D-mesons and charmonium states in hot pion matter

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We calculate the in-medium D-meson self-energies in a hot pion gas induced by resonance interactions with pions. The appropriate resonances in the s, p, and d waves of the D-meson–pion pair are represented by low-lying scalar, vector, and tensor D^* mesons. At temperatures around 200 MeV the D-meson mass drops by 30 MeV and the scattering width grows to 60 MeV. Similar medium effects are found for the D^*-vector mesons. This opens and/or enhances the decay and/or dissociation channels of the charmonium states Ψ', χ_c, and J/Ψ to $D\bar{D}$, $D^*\bar{D}$, $D\bar{D}^*$, and $D^*\bar{D}^*$ pairs in pion matter.

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I. INTRODUCTION

Since the conjecture of the dissociation of charmonium states J/Ψ, Ψ', ..., in a quark-gluon plasma (QGP) because of color screening [1] J/Ψ suppression was considered one of the key signals for the creation of a QGP phase in heavy-ion reactions. An anomalous J/Ψ suppression has possibly been seen in central Pb + Pb reactions at the CERN Super Proton Synchrotron (SPS) [2]. However, the interpretation of data is strongly influenced by the final-state interactions of charmonium states in a hadron gas. The dissociation of J/Ψ's that is due to pion scattering $J/\Psi + \pi \to D\bar{D}$, $D^*\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}^*$ has extensively been discussed within the comover case [3]; for a review see Ref. [4]. The J/Ψ yield at the Relativistic Heavy Ion Collider (RHIC) was measured by the PHENIX Collaboration [5]. On the other hand, recent lattice QCD calculations indicate that J/Ψ might exist as a bound state even at temperatures above the critical temperature for a QGP phase transition [6].

Direct in-medium modifications of charmonium states, i.e., mass shifts and elastic collisional widths, are expected to be small compared with those of the D mesons [7]. Indirect modifications of the charmonium state can, however, appear because of medium modifications of the D-meson states. With the lowering of D masses the inelastic collisional width of charmonium states (because of dissociation to open charm) or, in some cases, even the ordinary width (because of on-shell decays to open charm) is increased or appears as a result of the lowering of corresponding thresholds [8]. These facts are important for both the production and the survival probability of J/Ψ mesons. About 20%, 14%, and 8% of J/Ψ's are produced in a pN interaction at 300 GeV/c by means of the decays of the excited charmonium states χ_1, χ_2, and Ψ', respectively [9]. A dissociation of these states in the medium can approximately reduce the J/Ψ production rate by a factor of 2. Moreover, the shift of the thresholds for the D-meson channels in J/Ψ-π collisions increases the J/Ψ-dissociation cross section and reduces the J/Ψ survival probability.

D mesons have an obvious analogy to K mesons' replacing strange with charm quarks. Medium modifications of D mesons and charmonium states have been considered by several authors. However, similar to that of kaons, the investigation of D-meson mass shifts was mainly restricted to the case of nuclear matter [10–13]. In ultrarelativistic heavy-ion collisions at CERN SPS or RHIC energies, the hadronic environment is, however, baryon dilute and meson rich [14]. Thus, in the present work, we investigate in-medium properties of D and D^* mesons and the resulting consequences for charmonia in hot pion matter. Previous investigations at finite temperatures concentrated to a large extent on the determination of charmonium dissociation cross sections [3,4,15–19], which, are, unfortunately, burdened by large model uncertainties.

The strangeness sector was investigated theoretically in Ref. [20] (see also the references therein), and it has been found that kaons acquire a negative mass shift and a substantial broadening that could explain the enhanced $\phi \to \mu^+\mu^-$ decay [21] relative to the $\phi \to K\bar{K}$ decay [22] possibly seen in heavy-ion collisions at the CERN SPS (see although Refs. [23,24] on possible explanation of the effect) and the $\phi \to e^+e^-$ to $\phi \to K\bar{K}$ enhancement possibly seen in heavy-ion collisions at the RHIC [25].

II. D MESONS AND CHARMONIUM STATES IN HOT PION MATTER

The self-energy Σ of a D meson in a pion gas is to leading order in pion density determined by the invariant $D\pi$ forward-scattering amplitude A:

$$\Sigma = -\int (A^+ dn_{s\pi^+} + A^0 dn_{s\pi^0} + A^- dn_{s\pi^-}). \tag{1}$$

Scalar $n_{s\pi}$ and vector-pion densities $n_{v\pi}$ [$dn_{s\pi} = dn_{v\pi}/(2E_\pi)$] are given by Bose-Einstein distributions at fixed temperature T:

$$dn_{v\pi} = \frac{d^3 p_\pi}{(2\pi)^3}\left[\exp\left(\frac{E_\pi - \mu_\pi}{T}\right) - 1\right]^{-1}. \tag{2}$$

Here $\mu_{\pi^+} = -\mu_{\pi^-}$ is the π^+ chemical potential, $\mu_{\pi^0} = 0$. In the isotopically symmetric pion matter that is expected to be formed in ultrarelativistic heavy-ion collisions at RHIC energies, the chemical potentials vanish ($\mu_{\pi^\pm} = 0$). Hence all pions (negative, neutral, and positive) are equally distributed.

In an isotopically symmetric pion gas, D^+ and D^0 obtain identical self-energies because of isospin symmetry, and these are further equal to the D^- and $\bar{D}^0$ self-energies because of charge-conjugation symmetry. Thus we can restrict ourselves in what follows to the discussion of the D^+ self-energy. In this context it should be noted that D mesons show a close analogy to kaons. In both cases a mass splitting between K and $\bar{K}$, respectively D and $\bar{D}$, occurs at finite nuclear density [12] whereas in isotopically symmetric pion matter kaons and antikaons obtain equal in-medium modifications [20].

The interaction of D mesons with pions or, more generally, the interaction of charmed heavy-light pseudoscalar and vector mesons with light pseudoscalar mesons has been already discussed in the literature. A local four-particle interaction motivated by chiral symmetry and by the similarity of kaons and D mesons was introduced in Ref. [26]. This tree-level interaction has further been iterated for s-wave scattering [26], and the poles of the amplitudes in specific channels were identified with recently observed scalar and axial D_s^* mesons [27,28]. The tree-level $D^+\pi$-scattering amplitude reads [26]

$$\begin{aligned} A(D^+\pi^+ \to D^+\pi^+) &= -\frac{1}{4F^2}(s-u),\\ A(D^+\pi^0 \to D^+\pi^0) &= 0, \\ A(D^+\pi^- \to D^+\pi^-) &= \frac{1}{4F^2}(s-u), \end{aligned} \tag{3}$$

where $F \approx 93$ MeV is the pion decay constant. This result can be presented by isospin 1/2 and isospin 3/2 amplitudes

$$\begin{aligned} A_{1/2} &= \frac{1}{2F^2}(s-u),\\ A_{3/2} &= -\frac{1}{4F^2}(s-u). \end{aligned} \tag{4}$$

The first amplitude $A_{1/2}$ is positive and attractive, the second amplitude $A_{3/2}$ is negative and repulsive. Iterating the $A_{1/2}$ amplitude to all orders in ladder approximation leads to a large value for the T matrix (at least in s waves) and a pole corresponding to a $D\pi$ resonance. The $A_{3/2}$ amplitude after iteration decreases [26]. The tree-level amplitudes contain only s and p waves. Not discussing the reliability of such an approach in what follows, we do not rely on these tree-level amplitudes but instead take only the observed s, p-, and d-, wave resonances in the $D\pi$ system into account. For orbitally excited mesons we take the experimental data from the BELLE Collaboration [29] (see Fig. 1 and Table I) where, for the first time, all four orbitally excited D-meson states have been observed simultaneously. The information on the very narrow vector mesons D^* (p-wave resonances close to threshold) is taken from the Particle Data Group [30].

For resonance scattering we include only the isospin 1/2 resonances, which lead to

$$\begin{aligned} A(D^+\pi^+ \to D^+\pi^+) &= 0,\\ A(D^+\pi^0 \to D^+\pi^0) &= \tfrac{1}{3}A_{1/2}, \\ A(D^+\pi^- \to D^+\pi^-) &= \tfrac{2}{3}A_{1/2}, \end{aligned} \tag{5}$$

TABLE I. Excited D-meson states that are taken into account as resonances in the $D\pi$ system.

Resonance	Mass (MeV)	Width (MeV)
D^*	2008.5	$\approx$0.1
D_0^*	2308 ± 60	276 ± 99
D_1'	2427 ± 61	384^{+201}_{-169}
D_1	2421.4 ± 2.7	23.7 ± 6.9
D_2^*	2461.6 ± 5.9	45.6 ± 12.5

and the sum of these amplitudes that enters the thermal average is equal to $A_{1/2}$. For the forward resonance amplitude $A_{1/2}$ we use the relativistic Breit-Wigner form:

$$A_{1/2} = \sum_{j=0,1,2} \frac{8\pi\sqrt{s}}{k}\frac{(2j+1)}{(2j_1+1)(2j_2+1)}\frac{-\sqrt{s}\Gamma_j^{D\pi}}{s-M_j^2+i\sqrt{s}\Gamma_j^{\rm tot}}, \tag{6}$$

where the $j = 0, 1, 2$ corresponds to the s-, p-, and d-wave resonances D_0^*, D^*, and D_2^* in the $D\pi$ system with masses M_j, partial and total widths $\Gamma_j^{D\pi}$ and $\Gamma_j^{\rm tot}$, respectively; $j_1 = j_2 = 0$ are the spins of the D and the pion, respectively, and k is the c.m. momentum. The energy dependence of the widths is regulated by the specified partial wave

$$\Gamma_j^{D\pi} = \left(\frac{k}{k_0}\right)^{2j+1}\frac{M_j^2}{s}\Gamma_{j0}^{D\pi}, \tag{7}$$

where the subscript 0 refers to on-mass-shell decay widths. When the same amplitude is evaluated for the $j_1 = 1$ D^* meson, the sum runs over the resonances D_1', D_1, D_2^*, and the ground-state D meson. For the branching of the tensor resonance we take the world average $\Gamma(D_2^* \to D\pi)$:$\Gamma(D_2^* \to D^*\pi) \approx 2{:}1$. Now the D, respectively the D^*, self-energy in a pion gas at rest [Eq. (1)] is obtained by integration over the pion distribution, which yields the corresponding modifications of the meson properties: The scattering width Γ and mass shift Re $\Sigma/2M$. The contribution of the narrow D^* resonance with a width of about 100 keV to the D-meson medium modifications is of the order of the D^* width and can be neglected (if one takes the in-medium modification of the D^* into account; this is no longer the case, as will be seen later on). The contributions of the scalar and tensor D^* mesons are, however, sizable and

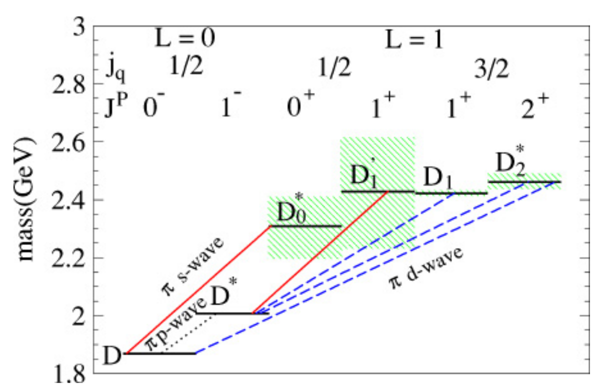

FIG. 1. (Color online) Levels of D-meson excitations from Ref. [29].

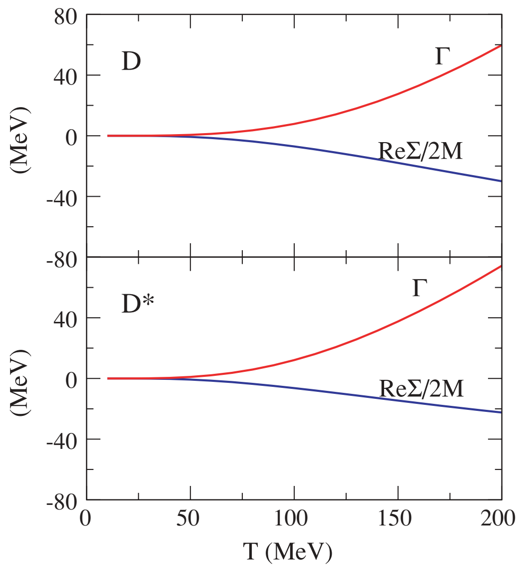

FIG. 2. (Color online) The scattering width $\Gamma = -\text{Im}\,\Sigma/M$ and the real part of self-energy $\text{Re}\,\Sigma/2M$ as functions of temperature T are shown for D mesons (top) and D^* mesons (bottom) at rest in pion matter.

are shown in Fig. 2 as functions of the temperature. Medium modifications of the vector D^* mesons that are of similar magnitude arise from the coupling to axial and tensor mesons; see also Fig. 2.

For further applications to charmonium states the off-shell properties of D and D^* mesons, namely the spectral functions, will be important. A spectral function is defined by the off-shell self-energy $\Sigma(m^2, |\mathbf{p}|)$ as follows:

$$\rho(m^2, |\mathbf{p}|) = \frac{1}{\pi} \frac{-\text{Im}\,\Sigma}{(m^2 - M^2 - \text{Re}\,\Sigma)^2 + (\text{Im}\,\Sigma)^2}. \quad (8)$$

In-medium spectral functions depend on not only the invariant mass squared of the particle but also on its momentum. For D and D^* mesons at rest in the hot pion medium with temperature $T = 200$ MeV, the spectral functions are shown on Fig. 3 as functions of the invariant mass. At other momenta typical for the decays of the charmonium states (see below) they do not change significantly because the velocities of D and D^* mesons are small compared with the thermal velocities of pions.

For D and D^* mesons we calculated the spectral functions both with vacuum (dashed curves) and in-medium (solid curves) propagators of D^* and D mesons. In the latter case, which is the first-order self-consistent iteration, the vacuum propagators of D and D^* in Eq. (6) are replaced with the corresponding in-medium propagators to obtain the iterated in-medium results

$$\frac{1}{s - M^2_{D(D^*)}} \to \frac{1}{s - M^2_{D(D^*)} - \Sigma_{D(D^*)}}. \quad (9)$$

The medium modification of the D meson has thereby a feedback on the D^* since it modifies the corresponding decay channel. The difference between the lowest order and the first iteration is significant at small invariant masses of the D and D^* mesons, which is important for the charmonium decays.

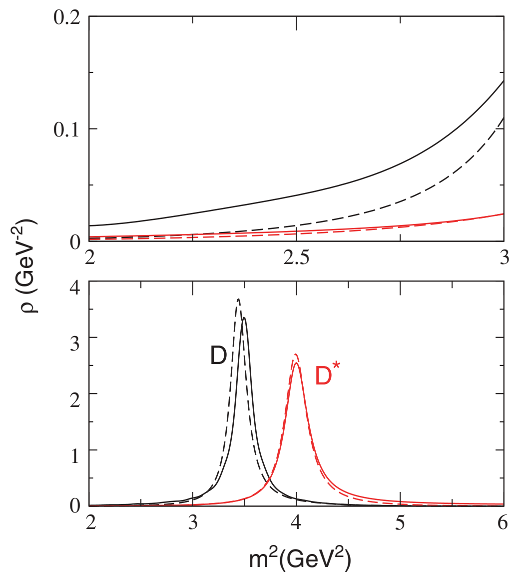

FIG. 3. (Color online) The in-medium spectral functions of D and D^* mesons at rest in the hot pion gas with temperature $T = 200$ MeV. The dashed and solid curves for the in-medium D- and D^*-meson spectral functions correspond to the lowest-order calculation and to the first-order self-consistent iteration of the in-medium spectral functions, respectively.

With this information, one is able to evaluate the dissociation widths of the charmonium states J/Ψ, χ_1, χ_2, and Ψ' in the pion medium. Let us take into account the fact that in the medium D and D^* mesons are not particles but resonances with finite collisional widths. Then the $J/\Psi \to D\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}$, $D^*\bar{D}^*$ decay can occur subthreshold and thus account for the reactions $J/\Psi\pi \to D\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}$, $D^*\bar{D}^*$ that are open in pion matter. The width $\Gamma(J/\Psi \to D\bar{D})$ can be easily found:

$$\Gamma(J/\Psi \to D\bar{D}) = \int \frac{g^2_{J/\Psi D\bar{D}}}{3\pi M^2_{J/\Psi}} p^3 \times \rho_D(m_1^2, p)\rho_{\bar{D}}(m_2^2, p) dm_1^2 dm_2^2,$$

where p is the c.m. momentum for the decay of the J/Ψ meson to D and D^* mesons with masses m_1 and m_2, respectively, and $g_{J/\Psi D\bar{D}}$ is the $J/\Psi D\bar{D}$ coupling constant. Taking the value of $g_{J/\Psi D\bar{D}} = 7.8$ from Ref. [8], one obtains a dissociation width of $\Gamma(J/\Psi \to D\bar{D}) = 0.54$ MeV at a temperature of $T = 200$ MeV. The other decay channels ($D\bar{D}^* D^*\bar{D}$, $D^*\bar{D}^*$) can be treated analogously. To do so, we use the coupling constants

$$g_{J/\Psi D^*\bar{D}^*} = g_{J/\Psi D\bar{D}}, \qquad g_{J/\Psi D\bar{D}^*} = \frac{g_{J/\Psi D\bar{D}}}{M_D}$$

in combination with appropriate phenomenological vertices [17]. In total, we thus obtain at a temperature of $T = 200$ MeV a J/Ψ collisional width of 1.15 MeV (see Fig. 4).

These values can now be compared with the collisional width $\Gamma(J/\Psi\pi \to D\bar{D}, D\bar{D}^*, D^*\bar{D}, D^*\bar{D}^*) = 5-14$ MeV. One obtains the latter by multiplying the average cross section for the J/Ψ dissociation through pions evaluated at the same temperature and equal to $\langle\sigma^{\pi J/\Psi} v\rangle \approx 0.75-2$ mb

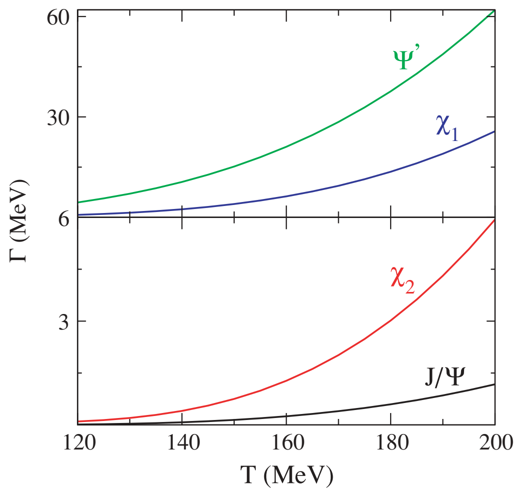

FIG. 4. (Color online) In-medium widths of J/Ψ, χ_1, χ_2, and Ψ' mesons.

[17] (v being the relative velocity) with the corresponding pion density. The order-of-magnitude agreement between the J/Ψ subthreshold decay width to D mesons and the $J/\Psi\pi$-dissociation width is not surprising because both effects are of a common nature. In fact, the J/Ψ dissociation through pion capture by one of the D-meson is connected to the D-meson collision widths. In the calculation of the J/Ψ decay rate the D-meson collision width appears in the denominator of the Breit-Wigner amplitude that, because of the subthreshold character of the J/Ψ decay, can be expanded in powers of the pion density entering the D-meson collision width. To lowest order the result coincides with the J/Ψ-dissociation rate through one-pion capture by one of the D mesons. However, the inclusion of realistic spectral functions turns out to reduce the J/Ψ dissociation. Therefore, the results of previous calculations [17] differ from the present ones because some contribution (contact four-particle interaction) is not considered in our approach (see diagram 1c in Fig. 1 in Ref. [17]) and because our amplitude is closer to the unitarity constraint. In this context it should be mentioned that there appear additional dissociation mechanisms at the quark level [18,19,31], e.g., s-channel box diagrams, which cannot be expressed in terms of effective meson degrees of freedom and may lead to an additional increase of the width.

The in-medium width of the excited Ψ' is estimated analogously, assuming the same $g_{\Psi' D\bar{D}}$ coupling constant as for the J/Ψ. Since the Ψ' lies only 52 MeV below the $D\bar{D}$ threshold in free space, its in-medium width is about 50 times larger than that of the J/Ψ. Finally, the in-medium widths of the χ_1 and χ_2 states were estimated with the phenomenological vertices $gM_D\chi_\mu(D_\mu\bar{D} + \bar{D}_\mu D)$ and $gM_D\chi_{\mu\nu}D_\mu\bar{D}_\nu$, $g/M_D\chi_{\mu\nu}\partial_\mu D\partial_\nu\bar{D}$ with $g = g_{J/\Psi D\bar{D}}$, respectively. As seen from Fig. 4, χ_1 and χ_2 mesons also receive a substantial width in pion matter.

III. CONCLUSION

In conclusion, the D-meson self-energies in pion matter have been determined to leading order in density, thereby taking resonances in the $D\pi$ amplitude into account. The resonances in s, p, and d waves of the D-meson–pion system were represented by low-lying scalar, vector, and tensor D^* mesons that were observed experimentally. This allows us to determine the D self-energy in a model-independent way. At a temperature around 200 MeV the D-meson mass is reduced by about 30 MeV and the scattering width is about 60 MeV. Similar medium modifications were found for D^*-vector mesons. Consequently the widths of the decay and dissociation channels of the charmonium states Ψ', χ_c, and J/Ψ to $D\bar{D}$, $D^*\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}^*$ pairs are enhanced (from $\Gamma_{J/\Psi} \simeq 1.15$ MeV to $\Gamma_{\Psi'} \simeq 62$ MeV at $T \simeq 200$ MeV). As a consequence, the feeding of J/Ψ states from excited charmonium states ceases in a hot pion gas, which characterizes the hadronic final state in high energetic heavy-ion reactions in good approximation.

Hence D-meson modifications in a hot pion medium are important for the production of J/Ψ during the fireball expansion in heavy-ion reactions. The back reactions of J/Ψ formation in D-meson collisions from a charmed meson-rich medium become important for corresponding transport simulations.

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[1] T. Matsui and H. Satz, Phys. Lett. **B178**, 416 (1986).
[2] M. C. Abreu *et al.* (NA50 Collaboration), Phys. Lett. **B477**, 28 (2000).
[3] C. Gerschel and J. Hüfner, Z. Phys. C **56**, 171 (1992); S. Gavin and R. Vogt, Phys. Rev. Lett. **78**, 1006 (1997); N. Armesto and A. Capella, Phys. Lett. **B430**, 23 (1998); E. Shuryak and D. Teaney, *ibid.* **B430**, 37 (1998); W. Cassing and C. M. Ko, *ibid.* **B396**, 39 (1997).
[4] R. Vogt, Phys. Rep. **310** 197 (1999).
[5] R. Granier de Cassagnac, J. Phys. G **30**, S1341 (2004); H. Pereira Da Costa for the PHENIX Collaboration, nucl-ex/0510051.
[6] S. Datta, F. Karsch, P. Petreczky, and I. Wetzorke, Nucl. Phys. B. (Proc. Suppl.) **119**, 487 (2003); M. Asakawa, and T. Hatsuda, Nucl. Phys. B. (Proc. Suppl.) **129**, 584 (2004).
[7] A. Hayashigaki, Phys. Lett. **B487**, 96 (2000).
[8] B. Friman, S. H. Lee, and T. Song, Phys. Lett. **B548**, 153 (2002).
[9] L. Antoniazzi *et al.* (E705 Collaboration), Phys. Rev. Lett. **70**, 383 (1993).
[10] F. Klingl, S. Kim, S. H. Lee, P. Morath, and W. Weise, Phys. Rev. Lett. **82**, 3396 (1999) [Erratum *ibid.* **83**, 4224 (1999)].
[11] S. Digal, P. Petreczky, and H. Satz, Phys. Lett. **B514**, 57 (2001).

[12] A. Sibirtsev, presented at the 2002 Conference on Quarks and Nuclear Physics, 9–14 June 2002, Julich, Germany.
[13] A. Mishra, E. L. Bratkovskaya, J. Schaffner-Bielich, S. Schramm, and H. Stöcker, Phys. Rev. C **69**, 015202 (2004).
[14] L. Bravina, A. Faessler, C. Fuchs, E. E. Zabrodin, and Z.-D. Lu, Phys. Rev. C **66**, 014906 (2002); K. Adcox *et al*. (PHENIX Collaboration), Phys. Rev. Lett. **86**, 3500 (2001); B. B. Back *et al*. (PHOBOS Collaboration), Phys. Rev. C **65**, 031901(R) (2002) .
[15] T. Hashimoto, O. Miyamura, K. Hirose, and T. Kanki, Phys. Rev. Lett. **57**, 2123 (1986).
[16] K. L. Haglin, Phys. Rev. C **61** 031902(R) (2000); C.-Y. Wong, E. S. Swanson, and T. Barnes, *ibid*. **62**, 045201 (2000).
[17] Z. Lin and C. M. Ko, Phys. Rev. C **62**, 034903 (2000).
[18] G. Burau, D. Blaschke, and Yu. Kalinovsky, Phys. Lett. **B506**, 297 (2001); D. Blaschke, G. Burau, T. Barnes, and Yu. Kalinovsky, and E. Swanson, J. Phys. G **28**, 1959 (2002).
[19] M. A. Ivanov, J. G. Körner, and P. Santorelli, Phys. Rev. D **70**, 014005 (2004).
[20] B. V. Martemyanov, A. Faessler, C. Fuchs, and M. I. Krivoruchenko, Phys. Rev. Lett. **93**, 052301 (2004).
[21] B. Alessandro *et al*. (NA50 Collaboration), Phys. Lett. **B555**, 147 (2003).
[22] S. V. Afanasiev *et al*. (NA49 Collaboration), Phys. Lett. **B491**, 59 (2000).
[23] S. C. Johnson, B. V. Jacak, A. Drees, Eur. Phys. J. C **18**, 645 (2001).
[24] P. Filip and E. E. Kolomeitsev, Phys. Rev. C **64**, 054905 (2001).
[25] D. Mukhopadhyay (PHENIX Collaboration), Nucl. Phys. **A715**, 494 (2003); Alexander Kozlov for the PHENIX Collaboration, presented at the Quark Matter 2005 Conference, August 2005, Budapest.
[26] E. E. Kolomeitsev and M. F. M. Lutz, Phys. Lett. **B582**, 49 (2004).
[27] BABAR Collaboration B. Aubert *et al*., Phys. Rev. Lett. **90**, 242001 (2003).
[28] CLEO Collaboration, D. Besson *et al*., Phys. Rev. D **68**, 032002 (2003).
[29] K. Abe *et al*. (BELLE Collaboration), Phys. Rev. D **69**, 112002 (2004).
[30] S. Eidelman *et al*., Phys. Lett. **B592**, 1 (2004).
[31] F. O. Durães, S. H. Lee, F. S. Navarra, and M. Nielsen, Phys. Lett. **B564**, 97 (2003).