Phi meson production in relativistic heavy ion collisions

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Within a multiphase transport model we study phi meson production in relativistic heavy ion collisions from both superposition of initial multiple proton-proton interactions and the secondary collisions in the produced hadronic matter. The yield of phi mesons is then reconstructed from their decaying product of either the kaon-antikaon pairs or the dimuon pairs. Since the kaon-antikaon pairs at midrapidity with low transverse momenta are predominantly rescattered or absorbed in the hadronic medium, they cannot be used to reconstruct the phi meson and lead thus to a smaller reconstructed phi meson yield than that reconstructed from the dimuon channel. With in-medium mass modifications of kaons and φ mesons, the φ yield from dimuons is further enhanced compared to that from the kaon-antikaon pairs. The model result is compared with the experimental data at the CERN/SPS and RHIC energies and its implications to quark-gluon plasma formation are discussed.

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I. INTRODUCTION

One of the major goals in relativistic heavy ion collisions is to study the properties of hot and dense matter and possibly to create and identify a new form of matter, the quark gluon plasma (QGP). It was suggested that enhanced strangeness production could serve as an important signal for the deconfined matter. The dominant production of s̅s̅ pairs via gluon-gluon interaction may lead to strangeness (chemical and flavor) equilibration times comparable to the lifetime of the plasma and much shorter than that of a thermally equilibrated hadronic fireball. The subsequent hadronization is then expected to result in an enhanced production of strange and multistrange particles and antiparticles. In particular, it has been argued that with the formation of quark-gluon plasma not only the production of phi mesons, which consist of s̅s̅, is enhanced but they also retain the information on the conditions of the hot plasma as it is believed that phi mesons interact weakly in the hadronic matter and therefore freeze out quite early from the system.

Using a proton or sulfur projectile at 200 GeV/nucleon and a tungsten or uranium target, phi meson production has been previously studied at CERN/SPS by the NA38 Collaboration and the HELIOS-3 Collaboration via the dimuon invariant mass spectra. The double ratio \( \frac{\phi}{(\omega + \rho^0)}_{SU(W)} \) has been measured and was found to have a value of 2 \( \sim \) 3. Various theoretical attempts have been made to understand this enhancement. In particular, an enhancement of phi meson yield may be a signature of the formation of a quark gluon plasma in the collisions. However, this enhancement can also be explained either using hadronic models if one takes into account the reduced phi meson mass in nuclear medium or via the fragmentation of color ropes that are formed from the initial strings.

Recently, phi meson production has also been measured in central Pb+Pb collisions at 158 A GeV at the CERN/SPS. The NA49 Collaboration has identified the phi meson via the decay channel \( \phi \rightarrow K^+K^- \), while the NA50 Collaboration measured it using \( \phi \rightarrow \mu^+\mu^- \) decay. It was found that the extracted number of phi mesons from dimuon channel exceeds by a factor between two and four from that extracted from the \( K^+K^- \) channel. This difference has been attributed to the fact that not all phi mesons can be reconstructed from \( K^+K^- \) resulting from their decays due to rescattering of the \( K^+ \) and \( K^- \) in the hadronic matter. The suppression factor can be 40-60% based on the RQMD model. This effect has been further studied in a schematic model by including the effect of changing kaon masses in the hadronic medium.

In the present paper, using a multiphase transport (AMPT) model we make a detailed and consistent study of the production of phi mesons reconstructed from the \( K^+K^- \) and \( \mu^+\mu^- \) decay channels. The effects of in-medium mass modification to the phi meson yield and spectra are also studied and are compared with the experimental findings by the NA49 and NA50 Collaborations at the SPS energies. We also present the phi meson yield and spectra at the RHIC energy of \( \sqrt{s} = 130 \) A GeV.

This paper is organized as follows. In Section I, we briefly review the AMPT model, discuss the phi meson production and interaction cross sections in hadronic matter as well as the medium effects on kaon and phi meson masses. The identification of phi mesons from both the dimuon and dikaon channels in the transport model is described in Section II. In section III, we show the results on phi mesons from heavy ion collisions at both SPS and RHIC. Finally, summary and conclusions are given in Section IV.
II. THE MODEL

A. A Multiphase transport model

To describe the heavy ion collision dynamics, we employ a multiphase transport model (AMPT) that includes both the initial partonic and final hadronic interactions. The AMPT model \[11\] is a hybrid model that uses as input the minijet partons from the hard processes and the strings from the soft processes in the HIJING model \[12\]. The dynamical evolution of partons are then modeled by the ZPC \[13\] parton cascade model, while the transition from the partonic matter to the hadronic matter is based on the Lund string fragmentation model \[14\]. The final-state hadronic scatterings are modeled by the ART model \[15\]. The AMPT model has been quite successful in describing the measured transverse momenta of pions and kaons, and the rapidity distributions of charge particles \[16\] as well as the particle to antiparticle ratios \[17\] in heavy ion collisions at both SPS and RHIC. Including melting of initial strings to partons, the model can also account for the observed large elliptic flow \[18\] and the measured two-pion correlation function \[21\] at RHIC. In the original AMPT model, phi mesons are produced only from initial string fragmentation. In the present work, we extend it to also include phi meson production and interactions in the hadronic matter.

B. phi meson production and interactions

For phi meson production from hadron scatterings in the ART model, we consider both the baryon-baryon interaction channels \(BB \rightarrow \phi N\) and the meson-baryon channels \((\pi, \rho)B \rightarrow \phi B\), where \(B \equiv N, \Delta, N^*\). The cross sections for these processes have been evaluated in the one-boson-exchange model \[21\] and are used here. We have also included phi meson production from the reaction \(K\Lambda \rightarrow \phi N\) with the cross section taken from Ref. \[5\] based on a kaon-exchange model.

Phi meson can be further produced from kaon-antikaon scattering. For a kaon-antikaon pair with invariant mass \(M\), the total cross section for \(KK \rightarrow \phi\) is taken to be a Breit-Wigner form

\[
\sigma_{KK \rightarrow \phi}(M) = \frac{3\pi}{k^2} \frac{(m_\phi \Gamma_\phi)^2}{(M^2 - m_\phi^2)^2 + (m_\phi \Gamma_\phi)^2},
\]

where the phi meson decay width to \(KK\) is given by

\[
\Gamma_{\phi \rightarrow KK}(M) = \frac{g^2_{\phi KK}}{4\pi} \frac{(m_\phi^2 - 4m_K^2)}{6m_\phi^2}^{3/2},
\]

with the coupling constant \(g^2_{\phi KK}/4\pi \approx 1.69\) determined from the empirical width of 3.7 MeV, corresponding to 83\% of the total width, at \(M = m_\phi\).

For phi meson interactions with baryons, we include the absorption reactions given by the inverse reactions of phi meson production from meson-baryon interactions given above. The corresponding cross sections are obtained using the detailed balance relations. The cross section for phi meson elastic scattering with a nucleon is taken to be 0.56 mb as extracted from the data on phi-meson photoproduction using the vector meson dominance model \[22\]. These cross sections are shown in the upper left panel of Fig. \[1\].

Phi mesons can also be scattered by mesons. Using effective hadronic Lagrangians, where coupling constants were determined from experimental partial decay rates, the total collisional width of \(\phi\) due to the reactions \(\phi\pi \rightarrow KK^*, \phi\rho \rightarrow KK, \phi K \rightarrow \phi K\) and \(\phi\phi \rightarrow KK\) was found to be less than 35 MeV \[23\] (where \(K\) denotes either a kaon or an antikaon as appropriate). However, recent calculations \[24\] based on a Hidden Local Symmetry Lagrangian shows that the collisional rates of \(\phi\) with pseudoscalar \((\pi, K)\) and vector \((\rho, \omega, K^*, \phi)\) mesons are appreciably large, especially for the \(K^*\), resulting in a much smaller mean free path, of about 2.4 fm in a hadronic matter at temperature \(T > 170\) MeV, compared to the typical hadronic system size of \(~ 10 - 15\) fm created in heavy ion collisions. We have included all these possible interactions, i.e., \(\phi M \rightarrow (K, K^*)(K, K^*)\), and \(\phi(K, K^*) \rightarrow M(K, K^*)\), where \(M \equiv (\pi, \rho, \omega)\) with cross sections determined from the partial collisional widths given in Ref. \[24\]. Specifically, we take matrix elements \(|M|^2\) of these reactions to be independent of the center-of-mass energy and extract their values from the collisional widths. The cross sections for these reactions are then given by \(d\sigma/d\Omega \sim |M|^2 k_f/(k_is^2)\), where \(s\) is the c.m. energy and \(k_i\) and \(k_f\) are, respectively, the initial and final c.m. momenta of the colliding hadrons. The cross sections for the inverse reactions of the above processes are then obtained from the detailed balance relations. In Fig. \[1\] we
show the cross sections for phi-pion and phi-rho scattering (upper right panel), phi-kaon scattering (lower left panel), and phi-$K^*$ scattering (lower right panel). The elastic cross section of phi meson with other mesons can be similarly obtained and is found to be about 2 mb.

FIG. 1. Phi meson scattering cross sections by nucleons (upper left panel), mesons (upper right panel), kaons (lower left panel), and $K^*$ (lower right panel).

C. Medium effects

Since the phi meson mass is only 32 MeV above the kaon-antikaon threshold, it is strongly coupled to the kaon and antikaon dynamics, i.e., to the strangeness content of the surrounding medium. A small change in the masses of either the phi meson or kaon thus would appreciably affect the decay width of phi meson.

Studies based on various approaches, such as the relativistic mean-field theory and the chiral effective Lagrangian, have led to a general consensus that $K^+$ feels a rather weak repulsive potential while the $K^−$ feels a relatively stronger attractive potential. With such modifications, the kaon yield and spectra could be successfully explained at SIS energies (1-2 GeV) and even at AGS energy (∼11 GeV). In the present study, we adopt the kaon and antikaon energies from chiral effective Lagrangian, i.e.,

$$\omega_{K,\bar{K}} = \left[ m_K^2 + k^2 - a_K \rho_s + (b_K \rho)^2 \right]^{1/2} ± b_K \rho ,$$

where $b_K = 3 f^2 / 8 \approx 0.333$ GeV fm$^3$, $a_K \approx 0.22$ GeV$^2$ fm$^3$ for kaons, and $a_{\bar{K}} \approx 0.45$ GeV$^2$ fm$^3$ for antikaons. The $K^+$ potential, defined by $U_K = \omega_K - \sqrt{m_K^2 + k^2}$ and given by the plus sign in Eq. (3), is then ∼ +20 MeV at normal nuclear density and is consistent with that determined from the impulsive approximation using the empirical kaon-nucleon scattering length. The $K^−$ potential, given by the minus sign in Eq. (3), at normal nuclear density is about −110 MeV and is somewhat less than that extracted from the kaonic atoms. The present set of parameters was found to reproduce well the $K^+$ and $K^−$ kinetic energy spectra and the ratio of their yields for heavy ion collisions at the SIS energy.
For the in-medium phi meson mass, the QCD sum rule studies show that it decreases slightly in hot dense matter \cite{34,35}. Using the result from Ref. \cite{34}, we have

$$m^*_\phi \approx 1 - 0.0255 \frac{\rho}{\rho_0},$$

where $\rho_0$ is the normal nuclear matter density.

The in-medium decay width of phi meson to kaon-antikaon pair is then given by

$$\Gamma^*_\phi \to K\bar{K}(M) = \frac{g^2_{\phi KK}}{4\pi} \frac{1}{6m^3_\phi} \left( \left( m^2_\phi - (m^*_K + m^*_\bar{K})^2 \right) \left( (m^2_\phi - (m^*_K - m^*_\bar{K})^2) \right) \right)^{3/2}.$$ \hspace{1cm} (5)

Although the phi meson mass decreases in the medium, the larger reduction of the overall kaon-antikaon mass with increasing density results in an increase of phi meson width $\Gamma^*_\phi \to K\bar{K}$ in the medium. At density $\rho = 2\rho_0$, the phi meson in-medium width is about 45 MeV.

### III. RECONSTRUCTION OF PHI MESONS

Since phi meson is unstable, it can only be detected from its decay product of either the kaon-antikaon pair or the lepton pair. The kaon-antikaon pair decaying from a phi meson is, however, likely to undergo appreciable rescattering in the medium, and this would lead to a reconstructed invariant mass situated outside the original phi meson peak. In fact, the momentum transfer to a kaon suffering one collision with a pion at $T = 150$ MeV can be estimated to be about 45 MeV which is much larger than the total phi meson width of $\Gamma_{\phi} = 4.45$ MeV. Hence phi mesons decaying in the dense medium is difficult to be identified via reconstructed kaon-antikaon pairs. In contrast, dileptons have negligible final-state interactions with the surrounding hadronic medium and therefore escape essentially unscathed during the entire evolution of the system. Dileptons are thus considered to carry useful information about hadron properties in hot and dense hadronic matter \cite{37}, which are expected to be different from those in free space.

#### A. dileptons

To detect a phi meson from its dimuon decay, we need the decay width for $\phi \to \mu^+\mu^-$ \cite{38}, which in the medium is

$$\Gamma^*_\phi \to \mu^+\mu^-(M) = C_{\mu^+\mu^-} \frac{m^{*4}_\phi}{M^2} \left( 1 - \frac{4m^2_\mu}{M^2} \right)^{1/2} \left( 1 + \frac{2m^2_\mu}{M^2} \right).$$ \hspace{1cm} (6)

The coefficient $C_{\mu^+\mu^-} \equiv \alpha^2/27(g^2_{\phi KK}/4\pi) = 1.634 \times 10^{-6}$ is determined from the measured width at $M = m_\phi$. Since dimuons are emitted continuously during the evolution of the system, the total number of dimuon is given by \cite{38}

$$N_{\mu^+\mu^-} = \int_0^{t_f} dt \ N_\phi(t) \Gamma^*_\phi \to \mu^+\mu^-(M) + N_\phi(t_f) \frac{\Gamma^*_\phi \to \mu^+\mu^-}{\Gamma_\phi},$$ \hspace{1cm} (7)

where $N_\phi(t)$ denotes the number of phi meson at time $t$. In the above, the first term corresponds to dimuon production before the freeze-out time of $t_f = 35$ fm/c considered in our calculation, while the second term refers to dimuon emission after freeze-out. The reconstructed phi meson number is obtained by dividing the above expression by the dimuon branching ratio in free-space of $\Gamma^*_\phi \to \mu^+\mu^- / \Gamma_{\phi} = 3.7 \times 10^{-4}$. Since most previous studies \cite{1,10} have neglected the phi meson annihilation and production channels via baryons and especially by pseudoscalar and vector mesons, the phi meson lifetime in these studies is thus comparable to the lifetime of the system. Consequently, phi mesons from dimuon channel get significant contributions only after freeze-out.

#### B. kaons

The number of kaon-antikaon pair stemming from phi meson decay can be similarly expressed as Eq. (5) for dimuon production, i.e.,
The phi meson abundance from kaon-antikaon decay is obtained by dividing Eq. (8) by the $K\bar{K}$ branching ratio in free-space $\Gamma_{\phi\rightarrow K\bar{K}}/\Gamma_\phi$. It is evident from Eqs. (3) and (8) that in absence of any medium effect on the masses and decay widths, i.e. for $\Gamma_{\phi\rightarrow K\bar{K}} = \Gamma_{\phi\rightarrow K\bar{K}}^*$ and $\Gamma_{\phi\rightarrow \mu^+\mu^-} = \Gamma_{\phi\rightarrow \mu^+\mu^-}^*$, the number of reconstructed phi meson from dimuon channel is same as that from the kaon-antikaon channel if all the kaon pairs escape the collision zone unscattered. On the other hand, with large in-medium phi meson width both the production and annihilation of phi meson from $\phi \leftrightarrow K\bar{K}$ is enhanced. If the production of phi meson dominates over its decay especially at the early dense stage of the collision, the dimuons originating from the phi meson decay will be enhanced. On the other hand, the kaon-antikaon pairs from phi meson decays will be essentially undetected in the phi meson reconstruction as they are expected to be rescattered and experience strong medium modifications of their masses.

IV. RESULTS

We have used the extended AMPT model described in the above to study phi meson production in heavy ion collisions at both SPS and RHIC energies.

A. SPS

1. time evolution

The time evolution of phi meson abundance at midrapidity for central Pb+Pb collisions at 158A GeV in the AMPT model is shown in the upper left panel of Fig. 2. The solid curves are the results from calculations where both kaon and phi meson medium effects are neglected. The minijet partons and predominantly string decays in the HIJING model at the SPS energy produces about 2.6 initial number of phi mesons per event. Since these phi mesons are produced at different times as a result of finite formation time, they appear successively in the ART hadronic transport. Subsequent multiple rescattering in the hadronic medium leads to a peak value of $N_\phi \approx 4.0$ at $t = 3\text{ fm}/c$, which finally decays to $\sim 2.3$ at an average freeze-out time of $t_f \approx 35\text{ fm}/c$. Because of small decay width of $\phi$ into $K\bar{K}$ pair, most of the phi mesons decay outside the fireball (see upper right panel of Fig. 2). In spite of this small width, the production of phi meson from the inverse reaction dominates over the decay due to considerable abundance of kaons from the HIJING model at the early stage of the reaction. At times $t > 15\text{ fm}/c$ the process $\phi \leftrightarrow K\bar{K}$ is seen to approach chemical equilibrium. Note that even at late times at around the freeze-out value there is a substantial phi meson production from the kaon-antikaon channel which has been neglected in the previous study [20].

Time evolution of the production and absorption rates of phi meson from different channels are shown in the lower panels of Fig. 2. Of all the collisional channels considered for the phi meson, the dominant ones are $\phi M \rightarrow (K, K^*)(K, K^*)$ and $\phi K^* \rightarrow M(K, K^*)$ ($M \equiv \pi, \rho, \omega$), which are of comparable magnitude. Although the cross section in the former reaction is smaller compared to that of $\phi - K^*$ (see Fig. 1), the larger abundance of pions relative to kaons ($K^+/\pi^+ = 0.12$ from the HIJING) leads to similar contribution to phi meson production in both these reactions. Moreover, the small abundance of phi meson results in identical production and annihilation rates for $\phi - M$ collision (lower left panel), i.e. chemical equilibrium in this reaction is rapidly achieved. In contrast, phi meson production overwhelms its destruction (lower right panel) due to larger abundances of the mesons $M(\equiv \pi, \rho, \omega)$ relative to $K$ and especially $K^*$. In particular, the process $MK^* \rightarrow \phi K^*$ with its largest cross section and smaller threshold contributes $\sim 80\%$ to the total $\phi + K^*$ formation. This enhanced production at about $3\text{ fm}/c$ is reflected in the rapid increase of the phi meson abundance (upper left panel). The production and annihilation rates for phi mesons in processes involving $K$ and $K^*$, which are not shown in the figure, exhibit similar qualitative features as for those with $K$ and $K^*$, but are about a factor of 1.5 smaller reflecting the $K/K^*$ ratio of 0.70 at the SPS energy. The phi meson collisional rate as observed here is considerably larger than that predicted in all previous calculations [23,29]. As the system expands the collisional rate drops and these reactions reach chemical equilibration at $t = 7\text{ fm}/c$. Finally, at a later time phi meson decay becomes more effective than its absorption. It may be noted that the initial dominance of phi meson production and its subsequent absorption as observed in the present transport calculation is different from the findings of Ref. [24], where $\phi$ mesons embedded in a gas of $(\pi, K, \rho, \omega, K^*)$ at chemical equilibrium, are found to decrease with evolution of the system.

The chemical equilibration of phi mesons via production and annihilation in the hadronic matter can be better seen by switching off the initial phi production from string decays in the HIJING model. As shown by the dash-dotted
FIG. 2. Upper left panel: Time evolution of midrapidity ($|y| < 0.5$) phi meson from Pb+Pb collisions at the SPS energy of 158A GeV at an impact parameter of $b \leq 3.5$ fm in the AMPT model. The results are for without (solid curve) and with (dashed curve) in-medium mass modifications, and with further increase of phi meson number by two in the HIJING model (dotted curve). The phi meson yield obtained from purely hadronic rescattering without any medium effects is shown by dash-dotted curve. Upper right panel: The phi meson production (solid curves) and decay rates (dashed curves) for the process $\phi \leftrightarrow K^+K^-$. The thin curves are without in-medium mass modification while the thick ones include medium mass modification. Lower panels: $\phi$ production (solid curves) and absorption rates (dashed curves) for different channels without any mass modifications; where $M \equiv \pi, \rho, \omega$.

curve in the upper left panel of Fig. 2, this leads to a suppressed peak in the time evolution of phi meson abundance but does not change much the phi meson number at later times, when compared to that in the case of including the initial phi mesons from string decays.

2. rapidity distribution

The rapidity distribution of phi mesons reconstructed from $K^+K^-$ and $\mu^+\mu^-$ channels in central Pb+Pb collision at 158A GeV is shown in Fig. 3. In absence of any medium effects, the results for phi mesons from the the $K^+K^-$ channel (thin solid curve) are in good agreement with the NA49 experimental data [7] (solid circles). With free-space decay width of phi meson, the rapidity distribution of all phi mesons from the $K^+K^-$, neglecting their scattering, is identical to that reconstructed from the $\mu^+\mu^-$ channel (thin dashed curve). Due to rescattering or absorption of the kaon pairs, $\sim 30\%$ of all $\phi$ mesons are lost in the reconstruction, of which about $40\%$ of the decaying kaons have at least one (anti)kaon that suffer elastic scattering. The maximum depletion of phi mesons from the $K^+K^-$ channel occurs at midrapidity where kaon-antikaon pairs undergo appreciable scattering in the dense hadronic medium. Note that around $y = 0$, phi meson from dimuon channel is about a factor 1.7 larger than from the kaon-antikaon channel, which is smaller than the factor of 2-4 enhancement observed in the NA50 data [8].
FIG. 3. Rapidity distribution of phi meson reconstructed from \( K^+ K^- \) pairs (solid curves) and from \( \mu^+ \mu^- \) channel (dashed curves) for Pb+Pb collisions at 158 A GeV at an impact parameter of \( b \leq 3.5 \) fm in the AMPT model. The results are for without (thin curves) and with (thick curves) in-medium mass modifications. The dotted curve corresponds to phi mesons from the dimuon channel with in-medium masses and with the phi meson number from HIJING increased by a factor of two. The solid circles are the NA49 experimental data [7] from the \( K^+ K^- \) channel.

3. transverse mass spectrum

In Fig. 4, we show the transverse mass spectra at midrapidity for phi meson from kaon-antikaon (solid squares) and dimuon (open squares) channel without medium effects. It is seen that at low \( m_T \) the phi meson from \( K^+ K^- \) channel is suppressed due to rescattering. Since the transverse momentum of a particle increases due to increasing number of scattering and due to pressure build-up inside the system, the decayed kaons at the early stages, which are predominantly scattered, thus have low transverse momenta. The transverse mass spectra can be approximately fitted by \( \exp(-m_T/T) \). The inverse slope parameter \( T \) reported by NA50 [8] from the \( \mu^+ \mu^- \) channel for \( 1.7 < m_T < 3.2 \) GeV/c\(^2 \) at midrapidity is \( T = 227 \pm 10 \) MeV, which agrees well with the AMPT model prediction of \( T = 228 \) MeV. In contrast, the slope parameter extracted by NA49 [7] from the \( K^+ K^- \) channel for \( 1 < m_T < 2.2 \) GeV/c\(^2 \) is \( T = 305 \pm 15 \) MeV. The depletion of reconstructed \( \phi \) at low \( m_T \) in the AMPT model leads only to a slightly higher slope of \( T = 267 \) MeV, and thus is much smaller than the NA49 data. The ratio of the yields at midrapidity, \( R(m_T) = N_{K^+ K^-}(\Gamma_{\phi \rightarrow KK})/N_{\mu^+ \mu^-}(\Gamma_{\phi \rightarrow \mu\mu}) \), from Eqs. (8) and (7) corrected by their respective branching ratios, is shown in the inset of Fig. 4. The maximum suppression of \( \sim 40\% \) at low \( m_T \) in the kaon channel as observed in the AMPT model (squares) is larger than the suppression factor of 60\% found in the RQMD calculation [9]. This can be traced back to enhanced phi meson production from large collisional scattering among the mesons leading to a peak in the \( \phi \) yield at the early stage (see Fig. 3, upper left panel). The dimuons from these phi mesons escape the fireball freely while the \( K^+ K^- \) are rescattered in the dense hadronic medium and do not contribute to the reconstruction of phi mesons.

4. In-medium effect

Modification of phi meson and kaon masses is expected to enhance the production and decay of phi meson in the medium and to lead to a possible further increase of the suppression factor \( R(m_T) \). The abundance of phi meson as a function of time of the colliding system with in-medium mass modification is shown in the upper left panel of Fig. 2 (dashed curve). The abundance exhibits 20\% increase at the peak, and it finally merges with the free-space value at large times when medium effects are negligible and chemical equilibrium in all channels sets in. This enhancement can be mainly attributed to the increase in the \( K^+ K^- \rightarrow \phi \) production rate due to larger width \( \Gamma_{\phi \rightarrow KK} \) in the dense medium, as shown by thick curves in the upper right panel of Fig. 2.
FIG. 4. Transverse mass spectra for midrapidity ($|y| < 1$) phi mesons reconstructed from $K^+K^-$ pairs (solid symbols) and from $\mu^+\mu^-$ channel (open symbols) for Pb+Pb collisions at 158A GeV at an impact parameter of $b \leq 3.5$ fm in the AMPT model. The results are for without (squares) and with (triangles) in-medium mass modifications. The solid circles are the NA49 data [7] for $\phi \rightarrow K^+K^-$ decay, and the open circles are the NA50 data [40] for $\phi \rightarrow \mu^+\mu^-$. In the inset is shown as a function of $m_T$ the ratio $R(m_T)$ for phi mesons decaying to kaon-antikaon pairs that are not scattered to those determined from the dimuon channel. The results are for without (squares) and with (triangles) in-medium mass modification, and with a further increase of phi meson number by two in the HIJING model (circles).

The rapidity distribution of $\phi$ from kaon pairs that have not suffered any collision is shown in Fig. 3 with in-medium masses (thick solid curve), which is found to lie within the error bars of the NA49 data. Since free-space branching ratio is used to determine the phi meson abundance from the kaon channel, it is evident from Eq. (8) that large in-medium width $\Gamma_{\phi \rightarrow K\bar{K}}^*$ leads to appreciable production and simultaneous decay of phi meson, resulting in $dN/dy \approx 7.1$ at $y \approx 0$ for all these kaon pairs. In contrast, since the branching ratio for $\phi \rightarrow \mu^+\mu^-$ is largely unaltered in the medium, the $dN/dy$ of the reconstructed phi mesons at $y \approx 0$ is 4.5 and thus about 1.9 times larger than that from the kaon channel.

The transverse mass spectra in the kaonic channel with medium effects (solid triangles in Fig. 4) reveals nearly identical slope as for the bare masses. On the other hand, the large number of dimuon production at low $m_T$ in the early stage of collisions with in-medium masses leads to a slightly steeper mass spectra with a slope parameter of $T = 220$ MeV. This is clearly seen in the inset of Fig. 4 (triangles) for the ratio $R(m_T)$ where the suppression at low $m_T$ is $\simeq 33\%$.

5. discussions

Our results on the phi meson yield reconstructed from kaon and dimuon channels differs at most by about a factor of two in the AMPT model, which corresponds only to the lower bound to the differences found in the NA49 and NA50 data. For a systematic comparison with theory it is instructive to undertake an experiment where both the kaon and muon pairs from phi mesons are determined in the same $m_T$ and $y$ range. If differences as large as a factor of four corresponding to the upper bound of the NA49 and NA50 data is indeed observed in the same experiment, this may then suggest that other mechanisms, such as formation of color rope [6] or quark-gluon plasma [2], are needed for phi meson production. In the QGP scenario, because of copious production of $s\bar{s}$ pair, its subsequent hadronization may result in a dramatic increase of phi meson abundance in excess of that produced purely by hadronic rescatterings [2]. The phi meson produced at the initial stage should contribute primarily to the dimuon channel. To mimic the effect of enhanced phi meson production in QGP, we make an ad hoc increase in the phi meson number by a factor of two in the HIJING model. The time evolution of $N_\phi$ is illustrated in Fig. 2 (dotted curve) where the phi meson yield, instead of exhibiting a peak, rapidly decreases to its equilibrium value which corroborates the findings of Ref. [2]. Including also the medium effect, the rapidity distribution from non-scattered kaon is increased by another $\sim 8\%$. 

8
whereas the yield from $\mu^+\mu^-$ channel is considerably enhanced (dotted curve in Fig. 3). The resulting suppression factor $R(m_T)$ at low $m_T$ is $\approx 21\%$ as is evident from the inset of Fig. 3 (circles).

The importance of initial phi mesons to the dimuon yield is also seen in the scenario of neglecting phi mesons from the initial string decays. In this case, we find that the phi number obtained from the $K^+K^-$ channel is essentially unaffected due to chemical equilibration via the hadronic scatterings, but the phi meson reconstructed from dimuons is, however, significantly suppressed.

B. RHIC

\[
\text{FIG. 5. The rapidity distribution (top panel) and the transverse mass spectra (bottom panel) for midrapidity (|y| < 0.5) phi mesons reconstructed from } K^+K^- \text{ pairs (solid curves) and from } \mu^+\mu^- \text{ channel (dashed curves) for Au+Au collisions at RHIC energy of } \sqrt{s} = 130A \text{ GeV at an impact parameter of } b \leq 5.3 \text{ fm in the AMPT model. The solid circles are the STAR experimental data} [41] \text{ for } 0 - 11\% \text{ central collisions for } \phi \text{ reconstructed from } K^+K^- \text{ decay.}
\]

In the AMPT model, heavy ion collisions at RHIC differ from that at SPS mainly in the increasing effect of minijet gluons. However, the initial heavy ion collision dynamics at RHIC remains dominated by soft string fragmentation processes as at SPS. In Fig. 3 (top panel), we present results from the AMPT model for the rapidity distribution of phi mesons reconstructed from $K^+K^-$ and $\mu^+\mu^-$ pairs for central Au+Au collisions at the RHIC energy of $\sqrt{s} = 130A$ GeV. Of the total phi meson yield of 37 per event, about 24% of these are lost in the kaonic channel by hadronic rescattering and absorption. Note that in spite of enhanced phi meson production in the early stages of the collision as compared to the SPS energy, its abundance at $y \approx 0$ is only about a factor of 1.5 large in the dimuon channel. This may be attributed to fewer kaons lost by rescattering at RHIC as they can escape rapidly out of the collision zone unperturbed due to of their large energies. It is seen that phi meson multiplicities reconstructed from $K^+K^-$ pairs at midrapidity in the AMPT model is consistent with the STAR data [41].

The transverse mass spectra of $\phi$ meson from the two channels are shown in the bottom panel of Fig. 3 and compared with the STAR data [41] for the $K^+K^-$ channel. Compared to a slope parameter of $T = 379 \pm 50$ MeV in the data, the AMPT model predicts a smaller value of $T = 335$ MeV in the kaonic channel in the range $0 < m_T - m_\phi < 1$ GeV. The slope parameter for phi mesons determined from the $\mu^+\mu^-$ channel is $T = 297$ MeV resulting in a suppression factor at low $m_T$ of $R(m_T) = 58\%$. Note that at both SPS and RHIC energy, the slope parameter of phi mesons from $K^+K^-$ decay is smaller compared to the experimental data. We have increased the phi meson elastic cross sections with baryons and mesons to 8.3 mb, which corresponds to the upper bound estimated from phi meson photoproduction data [21], and find that this increases only slightly the slope parameter. On the other hand, an enhanced flow is expected to be generated by converting the strings produced from soft processes into interacting partons in the high energy density created in ultra-relativistic heavy ion collisions [19]. Since in the default HIJING model the strings are basically noninteracting, the latter modification was found to reproduce the
large elliptic flow observed in Au+Au collisions at $\sqrt{s} = 130A$ GeV \cite{17}. Results based on this new AMPT model will be reported in the future.

V. SUMMARY AND CONCLUSIONS

In summary, we have investigated in a multiphase transport (AMPT) model the production of phi mesons reconstructed from $K^+K^−$ and $\mu^+\mu^−$ decays. Considering all possible collisions of $\phi$ with the hadronic medium, we find the phi meson yield from dimuon channel is about a factor of 1.7 higher than the kaon-antikaon channel for central Pb+Pb collisions at the SPS energy. The kaons originating from phi meson decay in the dense hadronic medium are predominantly scattered and absorbed and thus do not contribute to the phi meson yield, whereas all the $\mu^+\mu^−$ pair freely escape. Inclusion of in-medium modification of masses of kaons and phi mesons enhances the phi meson width and results in a factor of two increase of the phi meson yield from the dimuon channel compared to the kaon-antikaon channel. However, strikingly different results were found by two experiments: The NA50 \cite{8} measured $\phi \rightarrow \mu^+\mu^−$ and found its yield a factor of 2-4 larger with a smaller slope parameter compared to $\phi \rightarrow K^+K^−$ measurements by NA49 \cite{7} for central Pb+Pb collisions at 158A GeV. Such a large enhancement of four at low transverse mass from dimuon over the kaon channel could only be explained in the AMPT model by an ad hoc increase of phi meson number by about three from the initial stage. This may be suggestive of other mechanisms, such as the formation of color ropes or quark-gluon plasma in these collisions. To pin down these differences an experiment measuring phi meson from both dimuon and kaon decays in the same kinematic range is therefore called for. For heavy ion collisions at RHIC energy of $\sqrt{s} = 130A$ GeV, the AMPT model gives the yield and slope parameter of phi mesons from the $K^+K^−$ channel that are in reasonable agreement with the STAR data. Similar to the results for heavy ion collisions at SPS, the phi meson yield from the dimuon channel is about 1.5 times larger than that from the $K^+K^−$ channel in the absence of additional phi meson production due to the formation of the initial partonic stage. This number is expected to increase significantly if we include such enhanced production of initial phi mesons. Indeed at RHIC, large energy densities are expected to be reached, and a partonic matter with a longer lifetime and occupying a larger volume could be formed. Compared to SPS energy, larger $s\bar{s}$ production in the partonic stage and its subsequent hadronization would therefore result in an enhanced phi meson abundance, especially at the early stages. These phi mesons should contribute dominantly in the dimuon channel while most of them will escape detection in the kaonic channel. It is thus of great interest to have experimental data on phi mesons from the dimuon measurement at the RHIC energy.

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