Dilepton Suppression as a Signature for the Baryon-Rich Quark-Gluon Plasma

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(Received 13 June 1988; revised manuscript received 15 February 1989)

The dilepton yield at invariant masses between $2m_\pi$ and 1 GeV is shown to be reduced substantially if a baryon-rich quark-gluon plasma is formed in high-energy heavy-ion collisions. We suggest therefore to measure the total dilepton yield in this region of invariant masses as a function of the incident energy. The onset of a baryon-rich quark-gluon plasma is then signaled by a decrease in this excitation function.

PACS numbers: 25.70.Np, 12.38.Mh

The ultimate goal of heavy-ion collisions at ultrarelativistic energies is to create a deconfined quark-gluon plasma.[1] It is hoped that during the initial stage of the collision, a region of high-density will be produced so that a transition of the hadronic matter due to the quark-gluon plasma will take place. For future experiments at the proposed relativistic heavy-ion collider (RHIC) a baryon-free quark-gluon plasma is expected to be created due to the increasing transparency of the nuclear matter with increasing collision energies.[2] At present, the CERN experiments at both 60 and 200 GeV/nucleon indicate that the incident projectile is not completely stopped by the target and a high-energy density of many GeV/fm^3 has been reached.[1] The observation of the suppressed production of the J/ψ particle has already stimulated great excitement as it might be possible evidence for the formation of a quark-gluon plasma.[3] However, it will not be considered as a definitive signature until a better understanding of the dissociation of J/ψ by the hadronic particles is achieved.[4–6] For experiments carried out at the Brookhaven Alternating Gradient Synchrotron (AGS) at 14.5 GeV/nucleon,[7] the analysis of the final transverse-energy distribution indicates that the projectile is indeed completely stopped by the target and that a hadronic matter of density about 5 times the normal nuclear matter density has been reached in the initial stage. Whether a baryon-rich quark-gluon plasma has been formed in such a collision is still uncertain. It has been argued in the past that the formation of a quark-gluon plasma may be signaled by an enhanced production of kaons relative to that of pions.[8] Data obtained at AGS indeed show an enhancement of a factor of 4 for the K^+/π^+ ratio compared with that from the pp collision.[9] However, theoretical studies show that the same enhancement can be obtained by assuming either the formation of a quark-gluon plasma or a dense hadronic matter in the initial stage of the collision.[10,11] In view of the ambiguity associated with these observables as signatures for the quark-gluon plasma, it is extremely important to consider other observables which might be more unique as signatures for the quark-gluon plasma.

A very interesting suggestion in the past has been the dileptons. It was suggested that the disappearance of the ρ peak in the dilepton invariance-mass spectrum might signal the formation of a quark-gluon plasma.[12] Detailed studies including proper treatment of the expansion dynamics, however, do not support such a possibility.[13] These studies are all concerned with the baryon-free quark-gluon plasma that might be produced in future RHIC energies. At AGS energies in the range of about 15 GeV/nucleon, a dense hadronic matter will be formed if no quark-gluon plasma is created in the initial stage. In the hadronic matter, dileptons can be produced from both pn bremsstrahlung and the $\pi\pi$ annihilation. As shown in Refs. 14 and 15 for dense hadronic matter at high temperatures, the contribution from $\pi\pi$ annihilation is more significant than that from the pn bremsstrahlung for dileptons of invariant masses in the region of $2m_\pi$ to about 1 GeV, where m_π is the mass of the pion. It is also found in Ref. 15 that the modification of pion dispersion relation by the dense nuclear matter to the strong p-wave πN interaction can lead to enhanced production of dileptons at small invariant masses. This effect becomes more pronounced as the density of the hadronic matter increases. On the other hand, if a baryon-rich quark-gluon plasma is initially formed, then dileptons will be produced from the $q\bar{q}$ annihilation. After hadronization, dileptons can also be produced from the hadronic matter via pn bremsstrahlung and $\pi\pi$ annihilation. Since the total entropy cannot decrease during the transition, the final hadronic matter will be at a higher temperature and lower density than the initial quark-gluon matter. If the quark-gluon plasma contributes mainly to dileptons with larger invariant masses, then we expect a reduced production of dileptons with low invariant masses compared with the case without the formation of a quark-gluon plasma due to the low hadronic matter density after hadronization. In this case, it is of interest to measure the total dilepton yield in this region of invariant masses as a function of the incident energy. The onset of a baryon-rich quark-gluon plasma is thus signaled by a decrease in this excitation function.

To substantiate this conjecture, we have carried out calculations for dilepton production based on the hydrochemical description of heavy-ion collisions.[10,16] We assume that a baryon-rich fireball is formed in the collision of two heavy ions. For collisions between identical nuclei, the initial density can be estimated from the prescription that two Lorentz-contracted nuclei are stopped by each other with a density given by $2\gamma\rho_0$, where γ is the Lorentz factor. Including compressions via the shock model as in Ref. 17 will lead to an even larger initial density. Whether the initial fireball is in the hadronic or the quark-gluon phase depends on the structure of the nuclear phase diagram. We use that of Ref. 18. The nuclear phase diagram is determined by considering both the hadronic and the quark-gluon matter as composed of noninteracting nonstrange particles with the latter supplemented by a bag constant. The transition from one phase to the other is through a mixed phase of both kinds of matter very similar to that of the familiar gas-liquid transition. The boundary between the hadronic and the quark-gluon phase is determined by the condition that the temperature, pressure, and baryon chemical potential of the hadronic and the quark-gluon phase are equal. The inclusion of strong particles affects the phase diagram only slightly as pointed out in Ref. 19. Since the collision time in heavy-ion reactions is shorter than the equilibration time for strange particles, it is reasonable to neglect the strange particles in the consideration of the phase diagram. In constructing the phase diagram, we have used a bag constant $B=250$ MeV/fm^3, which leads to a critical energy density of ≈ 1 GeV/fm^3. Figure 1 shows such a nuclear phase diagram in the temperature and baryon density space. Also shown in the figure by the solid curve is the injection points for central collisions between identical nuclei at energies below the AGS. According to this phase diagram, a mixed phase of quark-gluon and hadronic matter is formed when the incident energy is above ≈ 2

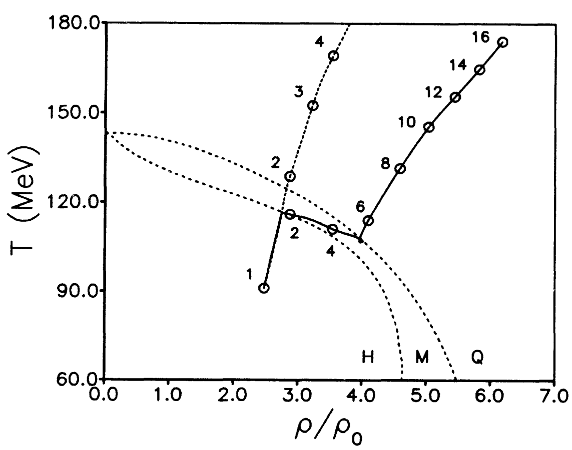

FIG. 1. Nuclear phase diagram in the space of temperature T and the baryon density ρ. The injection points from heavy-ion collisions between identical nuclei are shown by the solid curve. The numbers near the circles denote the incident energy per nucleon for collisions between identical nuclei. The dotted curve corresponds to injection points for a pure hadronic scenario.

GeV/nucleon, and a baryon-rich quark-gluon matter is produced once the incident energy is higher than ≈ 5 GeV/nucleon. The dotted curve corresponds to the injection points in a purely hadronic scenario. We like to emphasize that his phase diagram is meant to illustrate the possible scenarios that might happen in high-energy heavy-ion reactions and probably differs in details when more sophisticated models such as that of Ref. 20 are used. The expansion of the fireball is then described by the hydrochemical model in which the fireball is assumed to be in thermal but not chemical equilibrium. The thermal energy in the fireball is converted into the collective flow energy via a simplified relativistic hydrodynamical equation with linear scaling *Ansatz* for the velocity profile.[10,16] At any instant of time during the expansion of the fireball, the thermodynamical quantities such as energy, pressure, etc., are determined from standard equilibrium thermodynamics.

If the fireball is initially in the hadronic phase, the system will simply expand until it reaches the freezeout density at which the mean free path of the particles is comparable to the size of the fireball. Dileptons are then produced predominantly from the pion-pion annihilations, which can be calculated as in Ref. 15. On the other hand, if the fireball is initially in the quark-gluon phase, then dileptons are produced from q-$\bar{q}$ annihilations and can be calculated as in Refs. 12 and 13. The temperature and pressure of the fireball decrease during the expansion and eventually it reaches the boundary of the phase diagram and makes a transition to the hadronic matter. As the fireball transforms from the quark-gluon plasma to the hadronic matter, it goes through a mixed phase of these two kinds of matter. Assuming that the fraction f of quark-gluon plasma decreases linearly with time, i.e., $f=1-t/\tau$. The lifetime τ of the mixed phase depends on the hadronization rate of the quark-gluon plasma and is taken to be 5 fm/c, a value similar to that of Ref. 21. To determine the hadronic content from the hadronization of the quark-gluon plasma, we make use of the combinatoric breakup model of Biró and Zimányi.[22] In this model, the effective number of quarks and antiquarks in the plasma are given by $\overline{N}_q=N_q+f_qN_g$ and $\overline{N}_{\bar{q}}=N_{\bar{q}}+f_qN_g$, where N_q and $N_{\bar{q}}$ are the number of light quarks and antiquarks in the fireball while N_g is the number of gluons. The parameter f_q, which determines how gluons are converted into quarks during hadronization, is determined from the flux-tube model and has a value of 0.425. The flavor composition of hadrons formed from the plasma is then determined by the following rule of recombination: $N_\pi=\alpha\overline{N}_q\overline{N}_{\bar{q}}$, $N_N=\beta\overline{N}_q^3/3!$, etc. We have also induced hadrons such as ρ, Δ, etc., as in Ref. 18. The α and β for the baryons are determined from the condition that the total quark content in the hadrons is given by the effective number of quarks and antiquarks in the plasma, i.e., $\alpha=4A/(3A^2+B^2)$ and $\beta=8/(3A^2+B^2)$, where $A=\overline{N}_q+\overline{N}_{\bar{q}}$ and $B=\overline{N}_q-\overline{N}_{\bar{q}}$. In the mixed phase, dileptons are produced from both q-$\bar{q}$ annihilations in the quark-gluon matter and pion-pion annihilations in the hadronic matter.

In Fig. 2, we show the dilepton invariant-mass spectra from the collision of two ^{40}Ca nuclei at 14 GeV/nucleon. From Fig. 1, we see that the initial density is about $6\rho_0$, where ρ_0 is the normal nuclear matter density and the fireball is initially in the quark-gluon phase. The lifetime τ of the mixed phase is taken to be 5 fm/c and is similar to that of Ref. 22. The dashed curve is the contribution from the quark-gluon plasma, while the dotted curve is due to the $\pi\pi$ annihilation in the hadronic matter. The two peaks in the latter correspond to the ρ resonances at 770 and 1660 MeV, respectively. It is seen that the former becomes important for dileptons with invariant masses larger than 2 GeV. At smaller invariant masses, it is still dominated by $\pi\pi$ annihilation even though the corresponding hadronic matter is at a relatively low density of about ρ_0 after the complete hadronization from the initial quark-gluon plasma. Also shown in the same figure by the solid curve is the dilepton invariant-mass spectrum from $\pi\pi$ annihilation if we assume that no quark-gluon plasma is formed in the initial stage and that the initial matter is a dense hadronic matter of density of also about $6\rho_0$. We see that the dilepton yield is much larger than that from the scenario of the formation of an initial quark-gluon plasma. This is due to both the increased modification of the pion dispersion relation at higher densities and the higher initial temperature of the fireball. We therefore expect that a useful way for the diagnosis of the quark-gluon plasma is not to look for observables which are related directly to the quark-gluon plasma, rather to verify its formation indirectly via the suppression of the dilepton yields. In our discussions, we do not consider the production of dileptons from the Drell-Yan process as it is important for invariant masses that are larger than the region we are interested in. Also, the pn bremsstrahlung is not important as already pointed out in the above.

In theoretical studies carried out recently on dilepton production at LBL Bevalac energies,[15] we have shown that its yield from $\pi\pi$ annihilation dominates for invariant masses $M < 1$ GeV and increases significantly with the initial density of the hadronic matter. It is thus of interest to calculate the total dilepton yield with invariant masses $2m_\pi < M < 1$ GeV. Since the initial hadronic matter density increases with the incident energy of the projectile, this yield would increase as well due to both the increasing softening of the pion dispersion relation and the increasing initial temperature with increasing density. In Fig. 3, we show such an excitation function for this yield. It is calculated with the hydrochemical model as before for the reaction of ^{40}Ca on ^{40}Ca at zero impact parameter corresponding to central collisions. The solid curve is obtained when the initial conditions of the fireball are determined from the phase diagram of Fig. 1. It shows a steep rise of the dilepton yield at in-

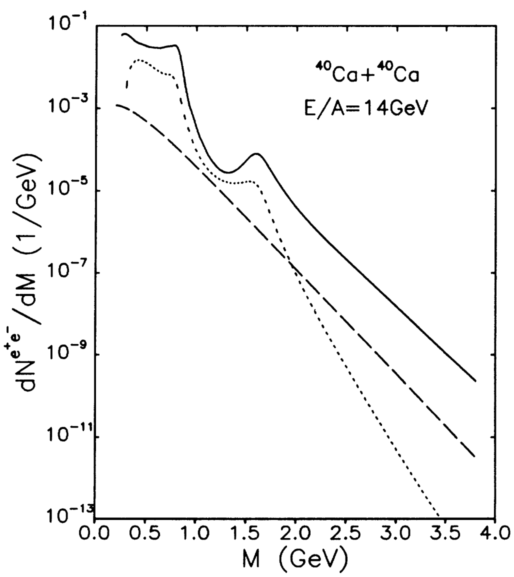

FIG. 2. Dilepton invariant-mass spectra from the central collision of Ca on Ca at 14 GeV/nucleon. The dashed curve is from the quark-gluon plasma and the dotted curve is from the $\pi\pi$ annihilation in the hadronic phase. The solid curve is from the $\pi\pi$ annihilation in the scenario that no quark-gluon plasma is formed in the collision.

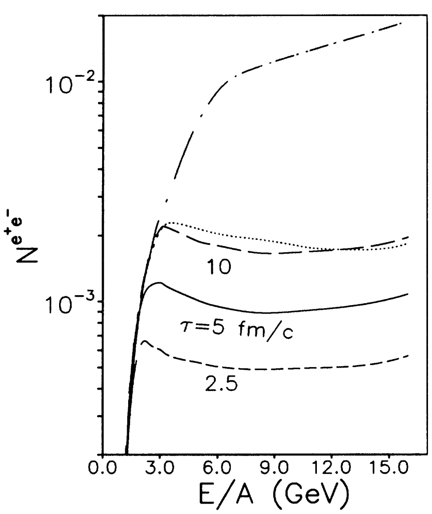

FIG. 3. The total dilepton yield for invariant masses between $2m_\pi$ and 1 GeV as a function of the incident energy per nucleon for the central collision of Ca and Ca. The solid curve is from initial fireball conditions determined from the phase diagram of Fig. 1 and a mixed-phase lifetime $\tau = 5$ fm/c. The dashed-dotted curve is from assuming that the fireball is initially always in the hadronic phase. Short- and long-dashed curves correspond to $\tau = 2.5$ and 10 fm/c, respectively. The dotted curve is obtained from a phase diagram with a bag constant of 400 MeV/fm^3 and a mixed-phase lifetime of $\tau = 5$ fm/c.

cident energies below about 2 GeV/nucleon as the initial hadronic matter density increases as a result of higher compression. When the initial energy density is large enough so that a mixed phase of quark-gluon and hadronic matter is formed, the dilepton yield is seen to decrease as a function of the incident energy. Also shown in the figure by the dashed-dotted curve is the dilepton yield from assuming that the initial fireball is always in the hadronic phase. As in Fig. 2, the dilepton yield at a given incident energy is higher in the latter case than the case when either a mixed or a quark-gluon phase exists. Because of the short formation time of the initial fireball, it is likely that the system may be superheated and still stays in the hadronic phase even though its energy density is high enough to be in the mixed phase. We then expect that the steep rise of the dilepton excitation function would continue to higher incident energies. In either case, the onset of the formation of a quark-gluon plasma in the initial high-density matter is accompanied by a decrease in the total yield of the dilepton with invariant masses $2m_\pi < M < 1$ GeV.

These results are not qualitatively modified when a different phase diagram and hydrodynamical description are used. The short- and long-dashed curves, corresponding to lifetimes for the mixed phase $\tau = 2.5$ and 10 fm/c, respectively, still show the suppression of dileptons when a baryon-rich quark-gluon plasma is formed. The same is true as shown by the dotted curve if we use a phase diagram obtained with a larger bag constant of 400 MeV/fm^3, which leads to a critical energy density of ≈ 2 GeV/fm^3 for the formation of the quark-gluon plasma. Using a quadratic scaling *Ansatz* for the velocity profile in the hydrodynamical expansion leads to only minor changes in the dilepton excitation function. We therefore conclude that the suppression of dilepton yield due to the formation of a baryon-rich quark-gluon plasma remains under these variations of the model.

It is thus of great interest to perform experimental measurements of dilepton yield for various incident energies in order to find the onset of such a suppression of the dilepton yield so that we will be able to see at what incident energies a quark-gluon plasma is formed in the collision. Experiments carried out so far at LBL Bevalac[23] are very useful in verifying the effect of the softening of the pion spectrum in dense nuclear matter on dilepton production through $\pi\pi$ annihilations. Future experiments at the AGS for dilepton production will certainly be extremely interesting in searching for evidence for the formation of a baryon-rich quark-gluon plasma in the initial stage of the collision.

One of the authors (C.M.K.) is grateful to Joe Kapusta for helpful discussions. This work was supported in part by the National Science Foundation under Grant No. PHY-8608149 and the Robert A. Welch Foundation under Grant No. A-1110.

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[1]"Quark Matter '87," Proceedings of the Sixth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions [Z. Phys. C **38** (to be published)].

[2]*Proceedings of the Second Workshop on Experiments and Detectors for a Relativistic Heavy Ion Collider (RHIC)* (Lawrence Berkeley Laboratory Report No. LBL-24604, 1987).

[3]M. C. Chu and T. Matsui, Phys. Rev. D **37**, 1851 (1988).

[4]S. Gavin, M. Gyulassy, and A. D. Jackson, Phys. Lett. B **207**, 257 (1988).

[5]C. Gerschel and J. Hüfner, Phys. Lett. B **207**, 253 (1988).

[6]R. Vogt, M. Prakash, P. Koch, and T. H. Hansson, Phys. Lett. B **207**, 263 (1988).

[7]J. Stachel and P. Braun-Munzinger, in *Proceedings of the Texas A&M Symposium on Hot Nuclei, College Station, Texas, December 1987,* edited by S. Shlomo, R. P. Schmitt, and J. B. Natowitz (World Scientific, Singapore, 1988).

[8]P. Koch, B. Müller, and J. Rafelski, Phys. Rep. **142**, 167 (1986).

[9]S. Nagamiya, in Proceedings of the International Conference on Medium and High Energy Nuclear Physics, Taipei, Taiwan, May 1988, edited by W.-Y. Pauchy Hwang, Keh-Fei Liu, and Yiharn Tzeng (World Scientific, Singapore, to be published).

[10]C. M. Ko and L. H. Xia, Phys. Rev. C **37**, 179 (1988).

[11]C. M. Ko and L. H. Xia, in Ref. 9.

[12]S. A. Chin, Phys. Lett. **119B**, 51 (1982).

[13]K. Kajanti *et al.*, Phys. Rev. D **34**, 811 (1986).

[14]C. Gale and J. Kapusta, Phys. Rev. C **35**, 2107 (1987).

[15]L. H. Xia, C. M. Ko, L. Xiong, and J. Q. Wu, Nucl. Phys. **A485**, 721 (1988).

[16]T. S. Biró *et al.*, Phys. Rev. C **27**, 2695 (1983).

[17]N. K. Glendenning, Phys. Rev. C **37**, 2733 (1988).

[18]U. Heinz, K. S. Lee, and M. J. Rhoades-Brown, Phys. Rev. Lett. **58**, 2292 (1987).

[19]K. S. Lee, M. J. Rhoades-Brown, and U. Heinz, Phys. Lett. B **174**, 123 (1986).

[20]B. D. Serot and H. Uechi, Ann. Phys. (N.Y.) **179**, 272 (1987).

[21]H. W. Barz, B. L. Friman, J. Knoll, and H. Schulz, Nucl. Phys. **A484**, 661 (1988).

[22]T. S. Biró and J. Zimányi, Nucl. Phys. **A395**, 525 (1983).

[23]G. Roche *et al.*, Phys. Rev. Lett. **61**, 1069 (1988).