Experimental signatures of phase transition to quark matter in high-energy collisions of nuclei

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Colliding high-energy heavy nuclei is the only known way to experimentally study the phase transition from nucleonic to quark matter. Observations are, however, frustrated by the fact that secondary π mesons are formed in the later stages of the interaction and are therefore insensitive to the early stages when quark matter is formed. We speculate on two types of experimental signatures of phase transition to quark matter. (i) The structure in the rapidity distribution of the secondaries from a near central collision of two heavy nuclei. We estimate that the reduction in shear viscosity between the colored quark-gluon plasma and the peripheral spectator part of each nucleus leads to an observable separation in rapidity of the secondaries from each component. (ii) Abundant production of prompt photons with $n_\gamma/n_\pi \simeq 30\%$ for central collisions with about 50 GeV energy per nucleon.

Early discussions[1] regarding the existence of quark matter speculated on its existence in the core of neutron stars. It is by now clear that the only controllable way to study the nonconfined quark-gluon phase of hadronic matter is after its formation in high-energy collisions of heavy nuclei, although one might speculate on its possible formation in hadron-hadron interactions. Anishetty *et al.*[2] showed that in a central collision of two heavy ions with center-of-mass energy of about $\sqrt{s}=50$ GeV/nucleon, the energy density of the nucleus rises to about

$$\rho_E = 2 \text{ GeV/fm}^3 . \tag{1}$$

This large density results from heating through individual NN interactions as well as the compression of the nuclei when traversing one another. This result is obtained by using standard experimental results on NN collisions. The density of Eq. (1) exceeds the energy density in a nucleon,

$$\rho_E^N = \frac{m_N}{\frac{4}{3}\pi R^3} \simeq 0.5 \text{ GeV/fm}^3 , \tag{2}$$

with $R \simeq 0.8$ fm. Therefore, quarks and gluons cannot be identified any more with individual nucleons and we have a transition to parton matter.

Observation of this phase transition is not an easy task. Secondary π's are formed at the late stages of the interaction and carry *on the average* very little information about the early stages when quark matter existed. Suggested resolutions of this problem are to look for virtual photons (lepton pairs)[3] or real photons with large transverse momentum.[4] These photons are radiated during the early violent stages of the interaction. The rates are, however, low and in presently feasible experiments, e.g., identified cosmic-ray nuclei interacting inside emulsions or the study of high-energy air showers with Fe primaries, their identification is impossible. Bjorken and McLerran[5] suggested that complete "globs" of this matter might be observable. Although it is difficult to understand the binding mechanism, this suggestion provides us with a possible explanation[5] of Centauro events. The purpose of this paper is to propose alternative signatures and to show that they are experimentally accessible: (i) remnant structure in the rapidity distribution of the secondaries as a result of the phase transition, and (ii) abundant formation of direct photons (*not* from $\pi^0 \to \gamma\gamma$) with small transverse momentum. They can then be detected by calorimetry through observation of large energy deposition in neutral, as opposed to charged, energy.

It should be pointed out from the start that the arguments presented here are fairly independent of energy. The phenomena discussed could be observable at significantly lower energies than our reference energy of $\sqrt{s}=50$ GeV/nucleon.

SINGLE-PARTICLE INCLUSIVE SPECTRA

Our first proposal for identification of quark matter in heavy-ion collisions is based on the speculation that the shear viscosity η between the part of an interacting nucleus that has been heated to quark matter in a near central collision and the peripheral spectator nucleonic matter is small. That η is small is due to the almost negligible exchange of particles between the two phases is a reasonable expectation. The exchange of particles between the two phases is a surface phenomenon due to the small mean free path of the particles in the quark plasma (about 0.5 fm, as we will see later on). The probability of the formation of color-singlet clusters in the surface layer that can interact with spectator nucleons is small. Quarks and gluons are, moreover, expected to move essentially parallel to the surface. This is true in the MIT bag model. In this model quarks and gluons cannot move into the hadronic matter; the interaction of the thermal hadrons with the quark matter bag is elastic. As a result of the small shear viscosity, the two phases will separate in rapidity. We will now show that we expect this effect to be observable in measurements of the rapidity of the secondary mesons.

We consider the prototype reaction of Ref. 2, U + U with $\sqrt{s}=50$ GeV/nucleon (see Fig. 1). Consider a target nucleus undergoing a near (but not completely) central collision with the nucleus projectile. For example, in U + U collisions with an average impact parameter $\langle b\rangle=6$ fm, about 90% of the target mass will overlap with the projectile, while 10% is left as a spectator piece at the periphery. The colliding region of the target becomes a high-temperature equilibrium fireball with small interior velocity gradients.[2] The projectile imparts longitudinal momentum to the plasma part of the target with[2] $\gamma\simeq 2$ or velocity $u_0\simeq 0.87$. Conversely, the fireball part of the projectile is slowed down by u_0 relative to its spectator part. Following estimates of the rapidity structure of the projectile will be presented in a frame where the projectile fireball is at rest. In that frame the spectator matter is racing away with velocity u_0. We describe the fireball as a nonrelativistic fluid with constant density ρ. This should be adequate at least for the initial stages ($t<4$ fm) of the interaction. Defining an x axis transverse to the projectile motion (see Fig. 1), we have

$$\frac{\partial u}{\partial t}=\nu\frac{\partial^2 u}{\partial x^2} \tag{3}$$

with

$$\nu=\frac{\eta}{\rho} \tag{4}$$

and the boundary conditions

$$u(0,t)=u_0 \tag{5}$$

$$u(x,0)=0 \quad (x>0)\ . \tag{6}$$

Equations (3) – (6) imply several approximations which we discuss first. For $0\le t\le t_0$ (~ 16 fm) we assume that the spectator velocity is equal to a constant u_0, which reflects the Lorentz separation $\gamma\sim 2$ of the plasma and spectator parts of the projectile. This is reasonable since, as will be shown further on, the percentage change of the spectator momentum during the interaction time $t\le t_0$ is small. Thus follows the boundary condition Eq. (5). Equation (6) reflects our choice of frame: at $t=0$ the interior velocities of the projectile fireball relative to its rest frame are approximately zero everywhere.[2] Equations (3) – (6) do not incorporate the full geometry of the problem. Calculations show that the disturbed part of the fireball for $t\le t_0$ due to the motion of the spectator is within an x interval that is much smaller than the dimension of the nucleus. We therefore prefer to treat the surface of the spectator at $x=0$ as infinite. Our model of the hadronic fluid is nonrelativistic. It has been shown[6] that the form of Eq. (3) and the coefficient of viscosity are compatible with those obtained in a relativistic calculation in the energy range under consideration. It should be made clear *ab initio* that we do not plan to make quantitative predictions; our aim is only to show that the reduced shear between the two phases leads to a measurable effect.

The solution of Eqs. (3) –(6) is

$$u(x,t)=u_0\left[1-\mathrm{erf}\left[\frac{x}{2\sqrt{\nu t}}\right]\right], \tag{7}$$

where erf is the error function. The probability of observing particles with velocity u is

$$P(u)=\frac{1}{\langle n\rangle}\frac{1}{\sigma}\frac{d\sigma}{du} \tag{8}$$

$$=\frac{\sqrt{\pi\nu t}}{u_0(2R-b)}\times\exp\left\{\left[\mathrm{erf}^{-1}\left[1-\frac{u}{u_0}\right]\right]^2\right\}. \tag{9}$$

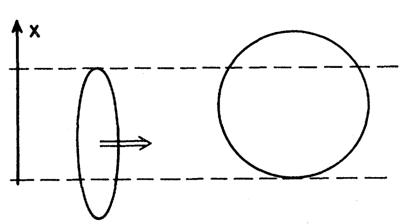

FIG. 1. Geometry of a nucleus-nucleus interaction.

Here R and b are the radius and impact parameter of the colliding nuclei and $\langle n \rangle$ the average multiplicity. In terms of the rapidity of the secondaries in the projectile rest frame,

$$P(y)=\frac{1}{\langle n \rangle}\frac{1}{\sigma}\frac{d\sigma}{dy} \tag{10}$$

$$=P(u)\frac{4e^{2y}}{(e^{2y}+1)^2} , \tag{11}$$

where

$$u=\frac{e^{2y}-1}{e^{2y}+1} .$$

It is known[6] that a gas model of pions is adequate to estimate the shear viscosity for incident energies below roughly 10−100 TeV. For a mean free path[2] $\lambda=0.2$ fm and an average velocity $\langle v \rangle$ corresponding to the calculated[2] temperature of 165 MeV, we obtain

$$\nu=0.3\lambda\langle v \rangle=2\times10^{-4}\ \mathrm{cm^2/sec} . \tag{12}$$

Taking into account nucleons does not change this number significantly.

Our results based on this value of ν and Eq. (11) are shown in Fig. 2. Their interpretation requires some discussion. For energies below phase transition the freezing-out time to about half nuclear-matter energy density is about 16 fm. Therefore, in the absence of phase transition, this would be

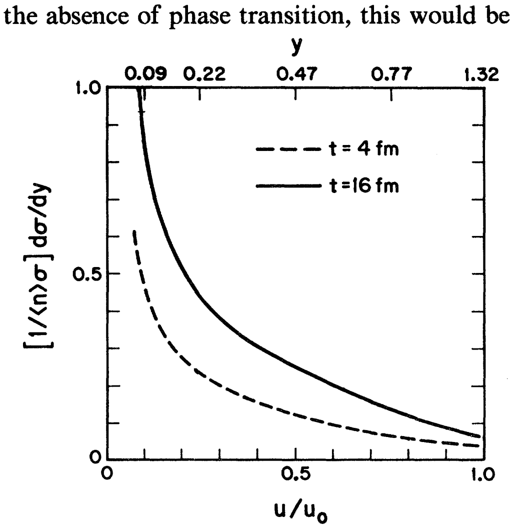

FIG. 2. The rapidity distribution of secondaries from a projectile nucleus when no phase transition to quark matter appears ($t=16$ fm) and when phase transition threshold has been reached ($t=4$ fm). The velocity u and rapidity y are calculated in the plasma-fireball rest frame. u_0 is the velocity of the normal spectator part of the nucleus.

the freeze-out time at this particular energy. Although the shear viscosity ν was estimated for pion matter, the results are not very sensitive to its precise value. It is therefore adequate to regard the curve labeled $t=16$ fm in Fig. 2 as the resulting rapidity distribution for the case of no phase transition. Above the critical energy for phase transition the fireball becomes quark matter and the shear between it and the spectator disappears. The quark matter in contact with the spectator curves downward similar to mercury in contact with a solid. After 6−8 fm, quark matter goes normal. Therefore, viscosity does not curve the surface of the fireball upward until roughly 12 fm. At freezing-out time the rapidity distribution is therefore similar to the one labeled $t=4$ fm in Fig. 2.

We conclude that the sudden decrease in rapidity of the density of charged pions when crossing the critical energy is observable. Indeed, the variation between the curves in Fig. 2 should be accessible as the average number of π's is large, estimated to be about 500, and the rapidities under consideration are large enough to be observed even in cosmic-ray experiments. We remind the reader that the rapidities in Fig. 2 are in the projectile-fireball rest frame and have not been boosted to the laboratory frame.

As mentioned earlier, due to the absence of shear viscosity, the spectator part of the projectile will be less slowed down. The momentum change is

$$\Delta p=\int_0^{t_0} A\eta\frac{du}{dx}\bigg|_{x=0} dt , \tag{13}$$

where A is the surface area between the spectator and the quark-gluon plasma. Equation (13) is evaluated using Eq. (7) and purely geometrical considerations. We take the spectator mass to be 11% of the total mass, corresponding to average impact parameter $\langle b \rangle = 6$ fm. One also has to take into account that in the projectile-fireball rest frame the area between the fireball and the peripheral spectator is reduced by a factor $\sim\frac{1}{4}$ due to the compression of the fireball and the Lorentz contraction of the spectator. We find that $\Delta p/p$, i.e., the reduction of the spectator's velocity by viscous effects is 27% when no transition occurs ($t_0=16$ fm), but is only 14% when a quark-gluon plasma is formed. This 13% acceleration of the fastest particles in the projectile fragmentation region when crossing the critical energy for phase transition should again be observable. This effect, combined with the reduction of the rapidities of the particles frozen out from the quark-gluon plasma, could lead to structure in rapidity.

The above discussions can of course be repeated for the target fragments. Observation is, however, more difficult because of their smaller rapidity in the laboratory frame.

PRODUCTION OF PROMPT PHOTONS

As previously discussed, in collisions with $\sqrt{s}=50$ GeV/nucleon, the projectile is heated and compressed to an energy density $\rho_E=2$ GeV/fm^3. As this density is similar to that inside individual nucleons where quarks carry on the average 0.3 GeV/fm^3, we compute a density of quarks,

$$\rho_q=\frac{\rho_E}{0.3\ \text{GeV/fm}^3}=7\ \text{quarks/fm}^3\ , \tag{14}$$

and the multiplicity of π's per fm^3 (ignoring baryon production) is

$$n_\pi \simeq \tfrac{1}{2}\rho_q\ . \tag{15}$$

Taking into account the compression of the volume, this leads to about 500 secondaries, as previously mentioned. Also, the mean free path of the quarks is similar to that inside nucleons. Using the quark-model result that the quark-meson cross section is

$$\sigma \simeq \tfrac{1}{3}\sigma_{\text{meson-nucleon}} \simeq 10\ \text{mb} \tag{16}$$

and the meson density of Eq. (15), we obtain for the interaction length of quarks in nuclear matter,

$$\lambda=\frac{1}{\rho\sigma}\simeq\tfrac{1}{2}\ \text{fm}\ . \tag{17}$$

Therefore, the quarks interact every $\frac{1}{2}$ fm for a total interaction time $t_{\text{int}}=8-16$ fm. In each interaction the probability to get a γ is roughly $\langle e_q{}^2\rangle\alpha$; therefore

$$n_\gamma \simeq \left[\tfrac{4}{3}\pi R^3\rho_q\right]\left[\frac{t_{\text{int}}}{\lambda}\right]\langle e_q{}^2\rangle\alpha\ . \tag{18}$$

The quantity in the first set of parentheses is the number of quarks; that in the second set is the number of interactions; $\langle e_q{}^2\rangle$ is the average quark charge squared. We then have

$$\frac{n_\gamma}{n_\pi}\simeq\left[\frac{\rho_q}{\rho_\pi}\right]\left[\frac{t_{\text{int}}}{\lambda}\right]\langle e_q{}^2\rangle\alpha=(0.1-0.2)\ . \tag{19}$$

This calculation can be done at the π-meson level.[7-10] Now, by similar arguments, $\lambda_\pi=\frac{1}{5}$ fm and $\langle e_2\rangle=\frac{4}{9}$; therefore

$$\frac{n_\gamma}{n_\pi}\simeq\left[\frac{t_{\text{int}}}{\lambda_\pi}\right]\frac{4}{9}\alpha\simeq 0.15-0.3\ . \tag{20}$$

The two calculations actually agree when taking into account the enhancement[7] of n_γ by multiple interactions of quarks during one typical interaction time.

The energy fraction deposited into photons is

$$\frac{E_\gamma}{E_{\text{tot}}}=\frac{2n_\gamma}{2n_\gamma+n_\pi}=(0.25-0.4)\ , \tag{21}$$

where we counted two polarization degrees of freedom for the photon. For a discussion on this point see, e.g., Ref. 11. Calorimetric comparison of energy deposition in neutral and charged energy should allow detection of the large energy deposition into γ's as an apparent violation of the isospin equality between π^0, π^+, π^-, once we cross the critical energy for quark-matter formation.

We close with a comment concerning the reliability of these estimates. The counting level at the π level presented above can be tested in nucleon-nucleon collisions using measured π multiplicities. At accelerator energies of about 1 TeV, where $n_\pi\simeq 12$, one obtains[8,10] $n_\gamma/n_\pi\simeq 15\%$, in agreement with experimental indications. Moreover, when the transverse momentum p_T of the π mesons becomes large, counting of γ's radiated by quarks can be done rigorously using perturbative QCD. Our counting matches the perturbative QCD results in the intermediate p_T range.[8,10]

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