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What can we learn from a second phi meson peak in ultrarelativistic nuclear collisions?

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The decay width of a phi meson is reduced from its vacuum value as its mass decreases in hot hadronic matter as a result of the partial restoration of chiral symmetry. This reduction is, however, cancelled by collisional broadening through the reactions $\phi\pi \rightarrow KK^*$, $\phi K \rightarrow \phi K$, $\phi\rho \rightarrow KK$, and $\phi\phi \rightarrow KK$. The resulting phi meson width in hot hadronic matter is found to be less than about 10 MeV for temperatures below 200 MeV. If hadronic matter has a strong first-order phase transition, this narrow phi meson with reduced mass will appear as a second peak in the dilepton spectrum in ultrarelativistic heavy-ion collisions. We discuss use of this second phi peak to determine the transition temperature and the lifetime of the two-phase coexistence region in the case of a strong first-order phase transition. We also discuss using the peak to determine the range of temperatures over which the transition occurs in the case of a smooth but fast change in the entropy density.

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I. INTRODUCTION

Recently, the study of vector meson properties in hot and dense matter has attracted much attention [1]. Asakawa and Ko have shown via the QCD sum rules that the phi meson mass decreases in hot hadronic matter because of the appreciable number of strange particles [2]. The phi meson mass is found to drop below twice the free kaon mass when the temperature is above about 150 MeV, as shown in Fig. 1. This finding is supported by preliminary results from lattice gauge calculations [3]. Since the kaon mass does not change much with temperature, the phi meson can only decay into a pion and a rho meson. Even including the decrease of the rho meson mass at finite temperatures, the decay width of a phi meson is substantially reduced from its width ($\sim$ 4 MeV) in free space.

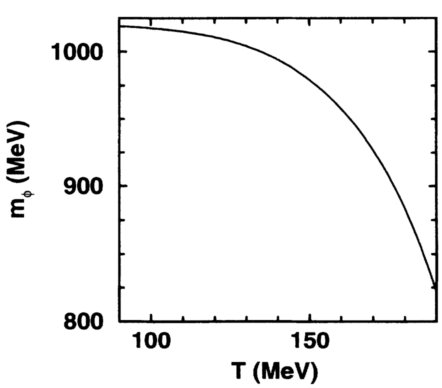

FIG. 1. The phi meson mass in hot hadronic matter from QCD sum rules [2].

Asakawa and Ko used this decrease of the phi meson mass to suggest a new signature for the quark-gluon plasma (QGP) to hadronic matter transition in ultrarelativistic heavy-ion collisions [4]. Specifically, it was shown that if there is a strong first-order phase transition between QGP and hadronic matter, then a double phi peak structure appears in the dilepton invariant mass spectrum. The low mass phi peak results from the decay of phi mesons with reduced in-medium mass in the mixed phase. Furthermore, they pointed out that due to the small transverse expansion of the matter during the phase transition, the transverse momentum distribution of these low mass phi mesons offers a viable means for determining the transition temperature.

In the above study, the change of the phi meson width in the medium is, however, not included. Shuryak and collaborators [5,6] 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 two kaon masses at high temperatures, this effect will not be important in our studies. However, there will be collisional broadening of the phi meson width due to its interaction with pions. Bi and Rafelski [7] estimated that this would also double the phi meson width. In this paper, we investigate explicitly the collisional broadening of the phi meson width using the in-medium mass in hot hadronic matter. We then discuss the use of this secondary phi peak in studying the physics of ultrarelativistic nuclear collisions.

II. THE PHI MESON WIDTH

The interaction of a phi meson in hot baryon-free hadronic matter is mainly through the reactions $\phi\pi \rightarrow$

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KK^*, $\phi K \to \phi K$, $\phi\rho \to KK$, and $\phi\phi \to KK$ shown in Fig. 2. The interaction Lagrangians needed to evaluate these diagrams are given by [8, 9]

$$L_{\phi KK} = ig_{\phi KK}[\bar{K}(\partial_\mu K) - (\partial_\mu \bar{K})K]\phi^\mu, \tag{1}$$

$$L_{K^*K\pi} = ig_{K^*K\pi}\bar{K}^{*\mu}\vec{\tau}\cdot[K(\partial_\mu\vec{\pi}) - (\partial_\mu K)\vec{\pi}] + \text{H.c.}, \tag{2}$$

$$L_{\rho KK} = ig_{\rho KK}[\bar{K}\vec{\tau}(\partial_\mu K) - (\partial_\mu \bar{K})\vec{\tau}K]\cdot\vec{\rho}^\mu. \tag{3}$$

The coupling constants $g_{\phi KK}$ and $g_{K^*K\pi}$ can be determined from the ϕ and K^* widths, i.e.,

$$\Gamma_\phi = \frac{g^2_{\phi KK}}{24\pi}\frac{(m^2_\phi - 4m^2_K)^{3/2}}{m^2_\phi}, \tag{4}$$

$$\Gamma_{K^*} = \frac{g^2_{K^*K\pi}}{16\pi}\frac{\{[m^2_{K^*} - (m_K + m_\pi)^2][m^2_{K^*} - (m_K - m_\pi)^2]\}^{3/2}}{m^5_{K^*}}. \tag{5}$$

Using the measured widths $\Gamma_\phi \sim 3.7$ MeV and $\Gamma_{K^*} \sim 51.3$ MeV for the decays $\phi \to \bar{K}K$ and $K^{*+} \to K^+\pi^0$, we obtain $g^2_{\phi KK}/(4\pi) \sim 1.82$ and $g^2_{K^*K\pi}/(4\pi) \sim 0.86$.

The ρKK coupling is one-half of the $\rho\pi\pi$ coupling according to the quark model [10]. From the width of the rho meson,

$$\Gamma_\rho = \frac{g^2_{\rho\pi\pi}}{48\pi}\frac{(m^2_\rho - 4m^2_\pi)^{3/2}}{m^2_\rho} \sim 153\,\text{MeV}, \tag{6}$$

one obtains $g^2_{\rho\pi\pi}/(4\pi) \sim 2.94$ which leads to $g^2_{\rho KK}/(4\pi) \sim 0.735$.

Averaging the square of the invariant scattering matrix over initial (and summing over final) isospins and polarizations, we obtain for the reaction $\phi\pi \to KK^*$,

$$\begin{aligned}\overline{M^2}(\phi\pi \to KK^*) &= \frac{4g^2_{\phi KK}g^2_{K^*K\pi}}{3(t - m^2_K)^2}\left[m^2_\phi - 2m^2_K - 2t + \frac{(m^2_K - t)^2}{m^2_\phi}\right] \\ &\quad\times\left[m^2_{K^*} - 2m^2_\pi - 2t + \frac{(m^2_\pi - t)^2}{m^2_{K^*}}\right].\end{aligned} \tag{7}$$

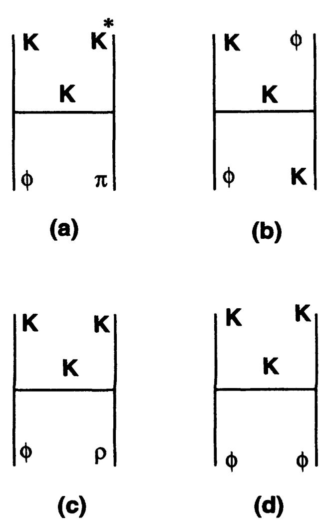

FIG. 2. Feynman diagrams for the reactions (a) $\phi\pi \to KK^*$, (b) $\phi K \to \phi K$, (c) $\phi\rho \to KK$, and (d) $\phi\phi \to KK$.

In the above, the four-momentum transfer t is given by

$$t = m^2_\phi + m^2_K - 2(m^2_\phi + p^2)^{1/2}(m^2_K + p'^2)^{1/2} + 2pp'\cos\theta, \tag{8}$$

where θ is the scattering angle in the center-of-momentum (c.m.) frame, and the initial and final c.m. momenta are given by

$$p, p' = \sqrt{[s - (m_1 + m_2)^2][s - (m_1 - m_2)^2]/(4s)}. \tag{9}$$

Here s is the square of the c.m. energy of the two interacting particles with masses m_1 and m_2.

The exchanged kaon in $\phi\pi \to KK^*$ can be on mass shell if the phi meson mass is greater than twice the kaon mass. In this case, the invariant amplitude becomes singular. This singularity is, however, removed by the imaginary part of the kaon propagator in the hot matter. In Ref. [6], the imaginary part of the kaon potential in the medium has been evaluated and is shown to be about 10 MeV at temperature $T = 150$ MeV, increasing to about 30 MeV at $T = 200$ MeV. For simplicity, we take the width of a kaon to be $\Gamma_K \sim 20$ MeV and replace the square of the kaon propagator in Eq. (7) by $(t - m^2_K)^2 + (m_K\Gamma_K)^2$.

The averaged and summed squared invariant amplitude for the reaction $\phi K \to \phi K$ is

$$\overline{M^2}(\phi K \to \phi K) = \frac{g^4_{\phi KK}}{3(t - m^2_K)^2}\left[m^2_\phi - 2m^2_K - 2t + \frac{(m^2_K - t)^2}{m^2_\phi}\right]^2. \tag{10}$$

Here, t is defined as in Eq. (8) with the kaon mass replaced by the pion mass. For the reactions $\phi\rho \to KK$ and $\phi\phi \to KK$, the averaged and summed squared invariant amplitudes are given by

$$\overline{M^2}(\phi\rho \to KK) = \frac{4g_{\phi KK}^2 g_{\rho KK}^2}{9(t-m_K^2)^2}\left[m_\phi^2 - 2m_K^2 - 2t + \frac{(m_K^2-t)^2}{m_\phi^2}\right] \times \left[m_\rho^2 - 2m_K^2 - 2t + \frac{(m_K^2-t)^2}{m_\rho^2}\right], \quad (11)$$

$$\overline{M^2}(\phi\phi \to KK) = \frac{4g_{\phi KK}^4}{9(t-m_K^2)^2}\left[m_\phi^2 - 2m_K^2 - 2t + \frac{(m_K^2-t)^2}{m_\phi^2}\right]^2, \quad (12)$$

respectively. In all cases, the four-momentum transfer t is defined in accordance with the Feynman graphs of Fig. 2, and the initial and final c.m. momenta are given by Eq. (9) with the appropriate masses.

Using Boltzmann distributions for phi mesons and pions, the rate for the reaction $\phi\pi \to KK^*$ is

$$\Gamma = \frac{3T}{64\pi^3 m_\phi^2 K_2(m_\phi/T)} \int_{z_0}^{\infty} dz\, K_1(z)\, p p' \times \int_{-1}^{1} d\cos\theta \overline{M^2}(s, \cos\theta). \quad (13)$$

In the above, K_1 and K_2 are modified Bessel functions of the first and second kind, $s = (zT)^2$, and $z_0 = \max\{(m_\phi + m_\pi)/T, (m_K + m_{K^*})/T\}$. Including Bose enhancement factors should introduce corrections of order ten percent to this result. Similar equations can be obtained for the reactions $\phi K \to \phi K$, $\phi\rho \to KK$, and $\phi\phi \to KK$. The collisional width of the phi meson is then given by

$$\Gamma_\phi^{\rm coll}(T) = \Gamma_{\phi\pi\to KK^*} + \Gamma_{\phi K\to\phi K} + \Gamma_{\phi\rho\to KK} + \Gamma_{\phi\phi\to KK}. \quad (14)$$

The width of a phi meson for T = 90–190 MeV is shown in Fig. 3. We show here also the temperature dependence of the phi meson decay width into KK and $\rho\pi$, assuming that the masses of K, ρ, and π remain unchanged at finite temperatures. The partial collisional widths are shown as indicated in the figure, taking Γ_K = 20 MeV for all curves. We see that the broadening due to $\phi\pi \to KK^*$ is larger than that from $\phi K \to \phi K$, $\phi\rho \to KK$, and $\phi\phi \to KK$. The total width of the phi meson is shown by the solid curve and is less than 35 MeV for $T < 190$ MeV.

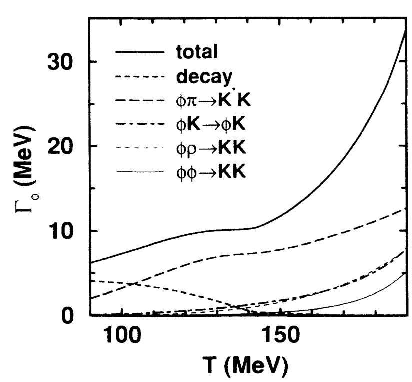

FIG. 3. The phi meson width in hot hadronic matter.

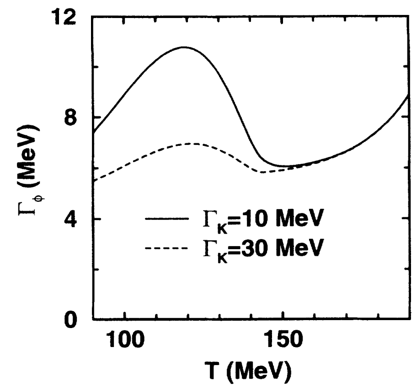

FIG. 4. The phi meson width in hot hadronic matter with vertex form factors (15).

The phi meson can also interact elastically with a pion through the rho meson exchange. The $\phi\rho\pi$ coupling constant is, however, an order of magnitude smaller than the ϕKK coupling constant, as shown by the smaller branching ratio for phi decay into pion and rho meson. As a result, the phi-pion elastic scattering, which is proportional to the fourth power of the $\phi\rho\pi$ coupling, has a very small cross section. The phi collisional width due to this reaction turns out to be only a few keV. The reactions $\phi\rho \to \phi\rho$, $\phi\phi \to \pi\pi$, and $\phi\phi \to \rho\rho$ are also proportional to the fourth power of the $\phi\rho\pi$ coupling and are expected to be insignificant as well. The reactions $\phi\pi \to \rho\rho$ and $\phi K \to \phi K^*$ involve the square of the $\phi\rho\pi$ coupling, so their contributions to the phi collisional width are also negligible.

To take into account the complicated structure of the strong interaction vertices, we introduce at the vertex a monopole form factor,

$$F(t) = \frac{\Lambda^2 - m_K^2}{\Lambda^2 - t}, \quad (15)$$

where Λ is the cutoff parameter whose value we take from Refs. [11] and [8], i.e., $\Lambda_{\phi KK} \sim \Lambda_{K^*K\pi} \sim \Lambda_{\rho KK} \sim 1.8$ GeV. We show the width with the form factor in Fig. 4, using Γ_K = 10 and 30 MeV; the dependence on Γ_K is clearly unimportant for T = 150–190 MeV. The total width at T = 190 MeV is reduced by approximately a factor of five with the form factor, so that the width is less than 10 MeV for T = 150–190 MeV.

III. EXTRACTING PHYSICAL PARAMETERS

As the secondary phi peak is narrow, there is a great possibility to extract information about the hadronic equation of state and the dynamics of ultrarelativistic nuclear collisions from its properties if the peak is experimentally observed. In this section, we discuss methods for determining the hadronic transition temperature, T_c

and the lifetime of the mixed phase, τ_m. If the transition is not first order, the range of temperatures over which the transition occurs, δT, may also be measurable.

The technique for determining T_c is discussed in Ref. [4]. This is similar to a proposal to use the transverse mass distribution of dileptons from ρ^0 mesons to measure T_c [12], but it has at least three advantages over that proposal. First, the second phi peak comes only from matter in the mixed phase (at T_c), so there is little contamination from phi mesons at temperatures below T_c. Second, the transverse flow is still small during the mixed phase period, giving less distortion of the transverse mass distribution from a stationary thermal distribution. Third, because the peak is narrower, subtractions from background will be easier as the background changes less from one side of the peak to the other.

The most serious disadvantage of the phi measurement is that if there is not a strong first-order transition, there may not be a secondary phi peak, so the phi measurement as proposed in Ref. [4] may be impossible. We find this not to be a problem as long as the transition is reasonably sharp. For example, suppose that the entropy density of the hot matter changes by a large factor over a small temperature range δT, centered on some transition temperature T_t. In this case, there will be a second phi peak, but it will be wider than a peak from fixed temperature hadronic matter. The width of the second peak will be

$$\Gamma^2 \simeq \Gamma^2(T_t) + \left(\delta T \frac{dm_\phi}{dT}\right)^2_{T_t} . \tag{16}$$

From Fig. 1, we estimate $dm_\phi/dT \simeq -3$ for $T = 150$–190 MeV, which is considered a likely range for T_t, so we would expect that $\Gamma \simeq 3\delta T$ from the width of the transition alone. Unless the transition occurs over $\delta T < 3$ MeV, the width of the second phi peak should be dominated by the contribution from δT. If this width is small enough, the peak will be observable; the exact width needed depends on experimental statistics and on the dilepton background which is not computed here. The only hard limit for observability is that Γ or $\Gamma_x < m_\phi(T_t) - m_x$ for all other nearby dilepton peaks x, so that the individual peaks can be separated. This condition should be satisfied as long as $\delta T < 20$–30, given the T dependence of m_ϕ from Ref. [4]. Thus, it seems that determination of T_t is feasible as long as there is a sharp transition, whether it is a first-order phase transition or not.

If the phi width is small throughout the collision, the second peak can also be used to determine the lifetime of the mixed phase, τ_m. The number of phi mesons in the secondary peak is

$$N_s = N_\phi \Gamma_{\phi\to l^+l^-} \tau_m/2, \tag{17}$$

where N_ϕ is the number of phi mesons that are created in the mixed phase. [The factor of two appears because we assume that the creation rate for phi mesons is approximately constant, so that the average phi meson is created halfway through the mixed phase lifetime.] If the width is small, then not many phi's will decay before the hadronic matter freezes out, so by detailed balance there must not be many phi's created after the phase transition, so N_ϕ is approximately equal to the total number of phi's created during the collision. Most of these phi's will have approximately their zero-temperature mass when they decay, so they will add to the original phi peak:

$$N_0 = N_\phi \Gamma_{\phi\to l^+l^-}/\Gamma_{\phi\to X}. \tag{18}$$

Combining Eqs. (17) and (18), we obtain

$$\tau_m = \frac{2N_s}{N_0 \Gamma_{\phi\to X}}. \tag{19}$$

Here we have assumed that $\Gamma_{\phi\to l^+l^-}$ and $\Gamma_{\phi\to X}$ are constant for illustrating the technique, but this could easily be relaxed if one wants to use more detailed models of ultrarelativistic nuclear collisions. In any case, we would expect that the ratio of the two peaks will provide a good measure of τ_m as long as $\Gamma_{\phi\to X}$ remains small. Note that the validity of this inference depends on the width of the phi at fixed temperature and not on the width of the second phi peak, so the technique may be valid even if a relatively wide second phi peak is observed as a result of a transition over a finite temperature range.

Finally, if the transition occurs over a range of temperatures δT, it may be possible to determine δT from Eq. (16), assuming that the phi width can be calculated accurately as a function of T. This is unlikely to be feasible if δT is small, but if the observed width is large then it might be possible to get a reasonably accurate estimate of δT. For example, if the observed width is three times the estimated thermal width then it should be possible to determine δT with 10% accuracy if the thermal width can be calculated to 50% accuracy.

IV. SUMMARY

We have evaluated the width of a phi meson in a hot hadronic matter. The reduction of the phi meson width due to the possible decrease of its mass at high temperature is found to be cancelled by the collisional broadening through the reactions $\phi\pi \to KK^*$, $\phi K \to \phi K$, $\phi\rho \to KK$, and $\phi\phi \to KK$. The resulting phi meson width at finite temperatures is not very much larger than its width in free space. The narrow phi meson width justifies the assumption of Ref. [4]. If there is a strong first-order phase transition between the quark-gluon plasma and the hadronic matter in ultrarelativistic heavy-ion collisions, then a low mass secondary phi peak is expected to be observed in the dilepton spectrum. This second peak allows us to infer the transition temperature and the lifetime of the mixed phase in the case of a first-order transition, and also the range of temperatures over which the transition takes place in the case of a smooth but fast transition.

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