Seeing the QCD phase transition with phi mesons

M. Asakawa* † and C. M. Ko‡
Cyclotron Institute and Physics Department
Texas A&M University
College Station, Texas 77843

Abstract

A double phi peak structure in the dilepton invariant mass spectrum from ultrarelativistic heavy ion collisions is proposed as a signal for the phase transition from the quark-gluon plasma to the hadronic matter. The low mass phi peak results from the decay of phi mesons with reduced in-medium mass during the transition. Furthermore, the measurement of the transverse momentum distribution of these low mass phi mesons offers a viable means for determining the temperature of the phase transition.

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[*] Electronic address: yuki@nsdssd.lbl.gov

[†] Address after October 1, 1993: Lawrence Berkeley Laboratory, Nuclear Science Division, MS 70A-3307, 1 Cyclotron Road, Berkeley, CA 94720, U.S.A.

[‡] Electronic address: ko@comp.tamu.edu

Heavy-ion experiments offer the possibility to create in the laboratory the deconfined quark-gluon plasma. This allows us thus the opportunity to study both the properties of the quark-gluon plasma and the nature of its transition to the hadronic matter. Many experimental observables have been proposed as signatures for its existence [1]. Since the quark-gluon plasma exists only at the initial stage of heavy-ion collisions, electromagnetic probes such as lepton pairs and photons are therefore more suitable than hadronic probes as they are not affected by final-state interactions. Indeed, we have shown recently that the M_T scaling in the dilepton spectrum is a plausible signature for the quark-gluon plasma expected to be formed in future experiments at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) [2].

In the present paper, we would like to propose a signature for identifying the phase transition of the quark-gluon plasma to the hadronic matter in ultrarelativistic heavy ion collisions. In hot hadronic matter the phi meson mass is expected to decrease as a result of the partial restoration of chiral symmetry [3, 4, 5]. If a first-order phase transition between the quark-gluon plasma and the hadronic matter occurs in heavy ion collisions, then a low mass phi peak besides the normal one will appear in the dilepton spectrum. This is due to the nonnegligible duration time for the system to stay near the transition temperature (about 10 fm/c in boost invariant hydrodynamical calculations with transverse flow) compared with the lifetime of a phi meson in the vacuum (~ 45 fm), so the contribution to dileptons from phi meson decays in the mixed phase becomes comparable to that from phi meson decays at freezeout.

This scenario can be described more quantitatively. We first determine the phi meson mass at finite temperatures using the QCD sum rules [6], which relate via the dispersion relation the phi meson mass to the quark and gluon condensates in the matter. Following the treatment of Ref. [7], we include up to dimension 6 all scalar operators and tensor operators with twist 2. The temperature effect is then included via the change of the condensates. For example, the strange quark condensate at finite temperatures $\langle \bar{s}s \rangle_T$ is approximately related to its value at zero temperature $\langle \bar{s}s \rangle_0$,

$$\langle \bar{s}s \rangle_T \approx \langle \bar{s}s \rangle_0 + \sum_h \langle \bar{s}s \rangle_h \rho_h, \tag{1}$$

where $\langle \bar{s}s \rangle_h$ and ρ_h are, respectively, the strangeness content and density of hadron h. Assuming that all hadron densities are given by their equilibrium values, the resulting temperature dependence of the strangeness condensate can be calculated.

We show in Fig. 1 the temperature dependence of the phi meson mass at rest m_ϕ in a hot hadronic matter with zero baryon density. We see that the phi meson mass decreases at high temperatures. The decrease of phi meson mass is mainly due to the presence of strange particles, which have larger strangeness content than nonstrange particles, in the hot matter. Because of the relatively small number of strange particles in the hot matter, the reduction in phi meson mass is less than that for the rho meson. Studies based on QCD sum rules [8] show that the temperature dependence of the rho meson mass is approximately given by

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

where T_c is the critical temperature for the chiral restoration transition. Recent lattice calculations have shown that this temperature is similar to that for the quark-gluon plasma to hadronic matter transition [9]. However, the omega meson mass does not change much with the temperature as it has a different isospin structure from that of the rho meson [10]. We shall thus in the following assume that the omega meson mass is independent of the temperature. Details of the calculation for the temperature dependence of the phi meson mass will be reported elsewhere [11].

We note that calculations based on effective hadronic Lagrangians often give rather different behavior for the vector meson masses at finite temperatures [12, 13]. Also, some QCD sum rule studies [14] lead to results that are at variance with those of Refs. [7, 8]. However, recent lattice QCD calculations [15] show that both rho and phi masses are reduced at high temperatures. Our dropping phi meson mass at finite temperatures is thus likely to be correct.

To calculate the dilepton yield from the hot hadronic matter, we assume that in ultrarelativistic heavy ion collisions the system has a cylindrical symmetry and is in thermal equilibrium. At temperature T, the number of phi mesons that decay into lepton pairs per unit time and unit phase space is given by

$$dN_{\bar{\ell}\ell} = \frac{g_\phi}{(2\pi)^3}\cdot\frac{1}{\gamma_\phi}\cdot\Gamma_{\bar{\ell}\ell}(T)e^{-\frac{p\cdot u}{T}}d^4x d^3p, \tag{3}$$

where $g_\phi = 3$ is the degeneracy of the phi meson and u is the four-dimensional flow velocity. The temperature-dependent decay width of the phi meson into a lepton pair is denoted by $\Gamma_{\bar{\ell}\ell}(T)$ and is proportional to the phi meson mass. The effect of the Lorentz dilatation is taken into account through the Lorentz factor of the phi meson γ_ϕ. We note that in Eq. (3) we have used the Boltzmann distribution for phi mesons. Assuming boost-invariance, we can integrate Eq. (3) over the phase space and obtain

$$\frac{dN_{\bar{\ell}\ell}}{dMdy} = \frac{g_\phi}{\pi}\int f_h(\rho,\tau)\, T m_\phi^2(T)\Gamma_{\bar{\ell}\ell}(T)F_\phi(M, m_\phi(T))K_1\left(\frac{m_\phi(T)}{T}\right)\tau\rho d\tau d\rho, \tag{4}$$

where M and y are the invariant mass and rapidity of the lepton pair, respectively. In the above, we have denoted by τ the proper time, ρ the radial coordinate, K_1 the modified Bessel function of the second kind, and f_h the volume fraction of the hadron phase. In Eq. (4) there is no dependence on the transverse expansion as the effects of the Lorentz dilatation and Lorentz contraction cancel each other.

The total width of a phi meson in hot hadronic matter is expected to change as well. Shuryak *et al.* [16, 17] have found that if the phi meson mass is assumed to be unchanged at finite temperatures its width is then approximately doubled as a result of the attractive kaon potential. With the phi meson mass reduced to much below twice kaon mass at high temperatures as shown in Fig. 1, this effect will not be important in our studies. However, there will be a collisional broadening of the phi meson width due to its interaction with pions. Bi and Rafelski [18] have estimated that this would also double the phi meson width. A more detailed study of the phi meson width in a hot hadronic matter has been carried out in Ref. [19]. Taking into account the scattering of a phi meson with pions, kaons, rho mesons, and phi mesons in the matter, it is found that the width of a phi meson is less than 10 MeV at all temperatures. Also, the experimental mass resolution in future RHIC dilepton measurements is about $5 \sim 10$ MeV around the phi meson mass [20] and is comparable to the phi meson width discussed in the above, we have thus introduced in Eq. (4) a normalized smearing function $F_\phi(M, m_\phi(T))$ of the Gaussian form

$$F_\phi(M, m_\phi(T)) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(M-m_\phi(T))^2/2\sigma^2}, \tag{5}$$

where σ is a constant and is taken to be $\sigma = 10\,\mathrm{MeV}$.

We also include dileptons from phi meson decays at freezeout. For a transversely uniform system with a freezeout hypersurface $\tau = \tau_f$, this contribution is given by

$$\frac{dN_{\bar{\ell}\ell}}{dMdy} = \frac{g_\phi}{2\pi} r_f^2 \tau_f T_f m_\phi^2 B_{\bar{\ell}\ell} F_\phi(M, m_\phi) K_2\left(\frac{m_\phi}{T_f}\right), \tag{6}$$

where r_f is the radius of the system at freezeout, $B_{\bar{\ell}\ell}$ is the branching ratio of a phi meson decaying into a lepton pair, and K_2 is the modified Bessel function of the second kind. The phi meson mass at freezeout m_ϕ is taken to be its free mass.

The contribution to dileptons from omega mesons in both the hot phase and at freezeout can be similarly evaluated. On the other hand, we include the rho meson contribution to dileptons via the pion-pion annihilation. This should be similar to treating directly the rho decay into dilepton.

Using the hydrodynamical code of Ref. [21], we have carried out a boost-invariant hydrodynamical calculation with transverse flow for a hot system that is expected to be formed in the central collisions of $^{197}\mathrm{Au} + ^{197}\mathrm{Au}$ at RHIC and LHC. For the equation of state, we take both the quark-gluon plasma and the pionic matter as free gases. The phase transition between the two phases is then of the first order. The initial radial velocity at the surface of the cylinder is chosen to be $v_0 = 0$. The critical temperature $T_c = 180$ MeV and the freezeout temperature $T_f = 120$ MeV are taken to be the same as in our previous work [2]. We include dilepton production from the phi and omega decays, the $\pi\pi$ annihilation, and the $q\bar{q}$ annihilation in the quark-gluon plasma. For dileptons from the $\pi\pi$ and $q\bar{q}$ annihilations, we do not introduce the smearing function as the yield does not change much within the experimental resolution.

In Fig. 2 the dilepton spectrum in the rho, omega, and phi region is shown by the solid curve for the standard initial temperature $T_i = 250\,\mathrm{MeV}$ and initial proper time $\tau_0 = 1\,\mathrm{fm}$. We indeed see a second phi peak around 880 MeV between the omega meson and the normal phi meson. We note that it is exclusively from phi meson decays in the mixed phase. Due to its temperature-dependent mass, the rho meson peak not only shifts to lower masses but is also much broadened. Also shown in Fig. 2 by the dotted curve is the result from the hadronic scenario in which the initial state is taken to be a hot hadronic matter at a temperature just below T_c. In this case, the dropping phi meson mass only leads to a slight enhancement of the low mass side of the phi meson peak. Because of the shorter lifetime of the hot phase in the hadronic scenario, the dilepton yield is also seen to be substantially reduced.

Our results remain essentially unchanged if we use the same critical temperature $T_c =$ 180 MeV but different initial temperatures. In particular, we still see a double phi peak structure using an initial temperature of 450 MeV as in the hot glue scenario that has been suggested by recent studies based on parton scatterings [22, 23, 24].

Since the transverse expansion velocity during the mixed phase is relatively small, the low mass phi mesons should also provide information about the critical temperature of the phase transition. This temperature can be extracted from the transverse momentum distribution of phi mesons corresponding to the low mass peak. In Fig. 3, we show the slope parameter of the dilepton distribution at small transverse momenta as a function of the initial temperature. The initial proper time is taken to be $\tau_0 =$ 1 fm, independent of the initial temperature. The solid curve is the slope parameter of the low mass peak at about 880 MeV. It depends weakly on the initial temperature and is close to the critical temperature T_c assumed in our study and shown by the dashed line. The dotted curve is the slope parameter of the normal phi meson peak at 1019 MeV. It is much larger than the slope parameter of the low mass peak and increases with the initial temperature as a result of the appreciable transverse flow at freezeout.

The determination of the critical temperature for the quark-gluon plasma to hadronic matter transition from the transverse momentum distribution of the rho meson has been proposed by Seibert [25]. As dileptons from rho meson decays during the expansion of the hadronic matter are not negligible, its slope parameter does not give as accurate a measurement of the transition temperature as the low mass phi mesons proposed in the present study.

In our study, we have assumed that the rho meson mass vanishes at the critical temperature as shown in Eq. (2), and there is thus no dileptons from rho decays in the mixed phase. If the rho meson mass remains finite at this temperature, then there will also be a low mass rho peak in the dilepton spectrum. However, to observe it will be difficult as its invariant mass is quite low and there is also a large dilepton background from the Dalitz decays.

The double peak structure has also been suggested in the literature for the J/ψ due to possible changes of the string tension in hot matter [26]. However, this turns out not to be the case as already pointed out in Ref. [27]. Since the lifetime of J/ψ is much longer than the duration time of the hot phase expected in ultrarelativistic heavy ion collisions, only a negligible number of J/ψ decay in the hot phase and the low mass J/ψ peak can thus not be seen.

In our calculation, we have used the normal Maxwell construction to determine the volume fraction of the quark-gluon plasma and the hadronic matter in the mixed phase. Including the effect of supercooling [28] would increase the duration time of the mixed phase and make the double peak structure of the phi meson more prominent.

On the other hand, the second low mass peak may become less visible because of the following reasons. 1) If the largest fraction of the drop in entropy density in a first-order phase transition occurs already above T_c, where the system is still deconfined and no bound phi state exists, so the mixed phase lives much shorter. 2) The phi meson width in the mixed phase may be broadened by its interactions with partons in the quark-gluon plasma. 3) If the phase transition between the quark-gluon plasma and the hadronic matter is not of the first order as assumed in the above calculation but is of a second order or a crossover. To make definite statements in these cases requires, however, further detailed studies.

In conclusion, we have shown that the recent predictions from the QCD sum rules on the change of meson masses in hot hadronic matter have dramatic effects on the dilepton invariant mass spectrum from ultrarelativistic heavy ion collisions. Due to the dropping phi meson mass in a hot matter, a distinct low mass peak besides the normal one appears in the dilepton spectrum if the quark-gluon plasma to hadronic matter phase transition in heavy ion collisions is a strong first-order one. This low mass phi meson peak is thus a viable signal for the phase transition from the quark-gluon plasma to the hadronic matter. Furthermore, the measurement of the transverse momentum distribution of these low mass phi mesons also allows us to determine the transition temperature between these two phases of matter.

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Figure Captions

Fig. 1 The temperature-dependent phi meson mass in a hot hadronic matter.

Fig. 2 The dilepton invariant mass spectrum at the central rapidity. The solid curve is the result from the hydrodynamical calculations with the initial temperature $T_i = 250$ MeV and proper time $\tau_0 = 1$ fm. The dotted curve is obtained from the hadronic scenario assuming that the initial phase is a hadronic matter.

Fig. 3 The slope parameter of the phi meson transverse momentum distribution as a function of the initial temperature. Solid and dotted curves correspond to the low mass peak and the normal peak, respectively. The dashed line is the critical temperature for the quark-gluon to hadronic matter transition.