M_T Scaling in Dilepton Spectrum as a Signature for Quark-Gluon Plasma

M. Asakawa,[(a)] C. M. Ko,[(b)] and P. Lévai[(c)]
Cyclotron Institute and Physics Department, Texas A&M University, College Station, Texas 77843
(Received 27 April 1992)

In general, the spectrum of lepton pairs produced in nuclear reactions depends on both invariant mass and momentum. But under a few reasonable assumptions on the time evolution of the system, we show that once the quark-gluon plasma is created in ultrarelativistic heavy ion collisions, the observed dilepton spectrum between the ϕ and J/ψ peak becomes dependent essentially only on its transverse mass M_T and thus shows M_T scaling. This scaling will not be observed if the quark-gluon plasma is not created in collisions.

PACS numbers: 25.75.+r, 12.38.Mh, 24.85.+p

The Relativistic Heavy Ion Collider (RHIC) being built at the Brookhaven National Laboratory [1] offers the possibility to create in the laboratory the quark-gluon plasma that is believed to have existed in the first microsecond of the big bang. It is, however, nontrivial to verify the formation of the quark-gluon plasma in heavy ion collisions, as it is expected to be produced only in the initial stage of the collision while most particles detected in experiments are from the final hadronic matter. Many experimental observables have been suggested as possible signals for the deconfinement transition from hadrons to quarks and gluons in heavy ion collisions. Some of the proposed signatures are the J/ψ suppression [2], the ϕ enhancement [3], the strangeness enhancement [4], and photon [5] and dilepton production [6–14]. Among them, photons and dileptons are considered most promising because they do not suffer strong final-state interactions and are expected to retain therefore the information of the quark-gluon plasma. However, a recent calculation shows that for hadronic matter and the quark-gluon plasma having similar temperatures, the photon emission rates are comparable [15], and this makes photons a less viable signature for the quark-gluon plasma. For dileptons, the contribution from the quark-gluon plasma is expected to be important for invariant masses between ϕ and J/ψ, i.e., the continuum region. Above J/ψ the Drell-Yan process dominates while below ϕ the contribution from the hadronic phase is more important. The invariant mass spectrum of dileptons between ϕ and J/ψ is featureless, and it is thus unlikely that one can distinguish the origin of the dileptons simply from the shape of the invariant mass spectrum.

Siemens and Chin [11] recognized that the transverse momentum of dileptons could reflect the temperature of the system. They showed that if the quark-gluon plasma is produced, the ρ peak at large transverse momenta would disappear because dileptons with large transverse momenta are dominated by contributions from the quark-gluon plasma which has a higher temperature than the hadron phase. In their calculation, they neglected the transverse expansion. By carrying out a more realistic calculation, Kajantie *et al.* [12], however, showed that the ρ peak does not disappear even at large transverse momenta, as the transverse expansion in the hadron phase boosts the transverse momentum of dileptons. As a result dileptons with large transverse momenta are not dominated by those from the quark-gluon phase. These works are mainly concerned with the form of the ρ peak at certain transverse momenta. We shall consider a more global feature in the dilepton spectrum than Refs. [11] and [12] using a similar model as Ref. [12], and shall attempt to distinguish the origin of the dileptons in the continuum region. As shown in the following, comparing yields at different transverse momenta with the same transverse mass in the continuum region, it is still possible to find the signature for the quark-gluon plasma.

In principle, the dilepton spectrum from nuclear reactions depends on both the transverse momentum q_T and the transverse mass $M_T = \sqrt{M^2 + q_T^2}$, where M is the invariant mass of the pair. Under general conditions, however, it has been shown that the lepton pair spectrum depends only on the transverse mass [10, 16], i.e.,

$$\frac{dN}{dM_T^2\, dy\, dq_T^2} = F(M_T), \tag{1}$$

where y is the rapidity of the pair and the function F is only a function of M_T. In other words, at a fixed M_T, the differential yield does not depend on q_T. We note that in deriving the above results, the small lepton mass is neglected. The assumptions invoked in deriving the M_T scaling are (i) thermalization and the Boltzmann approximation ($M \gg T$), (ii) boost-invariant one-dimensional flow [17], and (iii) no other scales but T. This M_T scaling also holds if higher-order perturbative corrections in QCD are included as long as these assumptions are maintained [10, 16]. This is so because the M_T scaling is derived on the basis of the current conservation, which is not subject to the perturbative correction.

The condition (i) is plausible considering the recent estimate of the equilibration time, which is only 0.5–2 fm [18, 19]. Since the quark-gluon plasma formed in the initial stage of ultrarelativistic heavy ion collisions is not expected to have an appreciable transverse expansion and does not have other mass scales either, conditions (ii) and (iii) are also approximately satisfied, so the dilepton invariant mass spectrum from the quark-gluon plasma will show the M_T scaling. But this scaling is broken at the later stage of the time evolution when the transverse expansion becomes appreciable and extra mass scales appear in dilepton production from the hadronic matter because of the vector meson dominance.

We first discuss qualitatively how the transverse expansion affects dilepton production. In lowest order, dilepton production from a cylindrical boost-invariant system which undergoes the transverse expansion with the four-dimensional flow velocity,

$$u^\mu = (\cosh\zeta\cosh\eta,\ \sinh\zeta\cos\varphi,\ \sinh\zeta\sin\varphi,\ \cosh\zeta\sinh\eta), \tag{2}$$

is given by [12, 16]

$$\frac{dN}{dM_T^2\,dy\,dq_T^2} = \frac{5\alpha^2}{18\pi^2}\int f_q(\rho,\tau) I_0\left(\frac{q_T\sinh\zeta}{T}\right) K_0\left(\frac{M_T\cosh\zeta}{T}\right)\rho\tau\,d\rho\,d\tau + \frac{\alpha^2}{24\pi^2}F_\pi(M)\left(1-\frac{4m_\pi^2}{M^2}\right)^{3/2} \times \int f_h(\rho,\tau) I_0\left(\frac{q_T\sinh\zeta}{T}\right) K_0\left(\frac{M_T\cosh\zeta}{T}\right)\rho\tau\,d\rho\,d\tau, \tag{3}$$

where α is the fine structure constant of QED, ρ is the radial coordinate, τ the proper time, and η the coordinate space rapidity; ζ is a parameter which characterizes the transverse expansion and is related to the transverse velocity v_r by $v_r = \tanh\zeta$; $f_q(\rho,\tau)$ and $f_h(\rho,\tau)$ are the volume fraction of the quark-gluon phase and hadronic phase at (ρ,τ), respectively; $I_0(x)$ and $K_0(x)$ are the modified Bessel function of the first and second kind, respectively. In Eq. (3) we have included only the two massless u and d quarks in the quark-gluon phase and have assumed that the hadronic phase is a pionic gas. For dilepton production from the pion-pion annihilation, we include vector mesons $\rho(770)$, $\rho'(1450)$, and $\rho''(1700)$ [20]. The pion electromagnetic form factor $F_\pi(M)$ can thus be written as

$$F_\pi(M) = \sum_{\rho_i=\rho,\rho',\rho''} \frac{N_{\rho_i} m_{\rho_i}^4}{(m_{\rho_i}^2 - M^2)^2 + m_{\rho_i}^2\Gamma_{\rho_i}^2}, \tag{4}$$

where $\Gamma_\rho = 153$ MeV, $\Gamma_{\rho'} = 237$ MeV, and $\Gamma_{\rho''} = 235$ MeV; N_ρ, $N_{\rho'}$, and $N_{\rho''}$ have values 1, 8.02×10^{-3}, and 5.93×10^{-3}, respectively [21]. We note the difference between this form factor and the one in Ref. [22]. In our form factor, we have adequately taken into account the recent data for the mass, total width, and partial widths of $\rho'(1450)$ and $\rho''(1700)$.

In the case of vanishing transverse expansion ($\zeta = 0$), we easily see from Eq. (3) that the dilepton distribution from the quark-gluon plasma depends only on the transverse mass and thus shows M_T scaling.

For finite transverse expansion, i.e., for positive ζ, the dilepton distribution also depends on q_T through $I_0(x)$. Since $I_0(x)$ is positive definite and monotonously increasing for $x \geq 0$, the dilepton yield at a fixed M_T increases with q_T. Similarly, the M_T scaling is broken in the hadronic phase with finite transverse flow [23]. In the hadronic phase, the M_T scaling is further broken by the pion electromagnetic form factor $F_\pi(M)$. This is because $F_\pi(M)$ decreases monotonously above the $\rho''(1700)$ peak (practically above the ρ peak), so for invariant masses M in this region and at a fixed M_T, it increases with q_T. Consequently, the breaking of the M_T scaling by the transverse expansion in the dilepton spectra in the continuum region is further enhanced by the pion electromagnetic form factor. The pattern of the M_T-scaling breaking is thus unique in this region; i.e., the larger q_T is, the larger the yield at a fixed M_T.

To see whether the M_T scaling can be realized in ultrarelativistic heavy ion collisions, we have carried out the boost-invariant hydrodynamical calculations with transverse flow for a hot dense system that is expected to be formed in central collisions of ^{197}Au $+^{197}$Au at RHIC. This is done using the hydrodynamical code of Lévai and Müller [24]. We have taken the initial proper time $\tau_0 = 1$ fm, the critical temperature $T_c = 180$ MeV, and the freeze-out temperature $T_f = 120$ MeV. The initial temperature is varied to obtain different charge particle rapidity density dN_c/dy. This range of dN_c/dy in Figs. 1(a) and 1(b) corresponds to 130–410 MeV in the initial temperature.

In Fig. 1(a), we show by the solid curve the ratio R of $dN/dM_T^2\,dy\,dq_T^2$ for fixed $M_T = 2.6$ GeV at $q_T = 2$ GeV to that at $q_T = 0$ as a function of dN_c/dy. The initial radial velocity at the surface of the cylinder is chosen to be $v_0 = 0$. We have taken these values of q_T so that the corresponding values of M are in the continuum region [25]. If the M_T scaling is realized, this ratio should be 1. For low rapidity densities corresponding to initial temperatures below the critical temperature, the system starts in the hadronic phase and remains so during the expansion. In this case, the ratio R is about 30 and there is thus no M_T scaling. This M_T-scaling breaking is mainly due to the pion electromagnetic form factor, i.e., the existence of extra mass scales. The region of rapidity density between about 25 and 300 corresponds to the case in which the system is initially in the mixed phase. For higher rapidity densities, the initial tempera-

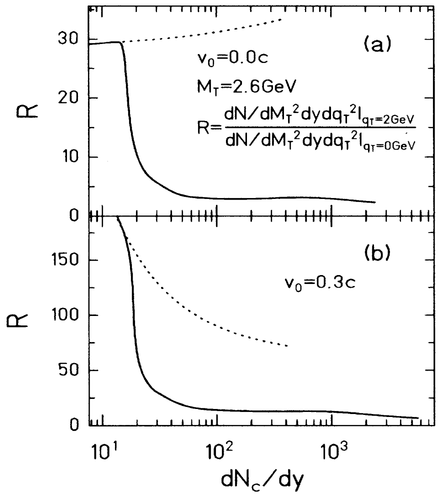

FIG. 1. (a) The ratio of the differential dilepton yield $dN/dM_T^2\,dy\,dq_T^2$ at $q_T = 2$ GeV to that at $q_T = 0$ in a central ^{197}Au$+^{197}$Au collision. Parameters are given in the text. The solid curve is the result with the initial state in the quark-gluon phase if the temperature is above the critical temperature while the dotted curve is obtained by assuming that the initial state is always in the hadronic phase. (b) Same as (a) except that v_0 is $0.3c$.

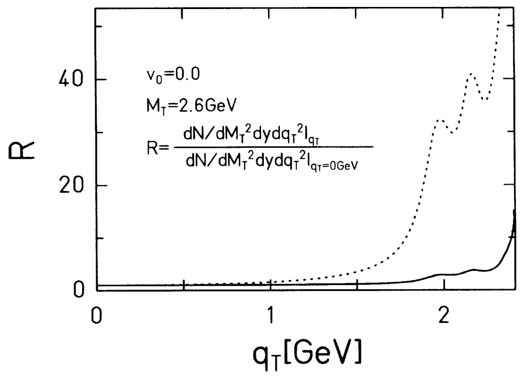

FIG. 2. The ratio of $dN/dM_T^2\,dy\,dq_T^2$ at $q_T \in [0,\ 2.4$ GeV] to that at $q_T = 0$. M_T and dN_c/dy are fixed at 2.6 GeV and 150, respectively. The definition of the solid and dotted curves is the same as in Fig. 1.

ture is above the critical temperature and the system is initially in the quark-gluon phase. We observe that even a small fraction of the quark-gluon phase decreases the ratio R dramatically, i.e., once the quark-gluon plasma is produced regardless of its initial fraction, the ratio R is about 3 and the M_T scaling is almost realized. If we assume that the initial state is in the hadronic phase even if the temperature is above the critical temperature, the ratio R is large as shown by the dotted curve, and the M_T scaling is badly violated. Even if we reduce the square of the sound velocity in the hadron phase from $0.33c^2$ to $0.15c^2$ to take account of interactions, the result remains similar. This is so because the M_T-scaling restoration is mostly due to the dominance of the leptons from the quark-gluon phase and has very little to do with the dynamics of the hadron phase. Therefore we believe that this phenomenon, the M_T-scaling restoration due to the quark-gluon plasma formation, is insensitive to the details of the equation of state and the phase transition.

To see the effect of finite initial radial velocity, we have repeated the calculation with $v_0 = 0.3c$ [26]. The results are shown in Fig. 1(b), and we find that its effect is appreciable, leading to an increase of the ratio R by an order of magnitude. So the M_T scaling is appreciably broken even if the initial state is in the quark-gluon phase. But if the observed value for the ratio R at $M_T = 2.6$ GeV is less than ~ 30, we may still conclude that the quark-gluon plasma has been formed in the initial stage of the collision. If v_0 is unrealistically large, then the M_T scaling will be highly broken even if the quark-gluon plasma has been created in the collisions. We have found that the smallest v_0 for which the ratio R exceeds ~ 30 is $v_0 \sim 0.4c$, which, however, seems unrealistically large to be realized in heavy ion collisions.

In Fig. 2 the ratio of $dN/dM_T^2\,dy\,dq_T^2$ at $q_T \in [0,\ 2.4$ GeV] to that at $q_T = 0$ is plotted with M_T and dN_c/dy fixed at 2.6 GeV and 150, respectively. The definition of the solid and dotted curves is the same as before. The small peaks are due to $\rho'(1450)$ and $\rho''(1700)$. We observe that at this M_T the optimal q_T to confirm the M_T scaling is around 2 GeV, where the ratio remains close to 1 if the quark-gluon plasma is formed while it takes quite a large value if the plasma is not created. The optimal q_T changes according to the value of M_T but is almost independent of dN_c/dy.

In the above considerations, we have not included the contribution from the Drell-Yan process. The result of the calculation including the perturbative and nonperturbative QCD effect seems to show that at a fixed y the dileptons from the Drell-Yan process also show approximately the M_T scaling. Strictly speaking, the M_T scaling thus differentiates only the degree of freedom. However, it is expected that at RHIC energy the contribution from the quark-gluon plasma overwhelms that from the Drell-Yan process at M smaller than about 2.4 GeV [27]. Therefore it would be significant to confirm the M_T scaling at several M_T smaller than this value. Since the Drell-Yan contribution has y dependence, it would be also possible to distinguish its contribution from the thermal contribution, which is independent of y in the boost-invariant scenario, by considering the y dependence of the dilepton yield if there is boost invariance. Furthermore, we can determine the Drell-Yan contribution in the continuum region by extrapolating from the measured data above the J/ψ peak. Then we can subtract its contribution from the total yield to obtain the dilepton yield from the quark-gluon plasma [28].

We have used the zero-temperature form factor for $F_\pi(M)$. This should be reasonable, as it has been shown recently that at zero baryon density hadrons are appreciably modified only near the critical temperature [29]. The effect of finite density is much larger but in the central rapidity region in RHIC experiments the baryon number density is expected to almost vanish.

We have seen that in the continuum region M_T scaling is broken by both the transverse flow and the pion electromagnetic form factor. Also we have observed that the effect from the latter is considerably large. Therefore, if the observed dilepton spectrum shows even approximate M_T scaling and the yield is considerably larger than that expected in the Drell-Yan process, then quark-gluon plasma formation can be unambiguously established. By carrying out the hydrodynamical calculations, we have found that if the quark-gluon plasma is created in ultrarelativistic heavy ion collisions, this M_T scaling will indeed be observed. In conclusion, the M_T scaling is a plausible signature for the formation of the quark-gluon plasma in ultrarelativistic heavy ion collisions. It will be useful to design detectors at RHIC with the capability of detecting dileptons with different transverse momenta for transverse masses between ϕ and J/ψ.

This work was supported in part by the National Science Foundation under Grants No. PHY-8907986 and No. PHY-9212209 and the Welch Foundation under Grant No. A-1110.

(a) Electronic address: yuki@comp.tamu.edu

(b) Electronic address: ko@comp.tamu.edu

(c) On leave from KFKI, Budapest, Hungary. Electronic address: levai@rmk520.rmki.kfki.hu

[1] S. Ozaki, Nucl. Phys. **A525**, 125c (1991).

[2] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).

[3] A. Shor, Phys. Rev. Lett. **54**, 1122 (1985).

[4] J. Rafelski and B. Müller, Phys. Rev. Lett. **48**, 1066 (1982).

[5] S. Raha and B. Sinha, Phys. Rev. Lett. **58**, 101 (1987).

[6] E. L. Feinberg, Nuovo Cimento **34A**, 391 (1976).

[7] E. V. Shuryak, Phys. Lett. **78B**, 150 (1978).

[8] G. Domokos and J. Goldman, Phys. Rev. D **23**, 203 (1981).

[9] R. Hwa and K. Kajantie, Phys. Rev. D **32**, 1109 (1985).

[10] L. D. McLerran and T. Toimela, Phys. Rev. D **31**, 545 (1985).

[11] P. Siemens and S. A. Chin, Phys. Rev. Lett. **55**, 1266 (1985).

[12] K. Kajantie, M. Kataja, L. McLerran, and P. V. Ruuskanen, Phys. Rev. D **34**, 811 (1986).

[13] C. M. Ko and L. H. Xia, Phys. Rev. Lett. **62**, 1595 (1989).

[14] M. Asakawa and T. Matsui, Phys. Rev. D **43**, 2871 (1991).

[15] J. Kapusta, P. Lichard, and D. Seibert, Phys. Rev. D **44**, 2774 (1991).

[16] M. Asakawa, Ph.D. thesis, University of Tokyo, 1990.

[17] J. D. Bjorken, Phys. Rev. D **27**, 140 (1983).

[18] E. Shuryak, Phys. Rev. Lett. **68**, 3270 (1992).

[19] K. Geiger and B. Müller, Nucl. Phys. **B369**, 600 (1992); K. Geiger, University of Minnesota report, 1992 (to be published).

[20] Particle Data Group, Phys. Rev. D **45**, S1 (1992).

[21] There is some ambiguity in $N_{\rho'}$ and $N_{\rho''}$ in Eq. (4) due to the lack of detailed information on $\rho''(1450)$ and $\rho''(1700)$. For more accurate determination of $N_{\rho'}$ and $N_{\rho''}$, further data are needed.

[22] K. Kajantie, J. Kapusta, L. McLerran, and A. Mekjian, Phys. Rev. D **34**, 2746 (1986).

[23] The phase space factor due to the pion mass is practically 1 and we shall neglect it in the following argument.

[24] P. Lévai and B. Müller, Phys. Rev. Lett. **67**, 1519 (1991).

[25] In Figs. 6–9 of Ref. [12], similar differential yields $dN/dM^2\,dy\,dq_T^2$ have been calculated, assuming quark-gluon plasma formation, as a function of M_T at M =0.3, 0.8, and 1.5 GeV to see the effect of the ρ peak on the dilepton spectrum. It is shown there that near the ρ peak dileptons from the hadron phase dominate, while the continuum region is dominated by those from the quark-gluon phase if it is created. No attempt to determine the origin of the dileptons in the featureless continuum region has been done in [12]. We, on the other hand, compare the differential yields at different q_T but with the same M_T in the continuum region in order to distinguish the origin of dileptons in this region. As is shown in the text, this comparison is remarkably effective for this purpose.

[26] This value is considerably larger than that from the naive estimate $v_0 \sim \tau_0/r_0$, where r_0 is the radius of the colliding nuclei. We carried out this calculation just to see the sensitivity of our results on v_0, and we do not consider this value a realistic one.

[27] P. V. Ruuskanen, Nucl. Phys. **A544**, 169c (1992).

[28] It is known that e^+ and e^- from the Dalitz decay of two uncorrelated π^0 and semileptonic decay of charmed mesons also contribute appreciably to the backgrounds. Studies to establish experimental cuts to reduce these backgrounds are in progress [for example, PHENIX Collaboration, "Preliminary Conceptual Design Report," 1992 (unpublished)].

[29] T. Hatsuda, in *Proceedings of the International Workshop on High Energy Nuclear Collisions and Quark-Gluon Plasma, Kyoto, Japan, 1991*, edited by M. Biyajima, H. Enyo, T. Kunihiro, and O. Miyamura (World Scientific, Singapore, 1991), p. 3.