of antimatter should be higher during the confining phase transition than in a hadronic gas in equilibrium with the same thermodynamic parameters. This way of reasoning is similar to the one which led to the suggestion of (anti-) strange particles as a signature for the plasma[6]; however, there are a few differences, several of which are in favor of non-strange antinuclei:

(a) All of them (except the antineutron) are stable in vacuum and negatively charged, and therefore more easily detected in an experiment than strange particles.

(b) The chemical equilibration time in the plasma phase for light antiquarks is typically by an order of magnitude faster than for strange quarks[7], and equilibration of their abundance is not so sensitive to the achievement of high temperatures ($\gtrsim$ 150 MeV) in the collision.

(c) Due to their masslessness light antiquarks, at least in a baryon number free ($\mu_b = 0$) system, are even more abundant in the plasma than strange quarks (at T = 200 MeV by about a factor of 3).

The disadvantage is that non-strange hadronic matter has a higher annihilation cross-section than strange particles, leading to a partial loss of the signal in the final hadronic expansion phase. Furthermore, the light quark abundances may be affected by the phase transition itself: in the transition a major rearrangement of the quantum chromodynamic (QCD) vacuum state takes place, developing a type of gluon condensate leading to color confinement and a condensate of light quark-antiquark pairs $\langle \bar{q}q \rangle$[10] resulting in the breaking of chiral symmetry, a large constituent mass for valence quarks inside hadrons, and a finite pion mass. The coupling of the light quarks to the change of the QCD vacuum may thus affect our predictions for relative hadronic particle abundances below the phase transition. These complications will here be neglected but are discussed more extensively in a forthcoming publication[11].

Our approach will be based on the assumption that the quark and antiquark content of the plasma phase is completely carried over into the hadronic phase during the hadronization phase transition. In other words, we assume that the phase transition happens fast on the timescale for $q\bar{q}$ annihilation into gluons which is typically 1 fm/c.[7] Even if this is not true, our assumption may not be too bad since the quarks and antiquarks initially are in equilibrium with the gluons, and the inverse process is also possible as long as not all of the gluons have been absorbed into hadrons and into the creation of the nonperturbative (gluon-condensate) vacuum around the hadrons.

The conservation of the quark and antiquark content will be implemented into a thermal model for the two phases (hadron gas and quark-gluon plasma) within the grand canonical formulation, by introducing appropriate Lagrange multipliers ("chemical potentials"). After hadronization particle abundances for the different types of hadrons in the hadron gas will be determined by the requirement that all the originally present quarks and antiquarks have been absorbed into hadrons through processes like $3q \to N, \Delta, \ldots$, or $q + \bar{q} \to \pi, \rho, \ldots$) etc. These hadronization conditions determine the chemical potentials and hence the relative concentrations of all hadron species in terms of the above mentioned Lagrange multipliers which control the total quark-antiquark content of the fireball.

The point where hadronization of the plasma sets in is determined by finding the phase coexistence curve between a hadron resonance gas and a quark-gluon plasma in thermal equilibrium. Since we are interested in particle abundances, the hadron gas is described explicitly as a mixture of (finite size) mesons, baryons and antibaryons and their resonances as they are found in nature[12,19], rather than using an analytical (e.g. polytropic) equation of state. Strange particles are here neglected, but will be included in further studies. Their impact on the phase transition itself is small. All particles are described realistically by using the appropriate relativistic Bose and Fermi distributions:

$$P_{had} = \frac{1}{1 + \varepsilon_{had}^{pt}/4B} \sum_i P_i^{pt} ;$$

$$\varepsilon_{had} = \frac{1}{1 + \varepsilon_{had}^{pt}/4B} \varepsilon_{had}^{pt} = \frac{1}{1 + \varepsilon_{had}^{pt}/4B} \sum_i \varepsilon_i^{pt} ;$$

$$\rho_{b,had} = \frac{1}{1 + \varepsilon_{had}^{pt}/4B} \sum_i b_i \rho_i^{pt} ;$$

$$s_{had} = \beta(\varepsilon_{had} + P_{had} - \mu_b \rho_{b,had}) .$$

The subscript "pt" denotes the familiar expressions for pointlike hadrons with mass m_i, chemical potential μ_i, degeneracy d_i, baryon number b_i, and statistics θ_i (θ_i = +1 for fermions, θ_i = -1 for bosons):

$$P_i^{pt} = \frac{d_i}{6\pi^2} \int_{m_i}^{\infty} (\varepsilon^2 - m_i^2)^{3/2} \frac{d\varepsilon}{e^{\beta(\varepsilon-\mu_i)} + \theta_i} ;$$

$$\varepsilon_i^{pt} = \frac{d_i}{2\pi^2} \int_{m_i}^{\infty} \varepsilon^2 \sqrt{\varepsilon^2 - m_i^2} \frac{d\varepsilon}{e^{\beta(\varepsilon-\mu_i)} + \theta_i} ;$$

$$\rho_i^{pt} = \frac{d_i}{2\pi^2} \int_{m_i}^{\infty} \varepsilon \sqrt{\varepsilon^2 - m_i^2} \frac{d\varepsilon}{e^{\beta(\varepsilon-\mu_i)} + \theta_i} .$$

These point particle expressions are corrected for a finite proper volume of the hadrons by multiplication with a common factor $(1 + \varepsilon_{had}^{pt}/4B)^{-1}$; this

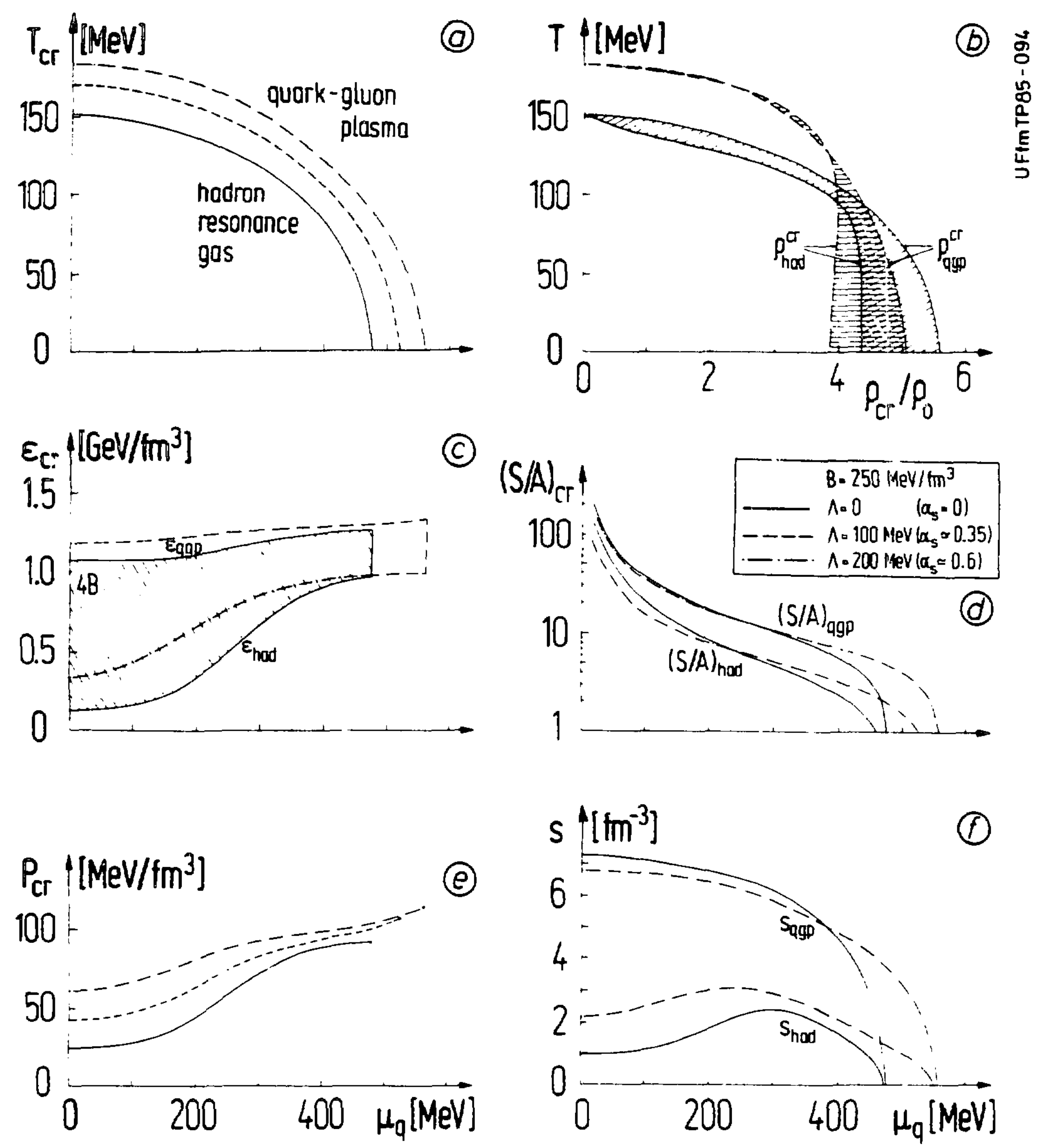


Fig. 1. (a) The critical line of phase coexistence between hadron resonance gas and quark-gluon plasma, for $B = 250$ MeV/fm^3 and different values for α_s. (b) The baryon density along the critical line as it is is approached from above (ρ^{cr}_{qgp}) and from below (ρ^{cr}_{had}). (c) The energy density along the critical line; the shaded area shows the amount of latent heat. (d) The entropy per baryon, (e) the critical pressure, and (f) the entropy density along the critical line.

prescription was derived by Hagedorn within the framework of the so-called "pressure ensemble"[13]. The parameter 4B defines the energy density inside hadrons and parametrizes the volume excluded from the available phase space for the hadrons due to their own finite size[14]. In our case the sum over i extends over all non-strange mesons with mass < 1 GeV and all non-strange baryons and antibaryons with mass $\leq$ 2 GeV[12].

The chemical potentials μ_i are determined by requiring chemical equilibrium with respect to all processes that can transform the hadrons among each other. These processes, like $N + N \rightarrow N + N^* + \pi$, $\eta \rightarrow 2\pi$, $\Delta \rightarrow N + \pi$, $N + \bar{N} \leftrightarrow m\pi$, etc. have in common that they conserve only baryon number; hence all chemical potentials can be expressed as multiples of a single chemical potential for the conservation of baryon number μ_b through $\mu_i = b_i \mu_b$ where b_i is the baryon number of hadron species i.

The quark-gluon plasma phase is described as a nearly ideal gas of light quarks and antiquarks and gluons, with perturbative interactions[15] and vacuum pressure $-B$. The corresponding expressions for P, ε, ρ_b and s are given in Refs. (11,15,16).

The phase transition line $T_{crit}(\mu_{b,crit})$ between the hadron resonance gas and the quark-gluon plasma is determined by the three conditions:

$$P_{had} = P_{qgp} \quad \text{(mechanical equilibrium) ;}$$

$$T_{had} = T_{qgp} \quad \text{(thermal equilibrium) ;}$$

$$\mu_b = 3\mu_q \quad \text{(chemical equilibrium) .}$$

The last equation imposes chemical equilibrium for the hadronization processes $3q \rightarrow$ baryon, $3\bar{q} \rightarrow$ antibaryon, $q + \bar{q} \rightarrow$ meson.

In Fig. 1a we show the critical line $T_{crit}(\mu_{b,crit})$ for $B = 250$ MeV/fm^3 and different values for the strong coupling constant α_s describing the interactions in the quark-gluon plasma. Larger values of B and/or α_s reduce the pressure in the quark-gluon plasma phase and push the phase transition point (i.e. the point where P_{qgp} becomes larger than P_{had}) towards larger values of T and μ.

Figs. 1b-1f show the critical values along the phase transition line for the baryon density, energy density, pressure, entropy density and

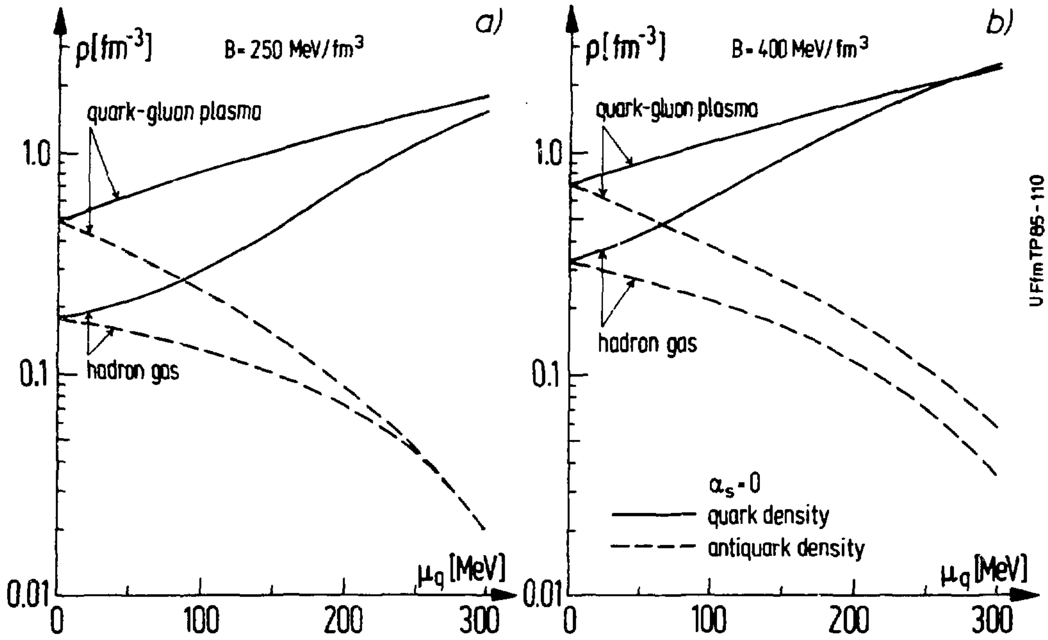
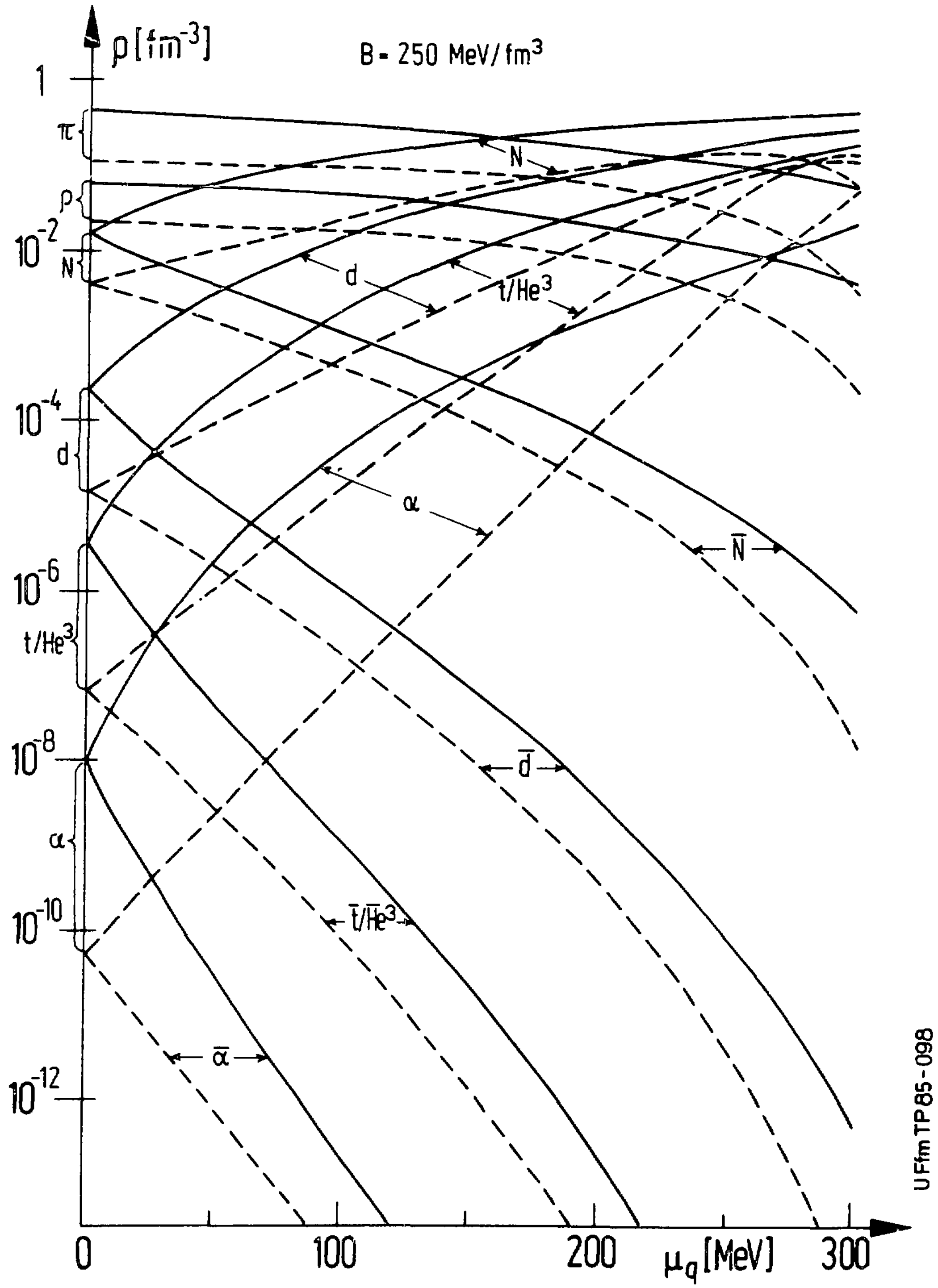


Fig. 2. (above) The quark and antiquark densities along the critical line in Fig. 1a, as it is approached from above ("quark gluon plasma") and from below ("hadron gas"). (a) B = 250 MeV/fm^3; (b) B = 400 MeV/fm^3. For this figure α_s = 0 was chosen.

Fig. 3. (opposite page) Densities of different hadrons at the critical temperature $T_{crit}(\mu_{q,crit})$ as a function of $\mu_{q,crit}$, as obtained from hadronization of a quark-gluon plasma (solid curves) or in an equilibrium hadron gas (broken curves). Note that generally all solid curves lie above their respective broken partners, reflecting the effect of the quark-antiquark overabundance in the plasma. Note also the larger gain factor for antibaryons and antinuclei. (α_s = 0; B = 250 MeV/fm^3.)



ρ [fm⁻³]
B = 250 MeV/fm³
1
π
ρ
10⁻²
N
N
d
t/He³
10⁻⁴
d
α
N̄
10⁻⁶
t/He³
10⁻⁸
d̄
α
10⁻¹⁰
t̄/H̄e³
ᾱ
10⁻¹²
0
100
200
μq [MeV]
300
UFfm TP 85-098

entropy per baryon, in the limit as one approaches the critical line fr below and from above, respectively. One sees that the transition is fi order and that there are large discontinuities in all the extensive quantities: there is a huge latent heat of the order of 1 GeV/fm^3 (som smaller at larger baryon densities) shown by the shaded area in Fig. 1c; a large latent entropy (the entropy density typically jumps by a factor 5 across the phase transition, Fig. 1f); the latter also shows up in the entropy per baryon (Fig. 1d) implying that it is not correlated with the discontinuity in the baryon density (Fig. 1b).

In Fig. 2 we show that not only the baryon density $\rho_b = \frac{1}{3}(\rho_q - \rho_{\bar{q}})$ but also the quark density ρ_q and antiquark density $\rho_{\bar{q}}$ themselves are discontinuous across the phase transition, typically by a factor 3. (Th quark and antiquark contents of the hadronic phase was determined by counting 3 (anti-) quarks for each (anti-) baryon and 1 quark plus 1 antiquark for each meson.) This means that in an equilibrium phase transition many excess $q\bar{q}$ pairs have to annihilate during the hadronizati process. The time scale for annihilation, although short[7], in a realisti hadronization process need not be small compared to the phase transition time, because in this realistic case there is no heat bath which can abso all the latent heat, latent entropy and excess $q\bar{q}$ pairs: the speed of th phase transition is rather given by the rate of change in temperature and density as dictated by energy, entropy and baryon number conservation whi control the global expansion of the hot nuclear matter.

To take an extreme example, let us assume that locally the phase transition takes place so fast that $q\bar{q}$ pairs don't have time to annihilat at all. (This says nothing about the time the system as a whole spends i the region of phase coexistence which may actually be rather long[17].) To simplify things further we assume that during the phase transition neither the volume nor the temperature changes, and that therefore after hadronization the quark and antiquark densities computed as above are exactly the same as before. This is not a realistic scenario since it doe not conserve entropy (the entropy density in the final state is still lowe than initially, although not quite as low as in an equilibrium hadronic phase at the same temperature and baryon density). To obtain at the same time entropy conservation and conservation of the number of quarks and antiquarks, we would have to allow for a change of volume and temperature. Such computationally more involved calculations are presently being done. Until their results are available, we will take the outcome of the above simple-minded hadronization calculation as an indication for the qualitative behavior to be expected.

Fig. 3 shows the expected densities for different hadrons and light (anti-) nuclei, assuming hadronization of a quark-gluon plasma with conservation of quark and antiquark content (solid lines), as compared to the corresponding values in an equilibrium hadron gas at the same temperature and baryon chemical potential (dashed lines). One sees that the necessity to absorb the higher quark-antiquark content of the original plasma phase into hadrons leads to an enhancement for the densities of <u>all</u> species; however, the increase is strongest and the (anti-) quark signal is therefore amplified in the larger (anti-) nuclei. Due to the usual suppression of antibaryons and antinuclei at finite chemical potentials, the signal to noise ratio is best for the antibaryons and particularly for larger antinuclei. Of course, absolute abundances decrease very steeply with the size of the antinucleus; looking for fragments larger than $\bar{\alpha}$ is increasingly hopeless. For $\bar{\alpha}$ the enhancement factor can reach 2 orders of magnitude, and if a central rapidity region with $\mu \approx 0$ is formed, there may even be a realistic hope to detect some $\bar{\alpha}$ in a collider experiment: assuming a reaction volume of 500 fm^3, Fig. 3 predicts about one $\bar{\alpha}$ in every 2×10^5 collisions in which a quark-gluon plasma was formed.

These numbers have to be taken with great caution: The major uncertainty in relating the curves of Fig. 3 to experimental multiplicities is the reaction volume which is essentially unknown. This uncertainty drops out if ratios of particle abundances are formed. This can be easily done from Fig. 3; however, we would like to await more realistic hadronization calculations before committing ourselves to predict numbers for measured particle ratios. Another correction stems from final state interactions during the remainder of the hadronic expansion phase before the particles actually decouple from each other. These will tend to drive the system after hadronization back towards hadronic equilibrium by, say, nucleon-antinucleon annihilation. Although the cross-section for the latter process is large (O(200mb)), the inverse reactions are also strengthened because all hadron species have appeared with large densities from the hadronization process. On the other hand, hydrodynamic calculations seem to indicate[18] that the time from completion of the phase transition to freeze-out is rather short (~1-2fm/c) such that we may hope for a large fraction of the signal to survive. On the other hand, as also noted in the context of strangeness production[6], the hadronic equilibrium value may never actually be reached during the lifetime of a collision without plasma formation; this will even enhance the antibaryon/antinucleus signal.

Two of the authors (UH and PRS) thank Prof. W. Greiner and the Institut für Theoretische Physik in Frankfurt, where most of this work was done, for the kind hospitality. Fruitful discussions with H. Stöcker are gratefully acknowledged. This work was supported by the Gesellschaft für Schwerionenforschung (GSI), Darmstadt, West Germany, the Alexander v. Humboldt Foundation (PRS), and the U.S. Department of Energy under contract DE-AC02-76CH00016.

REFERENCES

1. E. V. Shuryak, Phys. Rep. 61 (1980) 71.
2. "Quark Matter '83" (T. Ludlam and F. Wegener, eds.), Nucl. Phys. A418 (1984).
3. B. Müller, "The Physics of the Quark-Gluon Plasma," Lecture Notes in Physics, Vol. 225, Springer, Heidelberg, 1985.
4. J. Cleymans, M. Dechantsreiter, and F. Halzen, Z. Phys. C17 (1983) 341; J. D. Bjorken and L. McLerran, Phys. Rev. D31 (1984) 63.
5. G. Domokos and J. Goldman, Phys. Rev. D23 (1981) 203; K. Kajantie and H. I. Mietinnen, Z. Phys. C9 (1981) 341, and C14 (1982) 357; L. D. McLerran and T. Toimela, Fermilab preprint 84-T (1984); R. C. Hwa and K. Kajantie, Helsinki preprint HU-TFT-85-2 (1985).
6. P. Koch, J. Rafelski and W. Greiner, Phys. Lett. 123B (1983) 151; J. Rafelski, CERN-preprint TH-3745 (1983); J. Rafelski, in Ref. [2], p. 215c; P. Koch and J. Rafelski, Cape Town preprint UCT-TP 22/1985.
7. J. Rafelski and B. Müller, Phys. Rev. Lett. 48 (1982) 1066.
8. L. van Hove, Z. Phys. C21 (1983) 93; and Z. Phys. C27 (1985) 135.
9. N. K. Glendenning and J. Rafelski, preprint LBL-17938, Berkeley 1984; T. Matsui, B. Svetitsky and L. McLerran, private communication.

10. M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, Nucl. Phys. B147 (1979) 385.
11. U. Heinz, P. R. Subramanian, W. Greiner and H. Stöcker, "Formation of antimatter clusters in the hadronization phase transition", University of Frankfurt preprint (1985).
12. "Reviews of Particle Properties", Revs. Mod. Phys. 56 (1984).
13. R. Hagedorn, Z. Phys. C17 (1983) 265.
14. R. Hagedorn and J. Rafelski, in: "Statistical Mechanics of Quarks and Hadrons", H. Satz (ed.), North Holland, Amsterdam, 1981, p. 237 and p. 253.
15. J. Kapusta, Nucl. Phys. B148 (1979) 461.
16. H. Stöcker, in ref. [2], p. 587c.
17. L. McLerran, contribution to this Workshop.
18. G. Buchwald and G. Graebner, private communication.
19. A stripped-down version of this model, considering only pions and (anti-)nucleons and treating them as point-like particles, was studied by V. V. Dixit and E. Suhonen, Z. Phys. C18 (1983) 355. We thank K. Kajantie for bringing this work to our attention.