Spectator Temperature as a Signal for Quark-Matter Formation

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A new signature for quark-matter formation in relativistic heavy-ion collisions, in terms of the emission spectra in the fragmentation regions, is proposed.

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It is now generally believed that quarks and gluons are the building blocks of the hadronic world and that there may exist a quark-gluon phase (popularly referred to as a quark-gluon plasma) where the quarks and the gluons do not remember from which hadrons they came. Indeed, the prospect of quark-matter formation has been the primary motivation behind the proposed ultrarelativistic heavy-ion accelerators.

Since quarks and gluons cannot, apparently, be observed as individual particles, a number of investigators[1] have devoted their attention to the study of the experimental signatures of such a quark-gluon plasma, assuming that it is formed. In this Letter we propose a new signature for the formation of quark matter in heavy-ion collisions. As we shall argue in the following, this signature may have several advantages over the existing ones. The most important of these advantages appears to be its applicability to presently available energies for heavy ions.

Our starting point is the participant-spectator concept.[2] Although it is well known that the simple fireball model[3] derived from this concept does not adequately describe the experimental findings quantitatively, its qualitative features are probably valid. Kinematically, spectators and participants occupy different regions in rapidity space. In a first approximation, the spectators experience no excitation. On closer examination, however, it is expected[4] that they are also somewhat excited, albeit on a smaller scale than the participants. Thus, during the separation of the spectators from the participants, there must be some communication between them which results in the excitation of the spectators. As we shall show below, it may be that this communication strongly depends on whether or not the participants form a quark-gluon plasma. If so, then the energy imparted to the spectators may carry characteristic information about the formation of a quark-gluon plasma in the participant region. We present a model which utilizes this very idea. Our analysis is based upon a hydrodynamic scenario, but this is more for the sake of simplicity than as a matter of principle. The concept sketched above does not really rely on whether nuclei and quark-gluon plasmas behave as fluids or not.

We start from an earlier work[4] of ours where we investigated, within a hydrodynamic picture, how the spectators could be excited. It was proposed that during the collision of two nuclei, the participant parts shear off from their respective spectator partners. This occurs because the participants are slowed down (and perhaps stopped in the equal-velocity frame[5]) because of the collision, while the spectators, not meeting any obstacle, proceed along their line of flight. But during this process, the nonzero viscosity of the nuclear fluid causes friction over the region of contact. The work done against this friction shows up as heat in the cut surface. The total amount of heat generated would be equally distributed between the spectator and the participant parts, but, because of the large excitation expected in the participants, this small amount may be neglected there. On the other hand, this is the entire energy available to the spectators, and produces the particle emission in the target or projectile fragmentation regions. In Ref. 4 we calculated, in a first approximation, the amount of (thermal) energy in the separation surface of the spectator. If the width of the separation surface is denoted by h, then the total work done against the friction force is given by

$$W_{\text{friction}} \sim \eta v_x SD/h, \tag{1}$$

where η is the *effective* coefficient of shear viscosity between the participant and spectator parts of the nucleus, v_x is the relative velocity of separation, S is the area of the surface of separation, and D is the diameter of the surface. Then the corresponding excitation energy per nucleon in this surface is

$$W = W_{\text{friction}}/N = \eta v_x D/(h^2 n_0), \tag{2}$$

where N is the total number of nucleons in the volume Sh and n_0 is the number density over the surface of separation in the spectator. Now in accordance with the participant-spectator picture, let us assume that a quark-gluon plasma is formed in the participant region. The spectators naturally continue to be in the nuclear phase. Then, as argued by Halzen and Liu,[6] the effective friction between the spectator and the participant parts would be very different from what it would be were both parts in the nuclear phase. The friction between the quark-gluon plasma and the nuclear fluid is expected to be much less than that between two slabs of nuclear matter. This is easy to understand on microscopic grounds. Friction is caused by the exchange of particles between these two slabs, and if one of them is in a locally colored phase, then the exchange of particles between them would be strongly inhibited.

Let us remark at this point that Halzen and Liu have also used this argument to propose a method for detecting the existence of a quark-gluon plasma. However, as we shall show below, there are fundamental differences between our approach and theirs, which are reflected in the ultimate signature of quark-gluon-plasma formation.

Equation (2) tells us that, depending on the appropriate value of the *effective* coefficient of shear viscosity η between the two slabs, the temperature of the spectator nucleons on the separation surface can be very different, and thus depends on whether or not a quark-gluon plasma is formed in the participant part. At the present state of the art, there are no handles on the magnitude of this effective η. Nonetheless, it is quite reasonable to assume that the formation of a quark-gluon phase is accompanied by a drastic decrease of the effective viscosity η, when compared with the situation when no quark-gluon plasma is formed. Accordingly, the effective temperature T of the spectator nucleons, which is related to η by Eq. (2) and through the equation of state $W = W(T)$, will also be much smaller. In particular, if one assumes a Fermi-gas equation of state

$$W \propto T^2, \tag{3}$$

and a decrease in η of an order of magnitude (in Ref. 6, η, for the case of formation of a quark-gluon phase, is taken to be zero), then a change of T by a factor of 3–4 emerges. Such a change would be easily detectable.

In our opinion, this signature presents advantages over the other suggestions.[1] The tests proposed so far for the formation of a quark-gluon plasma (production of lepton pairs, photons, strange particles) rely on the estimates of yields in the hadron and quark-gluon phase, respectively. These estimates, however, presuppose a good knowledge of the dynamics of strong interactions in the two phases which, unfortunately, we do not have. To cope with this unsatisfactory situation one hoped to be able to use the onset of the phase transition as a supplementary criterion. This would have expressed itself in a sudden change of the yields as a function of center-of-mass energy associated with a strong phase transition. Earlier calculations suggested such a sharp transition.[7] This was also indicated by lattice calculations for pure-glue systems.[7] On the other hand, Morley[8] has already argued against a sharp phase transition, and recent lattice calculations[9] incorporating light quarks seem to support this. While, because of the arguments given above, this might throw some doubt on the applicability of the conventional signatures for the onset of the phase transition to a quark-gluon plasma, the effect we are here proposing will be unaffected. Indeed, as long as the kinematical separation between the participants and spectators is achieved, the excitation of the spectators is a clean signal not affected by any other background since it relies essentially only on the existence of the confinement effect for quarks and gluons which is supposed to be present independent of the nature of the phase transition.

We ought to point out a this stage the difference between our picture and that of Halzen and Liu.[6] These authors assume a large transparency effect in nuclear collisions, which might be appropriate for very high energies. We, on the other hand, refer to a lower energy where nuclei stop each other to a very great extent.[5] Therefore we end up with a situation where the participants rapidly shear off from the respective spectators, which essentially continue their motion. This is in contrast to Ref. 6, where no such process occurs. Thus in our scenario, in each event there are one or two highly excited fireballs, rich in baryon-number content, in the central rapidity region, and (under the assumption of identical colliding partners) two low-temperature fireballs in the fragmentation regions. On the other hand, the phase transition to a quark-gluon plasma is not expected to occur in every event. Those events in which this transition does not take place are expected to contribute with a higher "low" temperature in the spectator region. Thus when no event-by-event selection is made, two different temperatures are expected in the fragmentation region, both of which are lower than the participant temperature. In the scenario of Halzen and Liu, on the other hand, there are no large-baryon-number fireballs in the central rapidity region, and in the fragmentation regions one sees only one temperature.

In light of these considerations, two recent experimental results might take on new significance. Bhalla *et al.*[10] studied collisions of 1.7A-GeV Fe beams on emulsions and found that the transverse-momentum spectrum of α particles in the projectile-fragmentation region was characterized by two effective temperatures; 10 and 40–50 MeV. Baumgardt, Friedländer, and Schopper[11] have also reported the existence of two temperatures; 10 and 40 MeV. More importantly in Ref. 11 it was found that the two temperatures belonged to different events, which was interpreted as evidence for two different reaction mechanisms. This result has to be compared with the earlier findings of Baumgardt and Schopper[12] in which only the 40-MeV temperature was observed for target-related α particles in 800A-MeV ^{12}C beams on nuclear emulsions.

The fact that more energetic and heavier projectiles (which are expected to be more efficient in setting up collective behavior) yield two distinctly different temperatures in the fragmentation region may, in view of the foregoing discussion, be interpreted as a possible signal for the production of a quark-gluon plasma. In this case the ratio of 4 between the two temperatures would imply a decrease in the effective friction coefficient of an order of magnitude, in agreement with the conjectures we made above. This might lend some credibility to the implication that the 10-MeV temperature belongs to events where a quark-gluon plasma is formed in the participant region. If this scenario holds, it can be verified with present accelerators, firstly by improving the statistics of Ref. 11. Furthermore one could expect that by increasing the energy and size of the collision partners one would increase the percentage of *low*-temperature α particles from the fragmentation region, a prediction which has an element of piquancy in it. The formation of a quark-gluon plasma at energies of the order of $\sim A$ GeV is not totally unexpected; theoretical calculations have already indicated such a possibility.[13] If a strong shock is formed,[14] the formation of a quark-gluon plasma may be further facilitated.

We are certainly aware of the limitations of the emulsion experiments due to their low statistics. Thus the above considerations should not be interpreted as a claim that a quark-gluon plasma has already been formed at Bevalac, but rather as an inspiration for future experimental and theoretical work. In particular new high-statistics measurements of the transverse-momentum distributions of nucleons and α particles in the spectator region, as well as further theoretical work on transport between quark-gluon plasma and nuclear matter, appear to be urgent tasks.

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[5] W. Busza and A. Goldhaber have argued that nuclei may stop each other up to several gigaelectronvolts per nucleon center-of-mass energies, See, for example, W. Busza, in Proceedings of the Third International Conference on Ultrarelativstic Nucleus-Nucleus Collisions, Brookhaven National Laboratory, Upton, New York, September 1983 (to be published). For our purpose, however, it is really irrelevant whether the participants completely stop each other in the center-of-mass frame or not, as long as the participants and spectators separate in rapidity.

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