BNL-35294

CONF-8406183--5

STATUS OF THE THEORY OF QCD PLASMA

BNL--35294

DE85 001236

Joseph I, Kapusta*
Physics Department
Brookhaven National Laboratory
Upton, New York 11973

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

*Permanent address: School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455

The submitted manuscript has been authored under contract DE-AC02-76CH00016 with the U.S. Department of Energy. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

STATUS OF THE THEORY OF QCD PLASMA

Joseph I. Kapusta*
Physics Department
Brookhaven National Laboratory
Upton, New York 11973

ABSTRACT

There is mounting evidence, based on many theoretical approaches, that color is deconfined and chiral symmetry is restored at temperatures greater than about 200 MeV. Reasonable estimates of the energy density to be expected in high energy heavy ion collisions suggest that QCD plasma may be formed in the laboratory. Proposed experimental signals may allow us to infer such quantities as the temperature, the quark dispersion relation, the space-time evolution and, perhaps, even the order of the phase transition.

1. INTRODUCTION

An impressive variety of theoretical approaches, ranging from rather phenomenological to those attempting to solve QCD exactly, suggest that the strong interactions exhibit a phase transition at a temperature on the order of 200 MeV. An incomplete list is given below.

Hagedorn statistical bootstrap[1)]
MIT bag model[2,3)]
strong coupling lattice theory[4,5)]
perturbation theory[6-8)]
instantons[9-11)]
Savvidy magnetic field condensation[11,12)]
mean field potential models[13)]
computer simulations on the lattice[14-16)]

---

* Permanent address: School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455

Invited talk at the XV Symposium on Multiparticle Dynamics, Lund, Sweden, 11-16 June 198-.

What is meant by a phase transition is well-defined in thermodynamics. Forgetting about the possibility of nonzero chemical potentials for baryon number, etc., for the moment, we know that at constant volume the pressure P must be a continuous function of the temperature T. If, however, the n'th derivative of P with respect to T is discontinuous at some critical temperature T_c while all lower order derivatives are continuous then an n'th order phase transition is said to occur at T_c. For example, in a first order phase transition the entropy density

$$s = \frac{dP}{dT} \qquad (1)$$

and the energy density

$$\varepsilon = - P + Ts \qquad (2)$$

are discontinuous at T_c (there is a latent heat). In a second order phase transition the above quantities are continuous at T_c but the heat capacity per unit volume

$$C_v = \frac{d\varepsilon}{dT} \qquad (3)$$

is discontinuous.

Of course we need to develop an understanding of what characterizes each of the phases before we can grasp the significance of a phase transition in any particular system. In section 2 I will discuss what these characteristics are for QCD.

In section 3 I will discuss the most recent evidence for the existence and order of the phase transition. In my opinion, at the present time there are two dominant, complementary theoretical approaches. One is to start with a basis of quarks and gluons in the high temperature phase and calculate the corrections using weak coupling theory, then to start with a basis of stable hadrons (stable with respect to the strong interactions) in the low temperature phase and calculate the corrections using weak coupling theory. The other approach is to do computer simulations of lattice QCD and then take the continuum limit.

I will give the results of calculations which predict that sufficient energy densities can be reached in ultrarelativistic heavy ion collisions to form QCD plasma in section 4.

The difficult question of finding experimental signals for all of the interesting phenomena which are expected to occur in the plasma is taken up in section 5.

Finally in section 6 I make some conclusions concerning the current status of QCD plasma.

2. CHARACTERISTICS OF EACH PHASE

There are at least three probes of the properties of QCD matter which are useful for developing some intuition concerning the nature of the two phases (confining and nonconfining). Let me discuss each in turn.

The thermal Wilson line L(T) is related to the free energy of an isolated static quark $F_q(T)$ via

$$L = \exp\left(-F_q(T)/T\right) . \tag{4}$$

This is the most frequently calculated quantity in Monte Carlo simulations of lattice QCD. In the low temperature confining phase we expect that F_q is infinite and $L = 0$. In the high temperature nonconfining phase we expect that F_q is finite and $L > 0$. This behavior is realized in the aforementioned calculations when light dynamical quarks are not included.

Another familiar quantity is the static quark-antiquark free energy $F_{q\bar{q}}(T,R)$ as a function of separation R. In the low temperature confining phase we expect the general form

$$F_{q\bar{q}}(T,R) = V_0 - \frac{\alpha}{R} + \sigma(T)R . \tag{5}$$

Here $\sigma(T)$ is the string tension. In the high temperature nonconfining phase we expect the Debye screening form

$$F_{q\bar{q}} = - \frac{\alpha}{R} \exp(-m_{el}R) \tag{6}$$

where $m_{el}(T)$ is the color electric mass or inverse screening length. Again Monte Carlo simulations without light dynamical quarks confirm our expectations.

When light dynamical quarks are included then one must think a little harder about what these probes mean since the light quarks can screen the color of the static quarks. For an isolated static quark one should probably work in the canonical ensemble rather than in the grand canonical ensemble in order to rigorously fix the net color of the system at a nonzero value. For a static quark-antiquark pair the free energy of separation in the confining phase will be linear only over a limited range of separation.

Finally we have the coefficient of color conductivity c(T) defined by the relationship between color electric field and current

$$\vec{J} = c(T)\,\vec{E} \quad . \tag{7}$$

In the low temperature phase quarks and gluons are confined inside hadrons. These hadrons are widely separated in space. Therefore, color should not conduct due to the inability of quarks and gluons to travel through the vacuum. The low temperature phase should be an insulator, $c = 0$. The high temperature phase, being a plasma of deconfined quarks and gluons, should be a color conductor, $c > 0$. There is in fact not much discussion of this topic in the literature.[17,18]

3. IS THERE A PHASE TRANSITION?

Let us consider a pure SU(3) gauge theory without quarks since this is the best understood system. In the high temperature phase a weak coupling expansion gives the energy density as

$$\varepsilon/T^4 = \left(\frac{\Lambda B}{T}\right)^4 + \frac{8\pi^2}{15} - \frac{1}{2}\, g^2 + \frac{2}{\pi}\left(\frac{m_{el}}{T}\right)^3$$

$$+\mathcal{O}(g^4 \ln g^2, g^4) - 8\, C_3(\Lambda) \left(\frac{4\pi^2}{g^2}\right)^6 \exp\left(-\frac{8\pi^2}{g^2}\right) \tag{8}$$

where the electric mass is[19]

$$\frac{m_{el}^2}{T^2} = g^2 - \frac{3}{\pi}\left(\frac{1}{2}\, g^2\right)^{3/2} + \mathcal{O}(g^4) \quad . \tag{9}$$

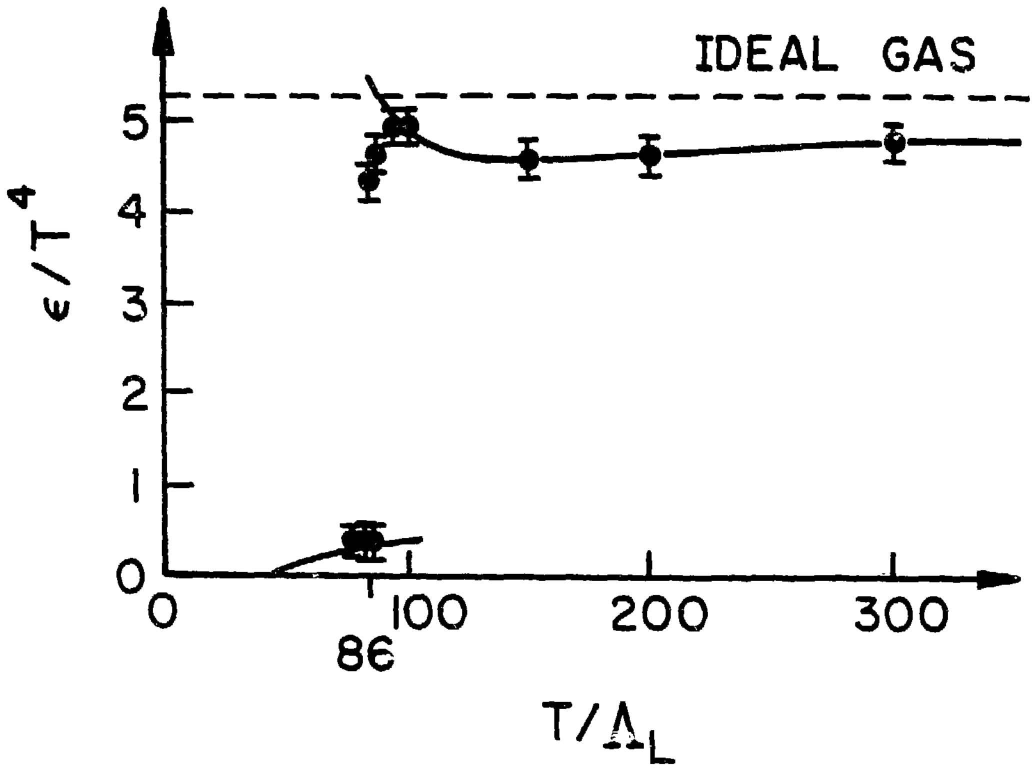

Fig. 1. The energy density from a Monte Carlo simulation of quarkless SU(3) on an 8^3x 3 lattice are represented by points.[23] The curves are from Eqs. (8-12).

The first term in eq. (8) is the vacuum energy density,[2] or bag constant B = Λ_B^4 . The second term is the Stefan-Boltzmann expression for eight massless spin-1 bosons. The third term is a two-loop correction[6-8] (gluon-gluon scattering). The fourth term is the result of summing an infinite set of diagrams, known variously as the correlation, ring or plasmon diagrams.[6,20] The fifth term represents the next g^4 perturbative contribution which is not known.[21] The last term is the contribution from instantons which is, in fact, negligible compared to the preceding terms.[10,11] At high temperature the lowest order result from the renormalization group is[6,22]

$$g^2 = \frac{8\pi^2}{11 \ \ln(T/\Lambda_T)} \qquad (10)$$

The relationship between the two scales Λ_T and Λ_B cannot be determined within the framework of perturbation theory.

For the low temperature confining phase let us assume an ideal gas of glueballs with mass m_{GB} and degeneracy d.

$$\varepsilon/T^4 = d \left(\frac{m_{GB}}{T} + \frac{3}{2} \right) \left(\frac{m_{GB}}{2\pi T}\right)^{3/2} \exp\left(- \frac{m_{GB}}{T}\right) . \qquad (11)$$

For example, if we assume that the 0^{++} and 2^{++} have equal masses, then d = 6.

In Fig. 1 is shown the energy density from a Monte Carlo simulation on an $8^3 \times 3$ lattice.[23] There is a phase transition at a temperature of $T_c = 86 \ \Lambda_L$. This is confirmed by an evaluation of the Wilson line.[24] We can fit Eq. (11) to the Monte Carlo points by making use of the ratios

$$m_{GB} : \sigma : T_c = 4:2:1 \qquad (12)$$

from an independent lattice calculation.[25] We can also fit Eq. (8) to the Monte Carlo points by choosing $\Lambda_T = 20 \ \Lambda_L$ and $\Lambda_B = 100 \ \Lambda_L$. Apart from the slight rounding of the Monte Carlo points in the high temperature phase near T_c, which may be due to finite size effects, excellent fits are obtained.

In Fig. 2 is plotted the inverse screening length m_{el} vs. T from Eq. (9). The temperature range between T_c and the temperature at which m_{el} vanishes corresponds to a metastable, supercooled plasma since color charge is still screened, Eq. (6). Since this is a first order phase transition there will also exist a metastable, superheated glueball phase. This would correspond to the qualitative temperature dependence of the string tension, Eq. (5), which I have sketched in Fig. 2 also.

The most interesting question at the moment is whether the incorporation of light dynamical quarks will smooth out the first order phase transition to a higher order phase transition or to no phase transition at all. Also there is the question of whether chiral symmetry is restored at the deconfinement temperature (if it is sharp) or whether it is restored at a higher temperature. These questions are, at the moment, best addressed by computer simulations of lattice QCD. So far results are being reported by five groups.

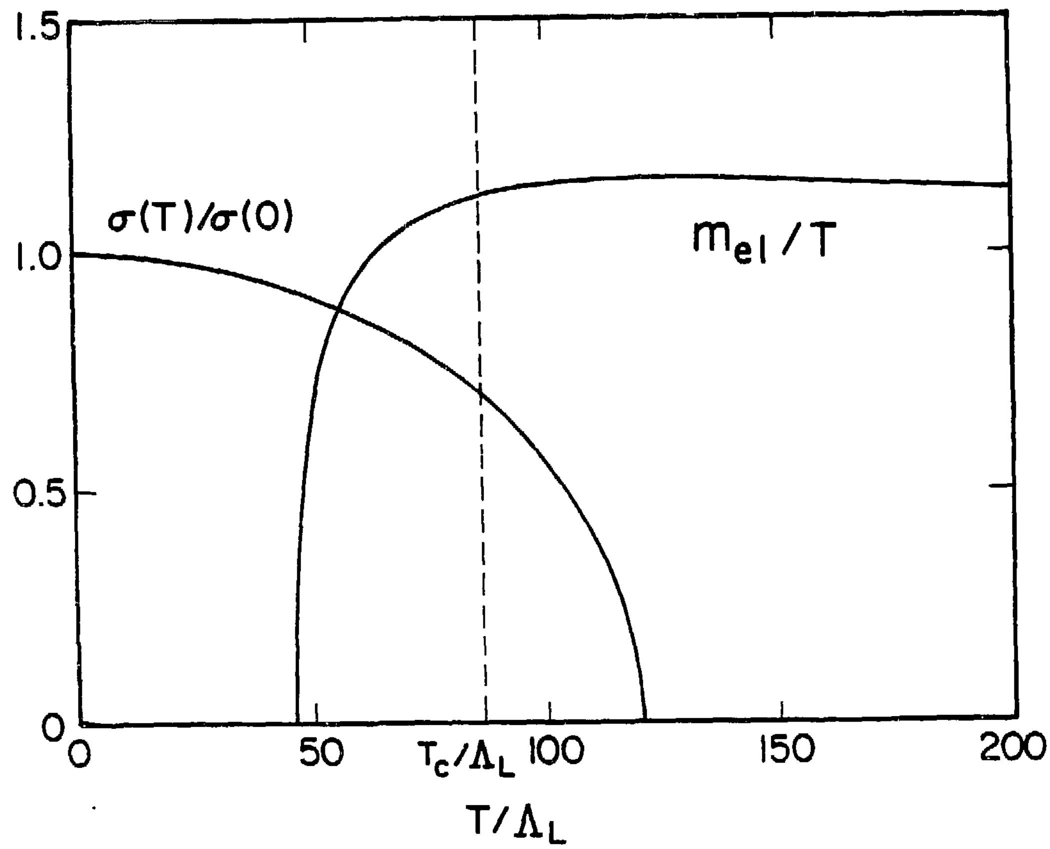

Fig. 2. The inverse screening length, or electric mass, from Eqs. (9-10), and the expected behavior of the string tension.

The group of Polonyi, Wyld, Kogut, Shigemitsu and Sinclair[26)] is using a new method, a microcanonical computer simulation, involving the integration of ordinary differential equations. In Fig. 3 is plotted ε/T^4 vs. T/Λ_L for an $8^3 \times 4$ lattice with four quark flavors with equal mass $m = 0.32$ T. Although there aren't many

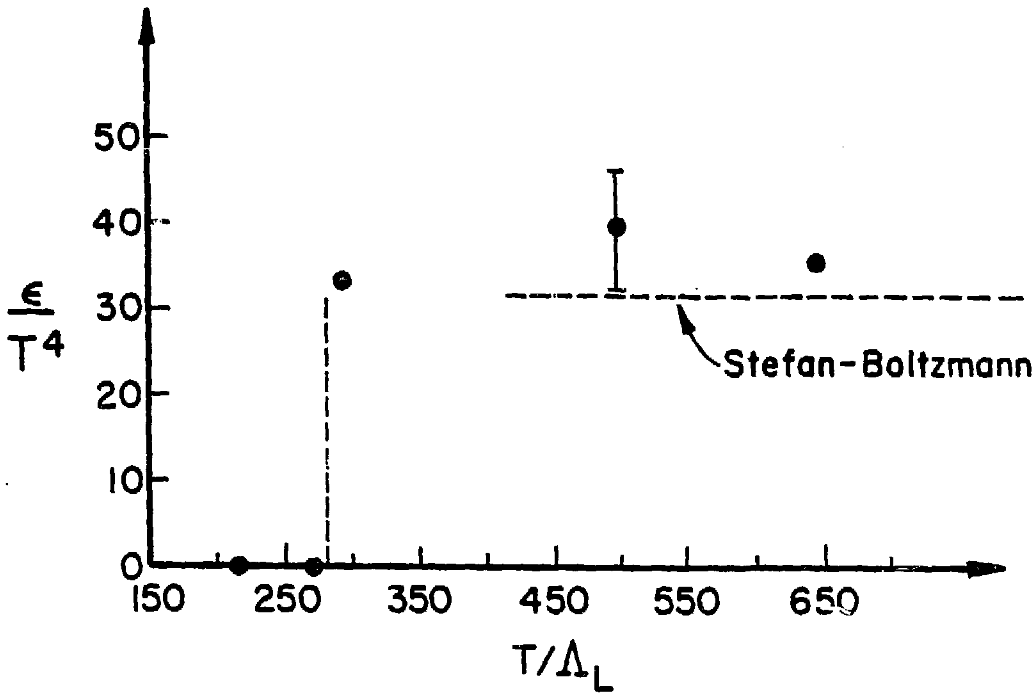

Fig. 3 The energy density from a microcanonical computer simulation of QCD on an $8^3 \times 4$ lattice.[26] There are four quark flavors with equal mass m = 0.32 T.

---

points it appears as if a first order phase transition occurs at $T_c = 280\ \Lambda_L$. They have also calculated the ensemble average $\langle\bar{\psi}\psi\rangle$ and the thermal Wilson line for several different values of the quark mass. A zero mass extrapolation for each quantity is shown in Fig. 4. From this figure we might also conclude that quarks are deconfined and chiral symmetry is restored at about the same temperature $T_c = 280\ \Lambda_L$. To give an idea of the amount of computing time involved, these calculations are the result of about 300 hours on a CRAY-1.

Similar results, but with less statistics, have been reported by Fucito, Rebbi and Solomon.[27] They use the pseudo-fermion method on $6^3 \times 4$ and $8^3 \times 4$ lattices. They conclude that the phase transition

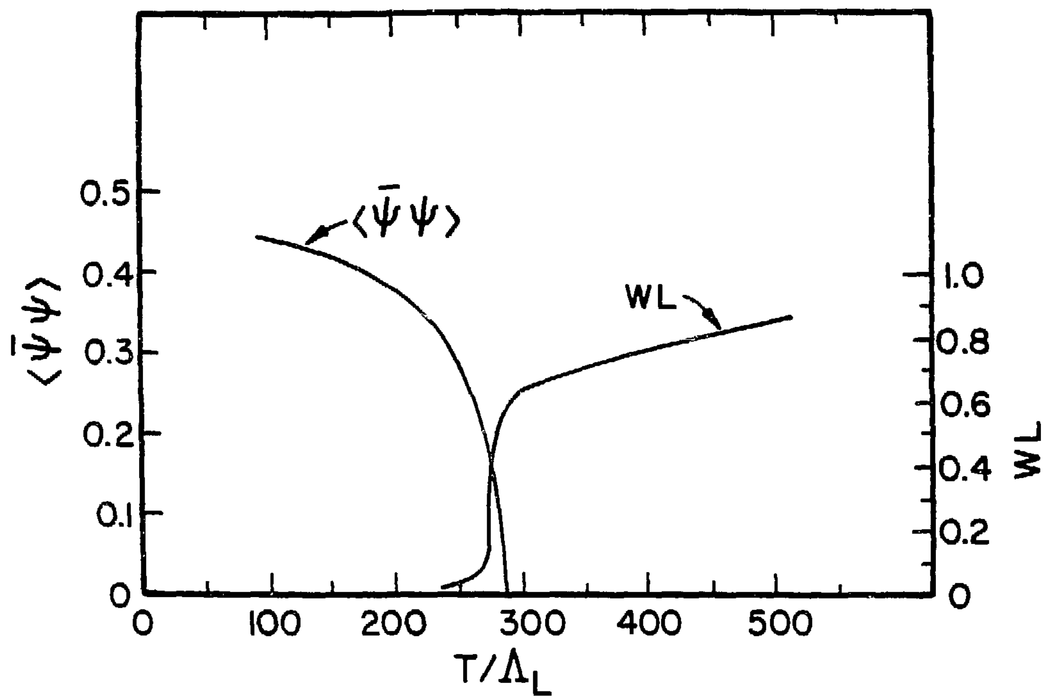

Fig. 4 The thermal average of $\langle\bar{\psi}\psi\rangle$ and of the thermal Wilson line from the same computer simulation as in Fig. 3. An extrapolation to zero quark mass has been taken.

---

is of first order. The pseudo-fermion method was also employed by Gavai, Lev and Petersson[28)] on a smaller $6^3 \times 2$ lattice. They conclude that the energy density, the thermal Wilson line and $\langle\bar{\psi}\psi\rangle$ all undergo rapid variations near some critical temperature but cannot determine the order of the phase transition.

The third method which has been used is the hopping parameter expansion, which is basically an expansion in inverse powers of the quark mass. Hasenfratz, Karsch and Stamatescu[29)] have performed Monte Carlo simulations to second order in a hopping parameter expansion on an $8^3 \times 2$ lattice. They find that the first order phase transition present in the pure SU(3) gauge theory no longer occurs when the quark mass is less than about 1 GeV. They argue that this is a result of

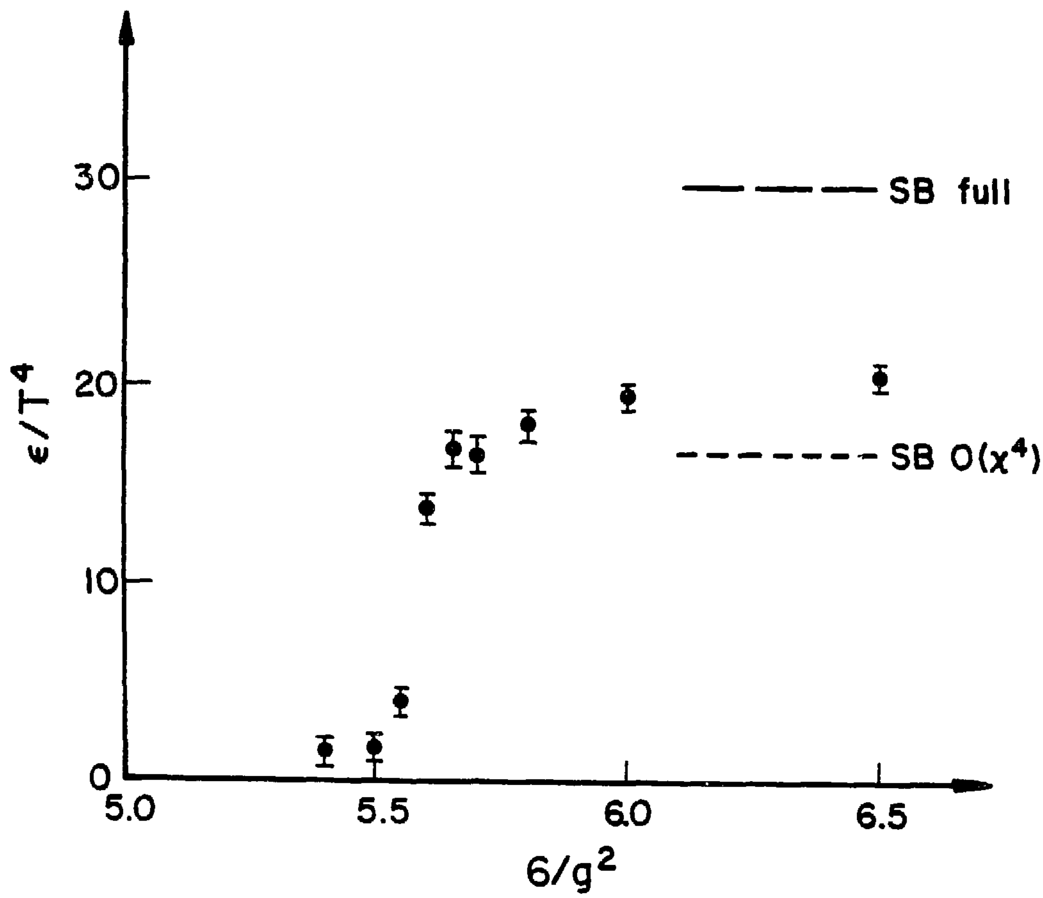

Fig. 5. The energy density from a Monte Carlo simulation of QCD to fourth order in a hopping paramter (χ) expansion on an $8^3 \times 4$ lattice.[30] Also shown are the noninteracting Stefan-Boltzmann limits, both the full limit and also the limit truncated at fourth order in χ.

---

light dynamical quarks screening color charges (see above) so that there is no reason for any phase transition. Recently Celik, Engels and Satz[30] have performed a fourth order hopping parameter expansion on an $8^3 \times 4$ lattice. Their results for ϵ/T^4 vs. $6/g^2$ (essentially T) are shown in Fig. 5. The smooth but rapid rise near $6/g^2 = 5.6$ is indicative of a second order phase transition. Again this is supported by calculations of the thermal Wilson line and $\langle\bar{\psi}\psi\rangle$.

What are we to conclude from this? I think it is fair to say that the latest computer simulations of lattice QCD do indicate a phase transition even in the presence of light dynamical quarks. However, the order has not yet been decided on by all of the lattice experts. Nevertheless my suspicion is that, of all the possibilities, the most likely is that a low order hopping parameter expansion is not entirely reliable. Note the qualitative difference between the second and fourth order expansions. Note also the fact that the energy density in the Stefan-Boltzmann limit in fourth order is only about one-half the exact value (see Fig. 5). Furthermore, there are now some general theoretical arguments[31)] that QCD with massless quarks belongs in a universality class known to have a fluctuation induced first order transition.

4. CAN QCD PLASMA BE FORMED IN THE LABORATORY?

In the last few years there has been a surge of interest in studying the possibility of colliding heavy nuclei like gold (197), lead (208) or uranium (238) at ultrarelativistic energies (~ 5 to 100 GeV per nucleon in the center of mass frame). Considerations based on what has been learned in proton-proton and proton-nucleus reactions, together with general theoretical considerations, suggest the following picture.[32-34)] See Fig. 6. At high energy the nuclei appear Lorentz contracted in the center of mass frame. When $E_{cm} \sim 50$ GeV/nucleon the nuclei are rather transparent to each other and do not stop. However, in its own rest frame, each nucleus is highly compressed and heated leading to a baryon rich plasma of quarks and gluons. Virtual particles (hadrons, partons, quarks and gluons, ...?) are also produced in the central rapidity region. It takes a proper time $\tau_0 \sim 1$ fm/c before these virtual particles can be dressed and appear as real particles. However it has been estimated that in heavy ion collisions, in contrast to pp or pA collisions, the particle density will be so high that the supposed real hadrons will overlap and cannot be treated as individual entities. Rather the description should be in terms of a more or less thermalized QCD plasma.

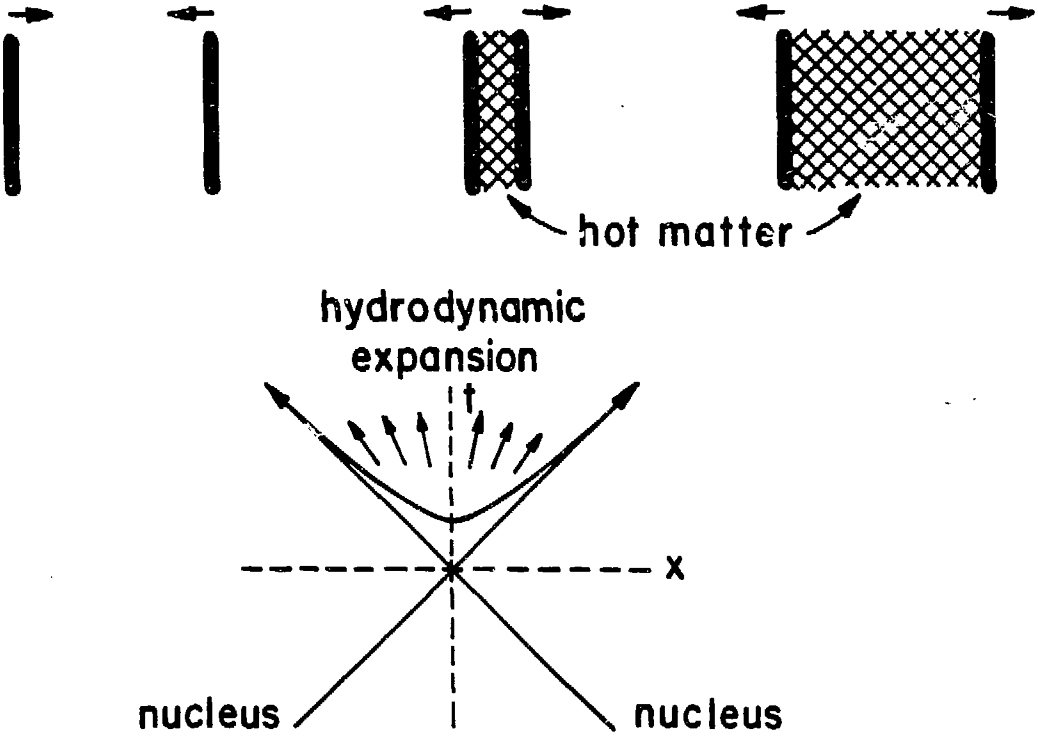

Fig. 6 Space-time evolution of an ultrarelativistic heavy ion collision. In the top picture the Lorentz-contracted nuclei pass through each, creating hot QCD plasma between them. In the bottom picture x represents position along the longitudinal, or beam, axis. After a proper time $\tau_0 \sim 1$ fm/c plasma appears and begins a longitudinal hydrodynamic expansion.

The initial energy density may be $\varepsilon(\tau_0) \sim 2$ to 6 GeV/fm^3 compared to the energy density of cold nuclei, 0.15 GeV/fm^3, or protons, 0.5 GeV/fm^3. The plasma will then expand longitudinally and, to a lesser degree, transversely. If hydrodynamics is a good model of the expansion, that is, if local thermal equilibrium can be maintained, then the energy density will fall with proper time like

$$\varepsilon(\tau) = \varepsilon(\tau_0)\,(\tau_0/\tau)^{4/3} \quad . \qquad (13)$$

Similar energy densities are expected in the baryon rich framgentation regions.

These dynamical questions are the most difficult aspect of the field to address. I think that the general consensus is that these are fairly realistic estimates of what will happen. Perhaps they are even a little conservative. The reader is referred to the current literature fore more detailed discussion.[35,36] .

5. WHAT ARE THE SIGNALS FOR QCD PLASMA FORMATION?

Suppose that QCD plasma is formed in ultrarelativistic heavy ion collisions. We need some experimental signals to know that plasma was formed, and to learn about its properties. A brief list of the most promising signals, and the information expected from them, is presented below.

Signal	Information
single photon production[37,38] $q\bar{q} \to \gamma\, g$	T
dilepton production[37-40] $q\bar{q} \to \gamma^* \to \ell^+\ell^-$	T, quark dispersion relation $\omega(k)$
strange quarks[41]	T, expansion rate
average transverse momentum[42-44]	initial energy density, expansion velocity
pion charge correlations[45]	plasma formation vs. jets, color charge screening
rapidity density[46,47] fluctuations	supercooling?
pion interferometry[48-50]	space-time evolution
pionic clusters[51]	first order nature of phase transition?

Since I have recently been working on the last proposed signal in the list, and since it may be able to confirm experimentally the first order nature of the phase transition, I will devote my brief remaining time to a quick explanation of the essential physics of it.

Two of the unique characteristics of a first order phase transition are latent heat and the existence of metastable phases. The problem is to find a mechanism which would give an unambiguous signal only if a first order transition occured. The solution is intimately connected with the dynamics of the phase change, i.e., nucleation theory.

It is quite plausible that at some stage of the heavy ion collision the matter will exist in a superheated pion vapor phase. This means that the temperature is greater than T_c, yet the matter is still in the hadronic phase. This could occur at low beam energy because there is not sufficient energy to overcome the latent heat globally. It could also occur if QCD plasma was formed initially but then expanded so rapidly that it supercooled, and finally made the transition by reheating to the pion phase. In either case droplets of plasma will form in the superheated pion vapor due to statistical or quantum fluctuations or to chance collisions. The relative probability for forming a droplet of mass-energy M can be estimated in the usual way (and by using the MIT bag model) to give

$$Y = \exp\left(- \Delta\Omega / T\right) = \exp\left[c_1(T)M/T - c_3(T)(M/T)^{1/3}\right]. \qquad (14)$$

Here $\Delta\Omega$ is the change in the free energy of the system when the droplet appears. The coefficients depend only on the degree of superheating $T/T_c - 1$ and satisfy $c_1 \geq 0$, $c_3 > 0$. In fact near T_c

$$c_1 \sim 1 - (T_c/T)^4 \quad . \qquad (15)$$

Below T_c such fluctuations fall off exponentially in M/T. At T_c they fall-off only exponentially in $(M/T)^{1/3}$. Above T_c the droplet size distribution has a minimum at a critical mass

$$M^* = (c_3/3c_1)^{3/2}\, T \quad . \qquad (16)$$

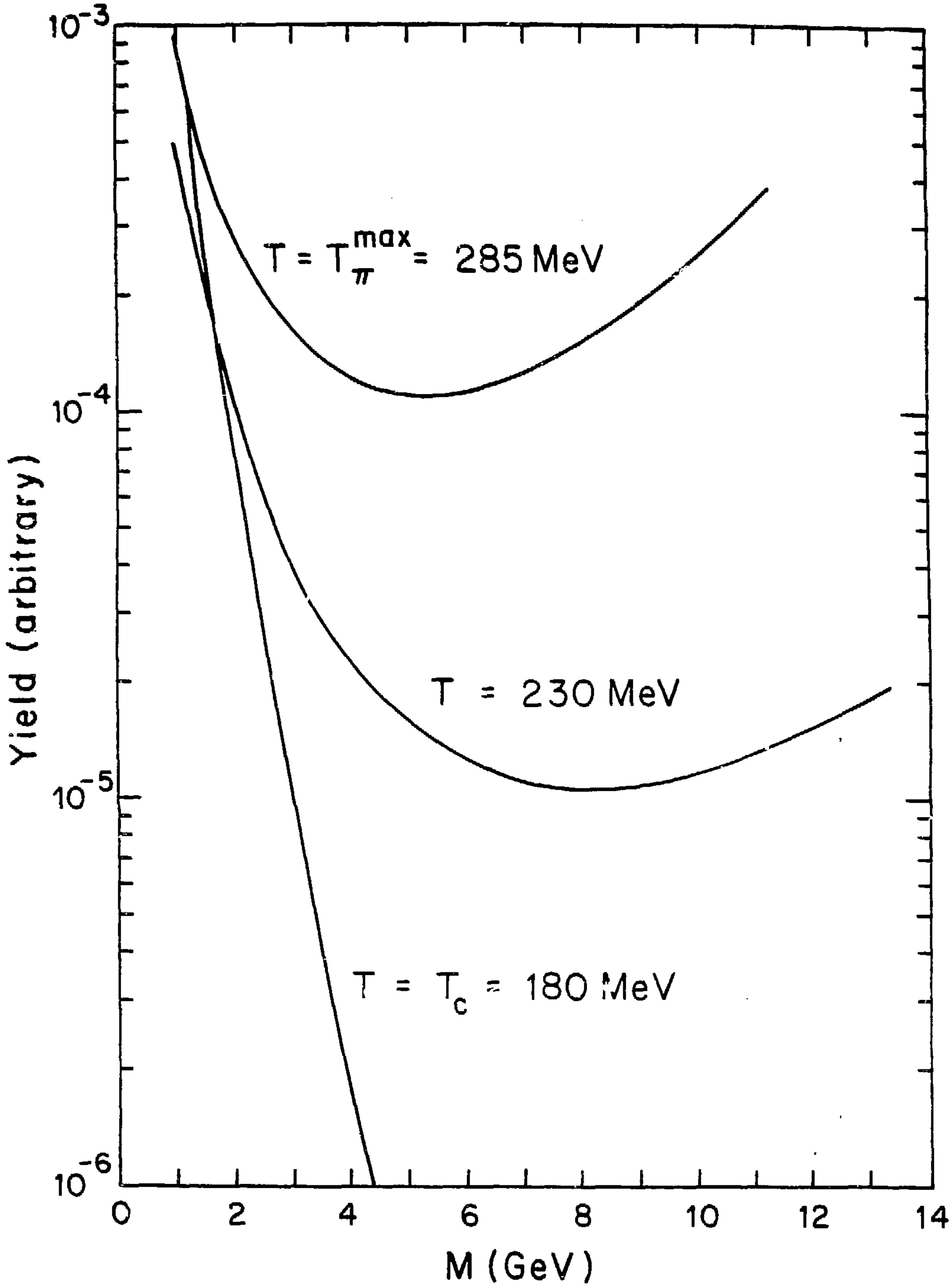

Fig. 7 Yield of QCD plasma droplets in a superheated pion vapor as a function of invariant mass for three different temperatures. Both absolute and relative normalizations are arbitrary.

See Fig. 7. A droplet of this size is in unstable equilibrium. Smaller droplets tend to evaporate due to a relatively large curvature free energy. Larger droplets grow by accretion to form macroscopic amounts of the thermodynamically stable phase. This is the basis of the classic theory of nucleation.

In an ultrarelativistic heavy ion collision these droplets may be observable under special circumstances. It is necessary that the expansion rate be greater than the evaporation rate of the droplets. In that case the droplets will be separated in velocity space. They finally explode into pions. The experiment then would be to identify stars or clusters of pions in three-dimensional phase space. If the observed cluster size distribution has a minimum then it would be very strong evidence that the transition is first order. A null measurement would of course not preclude the existence of a first order transition since the dynamics of heavy ion collisions may not be favorable for such a signal. However, the interpretation of medium mass nuclei in recent low energy experiments as droplet formation in a supersaturated nucleon vapor associated with the nuclear liquid-gas phase transition is cause for optimism[52)].

6. CONCLUSION

My own conclusions regarding the status of the theory of QCD plasma are the following.

Current approximations to QCD suggest a strongly first order phase transition. There is some uncertainty surrounding the consistency of different lattice calculations.

Phenomenology based on pp and pA reactions suggest that QCD plasma will be formed in high energy heavy ion collisions. At $E_{cm} \sim 2$ to 5 GeV/nucleon the central cores of heavy nuclei will stop each other and the plasma will be baryon-rich. At $E_{cm} \sim 30$ to 100 GeV/nucleon the nuclei will be essentially transparent to each other and a baryon-free plasma will form in the central rapidity region.

Although difficult to measure there are numerous suggested signals which will yield nontrivial information on QCD plasma. In particular, it may be possible to detect the first order nature of the transition in the laboratory.

I hope that I have convinced you that this is an exciting topic on the interfaces of nuclear physics, particle physics and statistical physics. My question now is: Where is the accelerator capable of exploring these phenomena?

ACKNOWLEDGEMENTS

This work was supported by the U. S. Department of Energy, at the University of Minnesota under contraact DOE/DE-AC02-79ER-10364, and at Brookhaven National Laboratory under contract DOE/DE-AC02-76CH-00016. I thank members of the Physics Department at Brookhaven National Laboratory for their hospitality and support while this manuscript was being written.

REFERENCES

1. R. Hagedorn, Nuovo Cim. Suppl. 3, 147 (1965); in Cargèse Lectures in Physics, ed. E. Schatzmann (Gordon and Breach, N. Y. 1973) vol. 6.
2. A. Chodos, R. L. Jaffe, K. Johnson, C. B. Thorn and V. F. Weisskopf, Phys. Rev. D9, 3471 (1974).
3. J. Kapusta, Phys. Rev. D23, 2444 (1981).
4. A. M. Polyakov, Phys. Lett. 72B, 477 (1978).
5. L. Suskind, Phys. Rev. D20, 2610 (1979).
6. J. Kapusta, Nucl. Phys. B148, 461 (1979).
7. S. A. Chin, Phys. Lett. 78B, 552 (1978).
8. E. V. Shuryak, Phys. Rep. 61, 71 (1980).
9. B. Harrington and H. Shepard, Phys. Rev. D18, 2990 (1978).
10. R. D. Pisarski and L. G. Yaffe, Phys. Lett. 97B, 110 (1980).

11. J. Kapusta, Nucl. Phys. B190, 425 (1981).

12. B. Müller and J. Rafelski, Phys. Lett. 101B, 111 (1981).

13. K. A. Olive, Nucl. Phys. B190, 483 (1981).

14. L. McLerran and B. Svetitsky, Phys. Lett. 98B, 195 (1981).

15. J. Kuti, J. Polónyi and K. Szlachányi, Phys. Lett. 98B, 199 (1981).

16. J. Engels, F. Karsch, I. Montvay and H. Satz, Phys. Lett. 101B, 89 (1981).

17. G. Baym, Physica 96A, 131 (1979).

18. O. Nachtmann and H. J. Pirner, Z. Phys. C21, 277 (1984).

19. K. Kajantie and J. Kapusta, Annals of Physics, to be published.

20. C.-G. Källman and T. Toimela, Phys. Lett. 122B, 409 (1983).

21. T. Toimela, Phys. Lett. 124B, 407 (1983).

22. J. C. Collins and M. J. Perry, Phys. Rev. Lett. 34, 1353 (1975).

23. T. Celik, J. Engels and H. Satz, Phys. Lett. 129B, 323 (1983).

24. T. Celik, J. Engels and H. Satz, Phys. Lett. 125B, 411 (1983).

25. Ph. de Forcrand and C. Roiesnel, CERN preprint TH.3858, March 1984.

26. J. Polonyi, H. W. Wyld, J. B. Kogut, J. Shigemitsu and D. K. Sinclair, Phys. Rev. Lett. 53, 644 (1984).

27. F. Fucito, C. Rebbi and S. Solomon, California Institute of Technology preprint, May 1984.

28. R. V. Gavai, M. Lev and B. Petersson, Phys. Lett. 140B, 397 (1984).

29. P. Hasenfratz, F. Karsch and I. O. Stamatescu, Phys. Lett. 133B, 221 (1983).

30. T. Celik, J. Engels and H. Satz, University of Bielefeld preprint, May 1984.

31. R. Pisarski and F. Wilczek, University of California-Santa Barbara/NSF-Institute of Theoretical Physics preprint December 1983.
32. R. Anishetty, P. Koehler and L. McLerran, Phys. Rev. D22, 2793 (1980).
33. J. D. Bjorken, Phys. Rev. D27, 140 (1983).
34. K. Kajantie, R. Raitio and V. Ruuskanen, Nucl. Phys. B222, 152 (1983).
35. Proceedings of the Workshop on Quark Matter Formation and Heavy Ion Collisions, ed. H. Satz (World Scientific Publishing Co., Singapore, 1982).
36. Proceedings of the Third International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions, ed. T. W. Ludlam and H. E. Wegner, Nucl. Phys. A418 (1984).
37. E. V. Shuryak, Phys. Lett. 78B, 150 (1978).
38. K. Kajantie and H. I. Miettenen, Z. Phys. C9, 341 (1981).
39. G. Domokos and J. I. Goldman, Phys. Rev. D23, 203 (1981).
40. J. Kapusta, Phys. Lett. 136B, 201 (1984).
41. J. Rafelski, Nucl. Phys. A418, 215c (1984).
42. E. V. Shuryak and O. V. Zhirov, Phys. Lett. 89B, 253 (1980).
43. J. Kapusta, in ref. 35 and in Phys. Rep. 88, 321 (1982).
44. L. Van Hove, Phys. Lett. 118B, 138 (1982).
45. J. A. Lopez, J. C. Parikh and P. J. Siemens, Texas A & M University preprint, May 1984.
46. L. Van Hove, Z. Phys. C21, 93 (1983).
47. M. Gyulassy, K. Kajantie, H. Kurki-Suonio and L. McLerran, Nucl. Phys. B237, 477 (1984).
48. C. Ezell et al., Phys. Rev. Lett. 38, 873 (1977).
49. S. Y. Fung et al., Phys. Rev. Lett. 41, 1592 (1978).
50. S. Pratt, University of Minnesota preprint, June 1984.
51. J. Kapusta, Phys. Lett. B, to be published.
52. A. Goodman, J. Kapusta and A. Mekjian, Phys. Rev. C, to be published.