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Quark-Gluon Phase Transition in the Baryon Rich Domain†

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Abstract

The hadron to quark-gluon phase transition is studied in charge symmetric matter. Nuclear field theory describes the hadronic phase, including baryons $N, \Delta, \Lambda, \Sigma, \Xi$, and thermal pions and kaons. The pion dispersion in medium is computed. The other phase is described as a gas of massless u and d quarks and gluons and massive s quarks, with or without gluon exchange. The Rankine-Hugoniot relation is employed to estimate the initial properties of matter produced in nuclear collisions as a function of energy. Within accepted uncertainties in the nuclear and plasma equations of state, the mixed phase could be formed in collisions with laboratory kinetic energy as low as 2.5 GeV.

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The most reliable predictions concerning the phase transition between hadronic matter and quark-gluon plasma are those of lattice gauge theory, which is a numerical solution of QCD [1,2]. Unfortunately, these predictions, for the foreseeable future do not encompass the actual physical means of investigating the phase transition in the laboratory. The lattice gauge calculations concern the adiabatic heating of uniform infinite matter. The experimental probe is a violent collision between nuclei. Indeed, up to the present, the lattice calculations pertain *only* to a baryonless plasma, and are able to predict only one point in the phase diagram, the transition point at finite temperature but vanishing baryon density. The predicted transition temperature is $T \sim 200$ MeV. But most important for the motivation of the present investigation is the gulf between the problem solved by lattice theory, and the nature of the experimental probe. The collision of nuclei, say a central one, at a given laboratory energy produces matter of some corresponding *definite* temperature and baryon density, *depending* on the collision dynamics. It will then evolve toward disassembly, possibly along an isentropic path. The entire phase diagram is therefore not accessible. The injection points will lie on a trajectory, each point of which corresponds to a given laboratory energy. In this work we approximate the dynamics by planar hydrodynamics so that the intitial state of the matter in the overlapping dense region is prescribed by the Rankine-Hugoniot relations.

Our purpose is to investigate, within reasonable parameterizations of each phase, the phase diagram, the trajectory in the phase diagram that is accessible in collisions of hadronic matter, and the properties of matter, and hence the possible signals, that correspond to the accessible region. Such a two model approach to studying the phase transition has been investigated by a number of authors (see [3,4,5] and references therein). We study a number of features of this approach including the role of baryon resonances and the pion polarization in the medium.

Relativistic nuclear field theory provides a good description of the bulk properties of nuclear matter as well as a large number of single-particle properties of finite

nuclei [6]. With appropriate extensions, the theory can be used to study matter under extreme conditions of temperature or density [7,8]. The extended Lagrangian is,

$$\begin{aligned}\mathcal{L} &= \sum_B \overline{\psi}_B \left[i\gamma_\mu(\partial^\mu + ig_{\omega B}\omega^\mu) - (m_B - g_{\sigma B}\sigma) \right] \psi_B \\ &\quad - \tfrac{1}{3} b m_n (g_\sigma \sigma)^3 - \tfrac{1}{4} c (g_\sigma \sigma)^4 + \tfrac{1}{2}(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2) \\ &\quad - \tfrac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \tfrac{1}{2} m_\omega^2 \omega_\mu \omega^\mu + \cdots \end{aligned} \tag{1}$$

Here ψ_B denotes a baryon spinor and the sum is over *all the charge states* of the stable baryons N, $\Delta, \Lambda, \Sigma, \Xi$. The pion and kaon are included as free thermal bosons and their Lagrangians are represented by the ellipsis. We include the pion dispersion in the medium due to $N^{-1}\Delta$ excitations.

Since the time scale (unlike supernovae or neutron stars) is very short on the weak interaction time ($\tau \sim 10^{-10}$ sec), strangeness is conserved throughout the duration of the collision and the evolution of its products. Similarly, the total electric charge and the baryon number are conserved. These conservation laws can be enforced in the usual way, through the introduction of chemical potentials, μ_b, μ_q and μ_s, for (positive) baryon number, electric charge and strangeness, respectively. They together with the field amplitudes σ, ω_0, can be determined through the three equations expressing the conservation laws and the two field equations.

The four coupling constants in the theory, g_σ/m_σ, g_ω/m_ω, b, c, are chosen so that the theory possesses the bulk properties of uniform symmetric matter, binding B/A = 16 MeV, saturation density $\rho = 0.15$ fm^{-3}. The compression modulus has been the subject of considerable debate. A decade ago it appeared to have been established as $K = 220 \pm 20$ MeV. Recent evidence suggests a value $K \sim 300$ MeV [9,10]. Evidence from high energy nuclear collisions is still provisional but suggests as high or higher value [11]. On the other hand the nucleon (Landau) effective mass at saturation is believed to lie within rather narrow bounds of about $m^\star_{Landau}/m \sim 0.83 - 0.85$ [12], implying a scalar effective mass at saturation of about $m^\star_{sat}/m \equiv (m_n - g_\sigma \sigma_{sat})/m \sim 0.78 - 0.8$. Since the range of uncertainty in $m^\star$ is so small we take 0.8. Of course nuclear matter properties do not determine the hyperon couplings. For simplicity we have assumed universal coupling.

The pion spectrum, $\omega(k)$ in nuclear matter is obtained as the poles of the pion propagator, $\mathcal{D}(k,\omega)$, in the medium, ie. as the solutions of

$$\mathcal{D}^{-1}(k,\omega) \equiv \omega(k)^2 - m_\pi^2 - k^2 - \Pi(k,\omega(k)) = 0 \tag{2}$$

where $\Pi(k,\omega(k))$ is the proper polarization [13]. We approximate it by the dominant contribution, the pion coupling to the $\Delta - N^{-1}$ excitations and their repeated scatterings in nuclear matter at density ρ, and include finite-size vertex cutoffs [13,14],

$$\Pi(k,\omega(k)) = \frac{\Lambda^2(k)\Pi_{res}(k,\omega)}{1 - g'(m_\pi/g_\Delta k)^2 \Lambda^2(k)\Pi_{res}(k,\omega)} \tag{3}$$

where the isobar polarization is

$$\Pi_{res} \approx \frac{8}{9}\left(\frac{g_\Delta k}{m_\pi}\right)^2 \rho \frac{\omega_\Delta(k)}{\omega^2 - \omega_\Delta^2(k)} \tag{4}$$

and $\omega_\Delta(k) = \sqrt{m_\Delta^2 + k^2} - m_n$, and the cutoff is $\Lambda(k) = \exp - \left(\frac{k}{7m_\pi}\right)^2$, [15]. There are two modes in this model which have the pion quantum numbers, one which is pion-like at small k and the other which is isobar-like. We include them both. The p-wave coupling strength, g_Δ, of pions and nucleons to isobars is related in the quark model to the p-wave pion-nucleon coupling, f, by $g_\Delta = (6\sqrt{2}/5)f$, where $f^2/(4\pi) \sim 0.08$ [14]. The spin-isospin anti-symmetric Landau parameter for coupling of delta particle-nucleon hole states is $g' \sim 0.7(g_\Delta/m_\pi)^2$ [16]. Results for the phase diagram are not sensitive, at the least, within the range 0.5-0.7.

We describe the quark-gluon phase by the asymptotically free equation of state corresponding to a thermal mixture of massless u and d quarks and gluons and massive strange quarks with $m_s = 150$ MeV. An equal mixture of u and d quarks automatically has an electric charge to baryon ratio of 1/2, and this is not changed with the addition of a strangeness conserving mixture of s and $\bar{s}$ quarks. For a charge symmetric quark gas ($q = \rho/2$) with vanishing strangeness content, we must set $\mu_u = \mu_d, \quad \mu_s = 0$.

We show in Fig. 1 the cold nuclear equation of state for the range of relevant densities for several values of K and $m^\star$, in the second case over a greater variation than is the probable uncertainty in this quantity. The energy differences shown here are small compared to the thermal energy at the temperatures on the shock adiabat, so that these kinds of uncertainties are unimportant as concerns the phase diagram as our detailed calculations bear out. The factors that have the greatest effect on the phase diagram are the full spectrum of stable baryons as compared to a hadronic phase described only in terms of nucleons, the medium effects on the pion dispersion, and the bag constant. The latter should be chosen to reproduce within the relatively large error, the predictions of lattice QCD for the baryonless phase transition temperature $T \sim 200 \pm 50$ MeV.

We show a sample of our results in Fig. 2 for $K = 300$ MeV, $B^{1/4} = 200$ MeV, and including both pion modes in the medium (pion and isobar), and the stable baryons listed following Eq.(1). The top panel shows the phase diagram in the $T-\rho$ plane. The solid lines denote the phase boundaries. The broken lines denote the trajectories that are the injection points accessible to experiment as approximated by the Rankine-Hugoniot shock relation. The dotted line denotes the continuation of the hadronic shock trajectory if no transition to quark-gluon phase were to take place. The squares denote the end points of the mixed phase on the shock trajectory. In the other panels of the figures, the temperature, pressure, density and entropy per baryon are shown on the shock trajectories as functions of the laboratory kinetic energy per projectile nucleon (fixed target). These figures show the conditions in which matter is created in a collision, assuming shock dynamics. The most notable feature is that once the threshold for the mixed phase is reached, the

initial temperature of the produced matter falls with increasing bombarding energy, until the energy is reached where matter is produced in the pure quark-gluon phase. There is also a rapid change in baryon number density through the mixed phase. Observables that depend sensitively on these changes in behavior will be the most favorable for detecting the quark-gluon phase. Di-lepton production seems especially favorable. The high temperature of the hadronic phase, if it persists above the transition point to mixed phase, will enhance di-leptons from $\pi^+ - \pi^-$ annihilation. Differences in the photon production may also be a strong signal. These and other results will be the subject of a future publication.

A plateau in temperature as a function of energy is frequently mentioned as a qualitative signal of the mixed phase, based on the notion of 'melting' (as of ice in water). The analogy is inaccurate inasmuch as the melting of the hadrons in a sequence of increasingly higher energy nuclear collisions is not a sequence of measurements at constant pressure (as in the heating of a pan of ice in the atmosphere). We have seen instead that the initial conditions, as estimated by the shock condition, are characterized by rising pressure and falling temperature as the bombarding energy is increased through the mixed phase. The transverse momentum is usually considered as a measure of the temperature. However the particle momentum is determined by both the temperature and the boost provided by the collective flow induced by the high pressure of the expanding matter. The decrease of T and increase of p, with increasing bombarding energy have opposite effects on the particle transverse momentum and may give rise to a plateau or perhaps a fall in p_t through the mixed phase, but not for the reason commonly given and certainly a plateau in temperature cannot be expected.

The phase boundaries are of special interest, since the baryonless transition is in the range of lattice QCD, but falls rapidly in T as the density increases, so that the mixed phase appears as low as $T = 115$ MeV, $\rho = 4.7\rho_0$ and $E_{lab} = 2.5$ GeV.

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Figure 1: Equation of state for several $m^\star$ and K over the relevant density range.

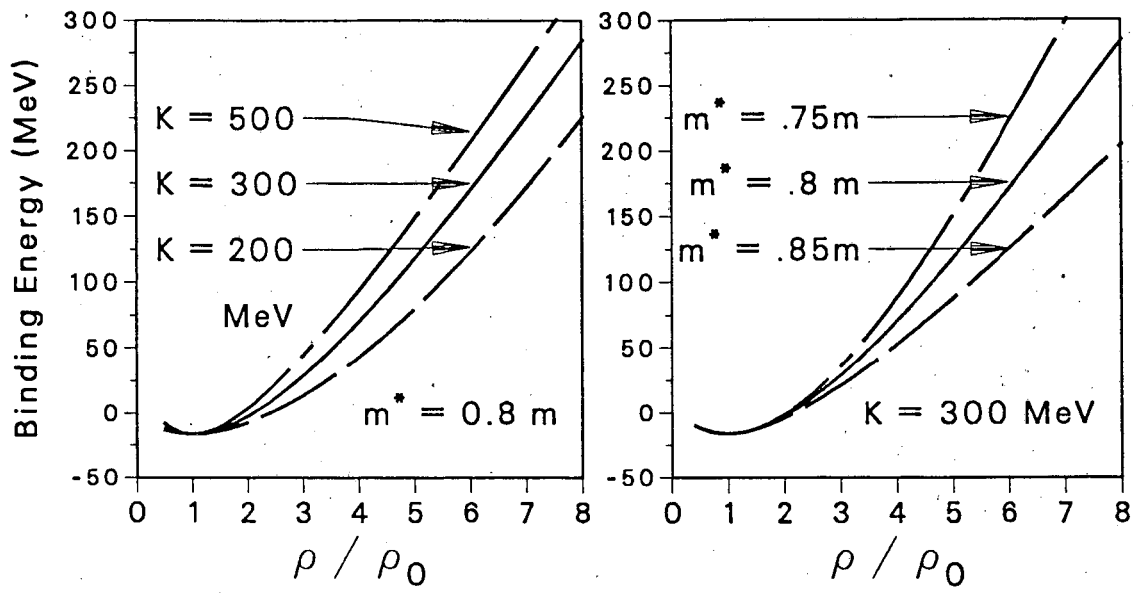
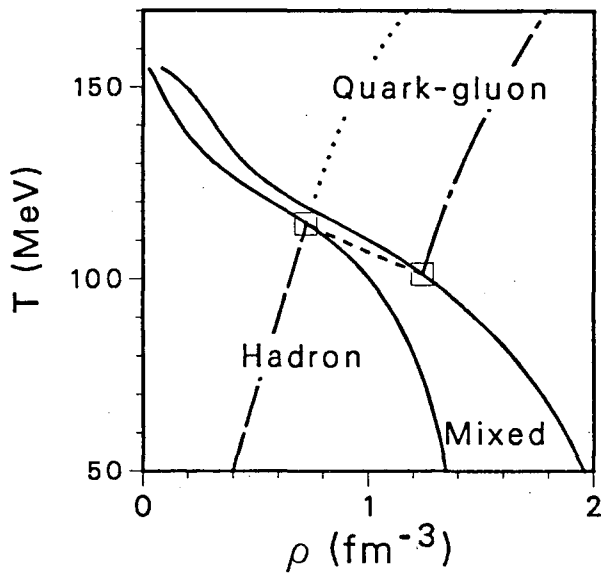
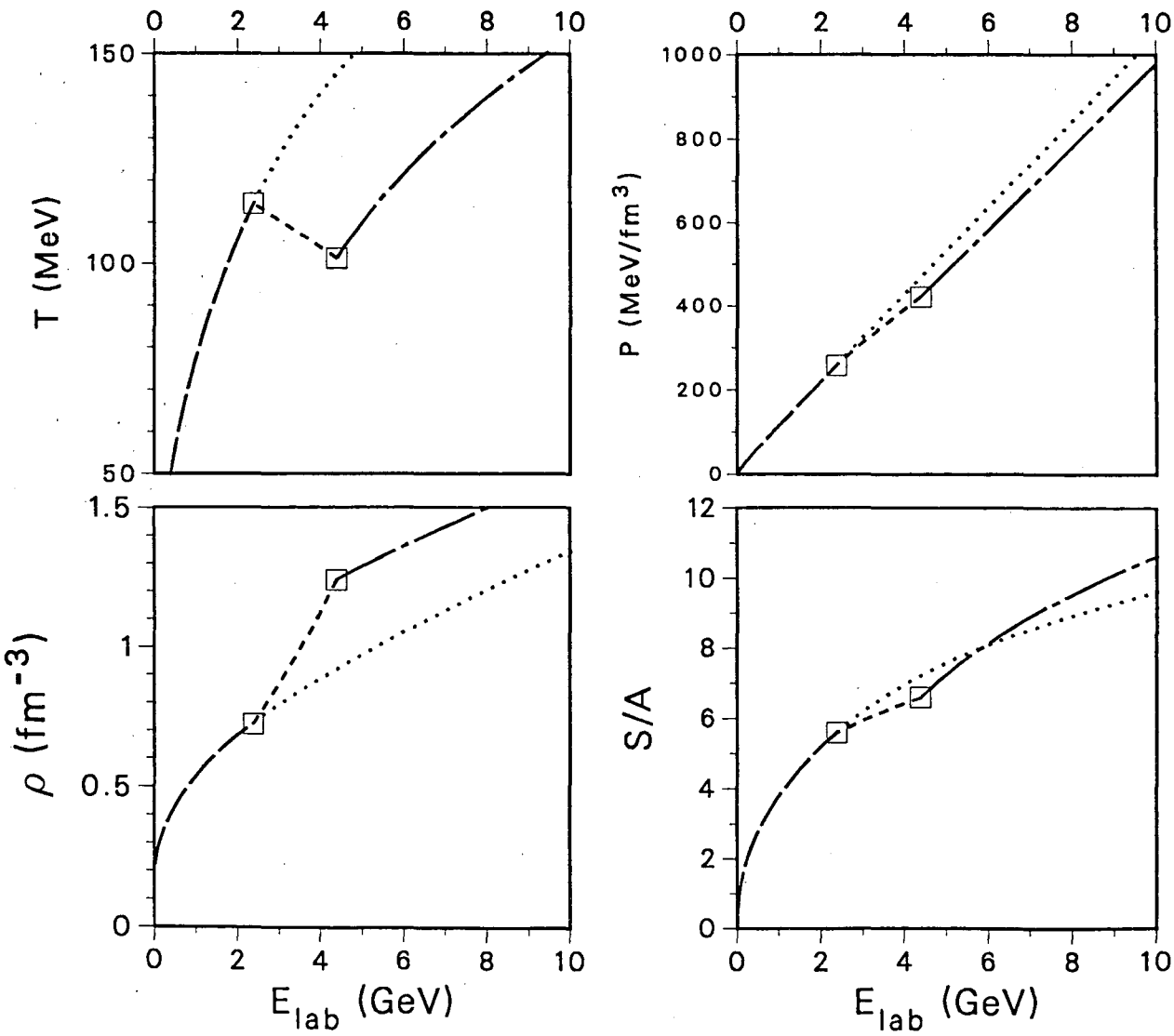


Figure 2: Top panel shows phase boundaries (solid lines) and the shock trajectories (broken). Other panels show properties along the shock trajectory. Hadronic phase includes nucleons, deltas, hyperons, mean field mesons and thermal pions (with medium effects) and kaons. $B^{1/4} = 200$ MeV, $K = 300$ MeV





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