Secondary phi meson peak as an indicator of a QCD phase transition in ultrarelativistic heavy-ion collisions

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In a previous paper, we have shown that a double phi peak structure appears in the dilepton invariant mass spectrum if a first order QCD phase transition occurs in ultrarelativistic heavy-ion collisions. Furthermore, the transition temperature can be determined from the transverse momentum distribution of the low mass phi peak. In this work, we extend the study to the case that a smooth crossover occurs in the quark-gluon plasma to the hadronic matter transition. We find that the double phi peak structure still exists in the dilepton spectrum and thus remains a viable signal for the formation of the quark-gluon plasma in ultrarelativistic heavy-ion collisions.

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In a previous paper [1], we have proposed that a double phi peak structure in the dilepton invariant mass spectrum from ultrarelativistic heavy-ion collisions can be used to confirm the phase transition from quark-gluon plasma to hadronic matter. Furthermore, the transverse momentum distribution of the low mass phi peak allows us to determine the transition temperature.

The low mass phi peak results from the decay of phi mesons with reduced in-medium masses during the transition. The reduction of the phi meson mass in hot hadronic matter is a result of the partial restoration of chiral symmetry [2–4]. In normal effective field theory, hadron masses do not decrease at finite temperature and/or density [5,6]. This result is, however, incomplete, because it neglects the modification of the vacuum due to medium effects. In QCD, the vacuum can be described in terms of expectation values of quark and gluon operators, i.e., condensates. The correlation function for current operators defined by quark fields can be calculated as a sum of condensates in the deep Euclidean region and can be identified as the hadron spectral function in the timelike region. Values of the correlation function in these two regions are related to each other through the dispersion relation. The behavior of condensates at finite temperature and/or density can be calculated with the appropriate approximation. Using these condensates on one side of the dispersion relation and the hadron spectrum function from an effective theory on the other side, it has been shown that hadron masses should decrease in the medium in order to satisfy the dispersion relation [7]. In effective field theory, the vacuum effect can also be included via nucleon-antinucleon polarization. Recent studies show that this indeed leads to a reduction of vector meson masses at finite temperature and/or density [8–11].

If a first order phase transition occurs between the quark-gluon plasma and the hadronic matter in heavy-ion collisions as assumed in Ref. [1], the system spends a relatively long time in the mixed phase (about 10–15 fm) during which the phi meson mass stays almost constant at a value different from that in free space. Since the duration of the mixed phase is not negligible compared to the lifetime of the phi meson in vacuum ($\sim$ 45 fm), a low mass phi peak besides the normal one thus appears in the dilepton spectrum. As the transverse flow during the mixed phase is not appreciable, the transverse momentum distribution of the low mass phi meson is largely determined by the temperature of the mixed phase and provides thus information on the transition temperature.

In the scenario described in Ref. [1], we have ignored the following effects: (i) the collisional broadening of the phi meson width due to its interaction with hadrons, (ii) the increase of the phi meson width in the mixed phase due to its interaction with partons in the quark-gluon phase, and (iii) the possibility of a smooth transition from quark-gluon plasma to hadronic matter instead of the mixed phase. If these effects are large, then the secondary phi peak proposed in Ref. [1] may not appear. Effects (i) and (ii) have recently been studied in Refs. [12] and [13], respectively. It has been found that the collision of the phi meson with hadrons increases its width to about 10 MeV while its interaction with partons adds another few MeV in the width. The resulting phi meson width remains small enough to make the secondary phi peak visible. In this paper, we shall study if the double phi peak structure is still present in the dilepton spectrum in the case of a smooth transition from quark-gluon plasma

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to hadronic matter.

According to recent lattice calculations [14], the QCD phase transition is a crossover but very close to the first order one. There exists a sudden change in the entropy density within a temperature interval of less than ~ 10 MeV [15]. To incorporate these features of the QCD phase transition, we parametrize the temperature dependence of the entropy density s of hot matter as follows:

$$s(T) = \frac{m s_h(T)\left[1-\tanh\left(\frac{T-T_c}{\Gamma}\right)\right] + n s_q(T)\left[1+\tanh\left(\frac{T-T_c}{\Gamma}\right)\right]}{m\left[1-\tanh\left(\frac{T-T_c}{\Gamma}\right)\right] + n\left[1+\tanh\left(\frac{T-T_c}{\Gamma}\right)\right]} = \frac{m s_h(T)\left[1-\tanh\left(\frac{T-T_c}{\Gamma}\right)\right] + n s_q(T)\left[1+\tanh\left(\frac{T-T_c}{\Gamma}\right)\right]}{(m+n)+(n-m)\tanh\left(\frac{T-T_c}{\Gamma}\right)}, \tag{1}$$

where $s_h(T) = 12aT^3$ and $s_q(T) = 148aT^3$ with $a = \pi^2/90$ are the bag model entropy densities with two flavors in the hadron and the quark phases, respectively; T_c is the critical temperature; m, n, and Γ are constants. The typical width of the phase transition is given by 2Γ with $\Gamma \sim 5$ MeV according to lattice calculations. For temperatures that satisfy $|T-T_c| \gg \Gamma$, the entropy density given by Eq. (1) approaches asymptotically to $s_h(T)$ and $s_q(T)$, respectively, for T below and above T_c. We have introduced m and n to include the possibility of an asymmetric phase transition. The case $m/n = 1$ corresponds to a symmetric phase transition. For $m/n > 1$, the transition is asymmetric, and the entropy density changes more in the quark phase than in the hadron phase.[1]

The pressure P and the energy density e can be straightforwardly evaluated from the entropy density. In this paper, we take the chemical potential to be zero, as we are interested in the central region of ultrarelativistic heavy-ion collisions, where the baryon density is expected to almost vanish. Then, the pressure and the energy density are given by

$$P(T) = \int_0^T s(t)dt,$$

$$e(T) = Ts(T) - P(T). \tag{2}$$

We note that only one of the three quantities s, P, and e is independent at fixed temperature T and chemical potential. In Figs. 1–3, we show s, P, and e by solid lines as functions of temperature. The parameters used in evaluating these quantities are $T_c = 180$ MeV, $\Gamma = 5$ MeV, and $m/n = 1$. The dashed lines show the equation of state obtained from the standard bag model.

In the following calculations, we use the same temperature dependence of the phi meson mass as in Ref. [1]. This is shown in Fig. 4. The decrease of the phi meson mass is mainly due to the presence of a considerable number of strange particles at high temperatures. The details can be found in Refs. [1, 16]. We note that the result shown in Fig. 4 has been calculated independently of T_c. As in Ref. [1], the rho meson mass is taken to have the temperature dependence

$$\frac{m_\rho(T)}{m_\rho(T=0)} = \left[1-\left(\frac{T}{T_c}\right)^2\right]^{1/6}, \tag{3}$$

and the omega meson mass is independent of temperature. The difference in the temperature dependence of vector meson masses is due to the difference in their isospin [17]. There are some ambiguities in the prediction of QCD sum rules on hadron masses in hot and dense matter. These are largely related to the temperature and/or density dependence of the four-quark condensate, which is usually evaluated using the factorization approximation. Although the four-quark condensate is important for rho and omega meson masses, it is, however, less important for the phi meson mass as a result of the large strange quark mass. Therefore, we expect that the phi meson mass at finite temperature and/or density calculated in QCD sum rules is more reliable than rho and omega meson masses. We would like to point out that the double phi peak structure in the dilepton spectrum depends more on the existence of the shift of the phi meson mass at finite temperature than the magnitude of

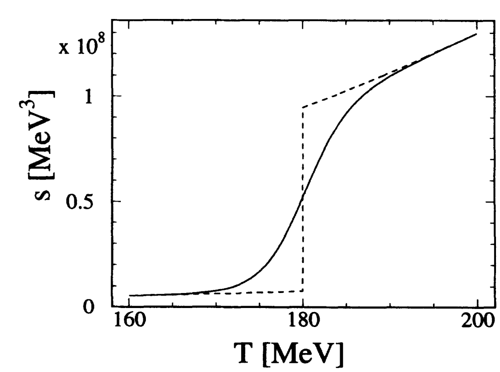

FIG. 1. Entropy density as a function of temperature. The number of flavors is taken to be 2 and T_c is 180 MeV. Solid and dashed lines correspond, respectively, to the crossover transition with $\Gamma = 5$ MeV and $m/n = 1$, and the first order phase transition with the bag model equation of state.

[1]Strictly speaking, if the phase transition is a crossover, the distinction between the hadron phase and the quark-gluon phase does not exist. Here we assume, however, that the system is in the quark-gluon phase if $T \geq T_c$ and the hadron phase if $T < T_c$.

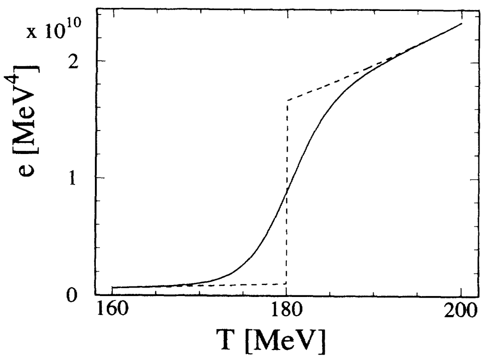

FIG. 2. Same as Fig. 1 for the energy density.

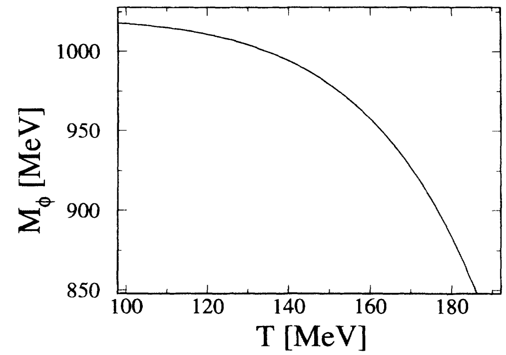

FIG. 4. Temperature-dependent phi meson mass in hot hadronic matter.

the shift.

We assume that in ultrarelativistic heavy-ion collisions the system has a cylindrical symmetry and is in thermal equilibrium. All formulas used in the following calculation are given in Ref. [1]. In particular, we include a normalized smearing function of Gaussian form for the phi meson mass in order to take into account the experimental mass resolution:

$$F_{\phi}(M, m_{\phi}(T)) = \frac{1}{\sigma\sqrt{2\pi}} e^{-[M-m_{\phi}(T)]^2/2\sigma^2}, \qquad (4)$$

where σ is a constant and is taken to be 10 MeV [18]. Since the collisional broadening of the phi meson is at most of the order of σ [12], we do not need to include it explicitly as it can be considered as included already in σ.

Assuming boost invariance, we have carried out a hydrodynamical calculation with transverse flow for a central collision of ^{197}Au $+^{197}$Au. We have modified the code of Ref. [19] to include the smooth quark-gluon plasma to hadronic transition. We have used the following values for the parameters [1, 20]: the initial proper time $\tau_0 =$ 1 fm and the initial radial velocity at the surface of the cylinder, $v_0 = 0$; the initial temperature $T_0 = 250$ MeV, the critical temperature $T_c = 180$ MeV and the freeze out temperature $T_f = 120$ MeV; one-half of the typical width of the crossover transition, $\Gamma = 5$ MeV, and the asymmetry factor of the crossover, $m/n = 1$. Unless specified otherwise, we use these default values in the calculation.

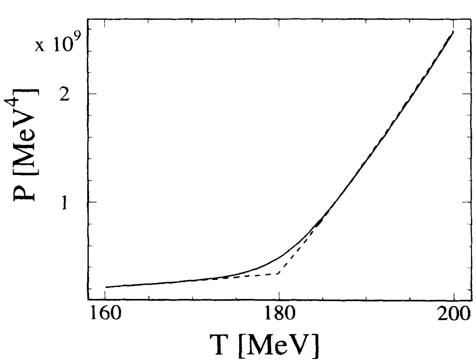

FIG. 3. Same as Fig. 1 for the pressure.

In addition, we have assumed that the volume fraction of the hadron phase is 1 and 0 at $T < T_c$ and $T \geq T_c$, respectively.

In Fig. 5, we show by the solid line the invariant mass distribution of lepton pairs $dN/dMdy$. We see that the second phi peak between the omega meson and the normal phi meson is still visible as in the case of a first order phase transition [1]. The low mass phi peak is, however, somewhat broadened as the temperature in the present case does not stay exactly at the same value during the transition. For comparison, we have also plotted in Fig. 5 the result for an asymmetric case by the dashed line. The asymmetric factor is chosen to be $m/n = 3$. In this case, the entropy density drops much more in the quark-gluon phase than in the hadron phase. This makes, however, practically no difference in the dilepton spectrum as the temperature stays near the critical temperature $T_c = 180$ MeV (dotted line in Fig. 6) for a relatively long time in both the symmetric and the asymmetric cases which are shown in Fig. 6 by the solid and the dashed lines, respectively. To understand this, we take the Bjorken scaling solution without transverse expansion and denote the critical entropy density as s_c, which is given by

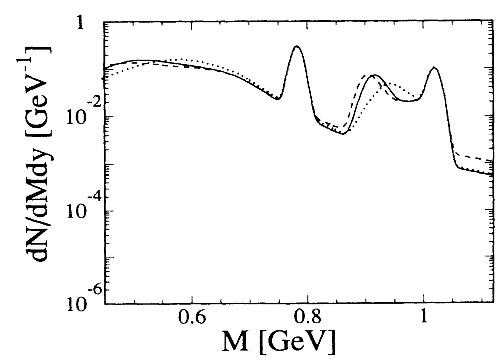

FIG. 5. Dilepton invariant mass spectrum at central rapidity. The solid curve is the result from the hydrodynamical calculations with the default parameter set. The dashed curve is obtained by changing the asymmetry factor of the phase transition m/n to 3 and the dotted curve by changing the width parameter of the transition Γ to 10 MeV.

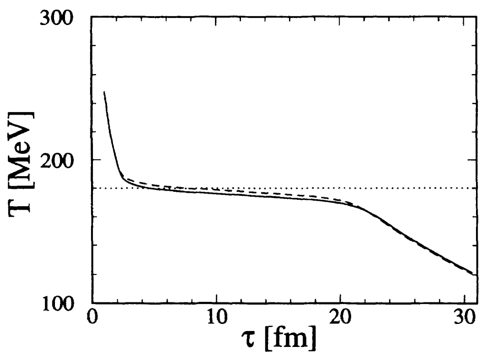

FIG. 6. Temperature as a function of proper time. The solid line corresponds to the case using the default parameters and the dashed line is obtained by changing m/n to 3. The dotted line is the critical temperature used in the calculation.

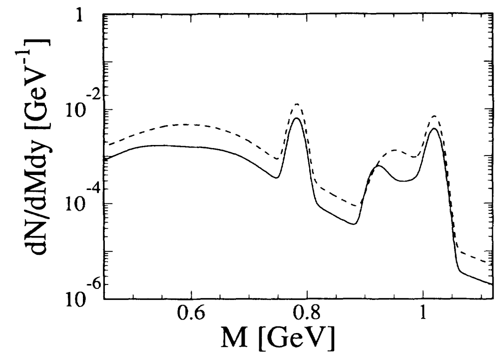

FIG. 7. Dilepton invariant mass spectrum at central rapidity. The default parameters are used except that the initial temperature is $T_0 = 175$ MeV for the solid line. For the dashed line, in addition, the width parameter of the transition Γ is changed to 10 MeV.

$$s_c = \frac{m s_h(T_c) + n s_q(T_c)}{m+n}. \tag{5}$$

The duration $\Delta\tau_c$ for which the temperature remains almost constant is then approximately given by

$$\Delta\tau_c = \frac{\tau_0 s_q(T_0)}{s_h(T_c)} - \frac{\tau_0 s_q(T_0)}{s_c} = \frac{\tau_0 s_q(T_0)}{s_h(T_c)} \frac{\frac{s_q(T_c)}{s_h(T_c)} - 1}{\frac{s_q(T_c)}{s_h(T_c)} + \frac{m}{n}}. \tag{6}$$

Since $s_q(T_c)/s_h(T_c)$ is very large ($= 37/3$), $\Delta\tau_c$ is barely affected by any reasonable change of the asymmetry factor.

In Fig. 5, we have also shown by the dotted line the case of a broader crossover with $\Gamma = 10$ MeV. The second peak is seen to be broader and closer to the normal phi peak. If the effective Γ becomes very large due to finite size effects in heavy-ion collisions, no separate second peak becomes visible as the temperature cannot stay at an almost constant value during the evolution of the system. We have found that the maximum Γ below which the second peak can be seen is around 20 MeV for the default parameter set. Since the width of the crossover is 2Γ, $\Gamma = 20$ MeV is already an extremely large value.

In Ref. [1], we have pointed out that for a first order phase transition the second phi peak does not appear if the initial temperature is less than the critical temperature. This is not the case for a smooth crossover as shown in Fig. 7 by the solid and dashed lines for $\Gamma = 5$ and 10 MeV, respectively. The initial temperature in these calculations is taken to be 175 MeV and is less than the critical temperature. The reason for this is that for the crossover transition the temperature does not stay exactly at T_c but around T_c, and so the second phi peak is expected to be visible if $T_c - T_0 \lesssim \Gamma$ is satisfied even if $T_0 < T_c$. The result of our numerical calculation supports this.

If the critical temperature is small, it is possible that the second phi peak may not be observed due to the small separation from the normal phi meson peak. In Fig. 8, we show by the solid line the result from the calculation with a lower critical temperature $T_c = 160$ MeV. The second peak is still visible. However, if the width parameter Γ of the crossover transition is larger, the second phi peak becomes broader and merges to the normal one. This is shown by the dashed line in Fig. 8 for a larger width parameter, $\Gamma = 10$ MeV, and the same critical temperature $T_c = 160$ MeV. We note that as in a first order transition our results do not change qualitatively for higher initial temperatures [21–23] as long as the critical temperature is kept the same [1].

In Ref. [1], we have also pointed out that the critical temperature for the QCD phase transition can be extracted reasonably accurately from the transverse momentum distribution of the low mass phi meson peak in the dilepton spectrum. A similar proposal to measure the phase transition temperature with the transverse momentum distribution of dileptons from rho mesons was proposed by Seibert [24]. The method with the phi meson, however, has several advantages over the latter one: (i) The second peak originates exclusively from the matter near the critical temperature, and so the signal to noise ratio is large. (ii) The transverse flow is still small

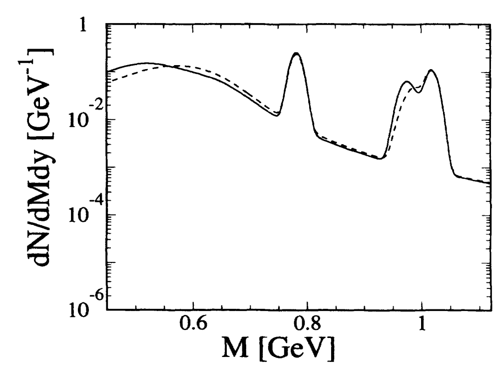

FIG. 8. Dilepton invariant mass spectrum at central rapidity. For the solid line, the default parameters are used except that the critical temperature is $T_c = 160$ MeV. For the dashed line, in addition, the width parameter of the transition Γ is changed to 10 MeV.

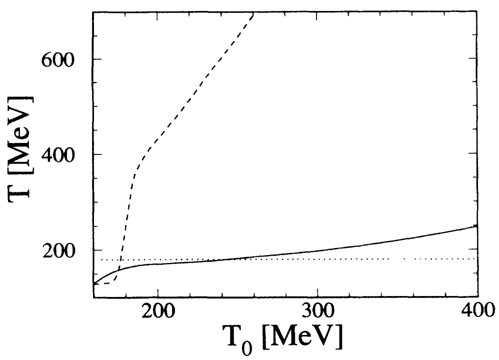

FIG. 9. The slope parameter of the phi meson transverse momentum distribution as a function of the initial temperature. Except for the initial temperature, the default parameters are used. Solid and dashed curves correspond to the low mass and the normal phi meson peaks, respectively. The dotted line is the critical temperature used in the calculation.

near the phase transition. Therefore, the transverse momentum distribution of the second peak reflects more faithfully the critical temperature. (iii) The phi peak is narrower than the rho peak, which makes the subtraction of backgrounds easier. We have repeated the same procedure as we did in Ref. [1] and have confirmed that the transition temperature can also be extracted from the low mass phi meson peak in the case of the crossover transition. In Fig. 9, we show the slope parameter of the dilepton distribution at small transverse momenta as a function of the initial temperature. The solid curve is the slope parameter of the low mass peak at about 916 MeV. It changes only slightly as the initial temperature increases. On the other hand, the slope parameter of the normal phi meson peak at 1019 MeV changes significantly as the initial temperature increases due to the resultant development of an appreciable transverse flow in the hadron phase. We note especially the sudden increase of the slope parameter of the normal phi meson peak in the region $T_c - \Gamma \lesssim T \lesssim T_c + \Gamma$, where the entropy density changes rapidly as the temperature increases.

In summary, due to the reduction of the phi meson mass in hot matter and the sudden change of the entropy density at the phase transition, a distinct low mass peak besides the normal one appears in the dilepton spectrum even if the quark-gluon plasma to hadronic matter transition in heavy-ion collisions is not first order. This concludes a series of investigations on the possibility of a double phi peak structure in the dilepton spectrum from ultrarelativistic heavy-ion collisions. With all factors which could potentially weaken the double phi peak structure ruled out, the low mass phi peak is thus a credible tool to verify the occurrence and to determine the critical temperature of the QCD phase transition in future ultrarelativistic heavy-ion experiments.

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