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HADRON FORM FACTORS AND J/ψ DISSOCIATION

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We analyze the results of the $SU(4)$ chiral meson Lagrangian approach to the cross section for J/ψ breakup by pion impact. The major weakness of this approach is the arbitrariness in the choice of hadronic form factors. We evaluate the dependence of the cross section on the masses of the final D-meson states and compare the result to a parametrization that has been employed for the study of in-medium effects on this quantity.

Проанализированы результаты приближения $SU(4)$ кирального мезонного лагранжиана в применении к сечению развала J/ψ налетающим пионом. Основной недостаток этого приближения заключается в произвольности выбора адронных формфакторов. Мы проводим вычисление зависимости сечения от масс конечных D-мезонных состояний и сравниваем полученный результат с параметризацией, примененной при изучении влияния эффектов среды на эту величину.

INTRODUCTION

The J/ψ meson plays a key role in the experimental search for the quark–gluon plasma (QGP) in heavy-ion collision experiments where an anomalous suppression of its production cross section relative to the Drell–Yan continuum as a function of the centrality of the collision has been found by the CERN-NA50 collaboration [1]. An effect like this has been predicted to signal QGP formation [2] as a consequence of the screening of color charges in a plasma in close analogy to the Mott effect. However, a necessary condition to explain J/ψ suppression in the static screening model is that a sufficiently large fraction of $c\bar{c}$ pairs after their creation have to traverse regions of QGP where the temperature (respectively parton density) has to exceed the Mott temperature $T_{J/\psi}^{\rm Mott} \sim 1.2{-}1.3T_c$ [3, 4] for a sufficiently long time interval $\tau > \tau_f$, where $T_c \sim 170$ MeV is the critical phase transition temperature and $\tau_f \sim 0.3$ fm/c is the J/ψ formation time. Within an alternative scenario [5], J/ψ suppression does not require temperatures well above the deconfinement one, but can occur already at T_c due to impact collisions by quarks from the thermal medium. An important ingredient for this scenario is the lowering of the reaction threshold for string-flip processes which lead to open-charm meson formation and thus to J/ψ suppression. This process has an analogue in the hadronic world, where, e.g., $J/\psi + \pi \to D^* + \bar{D} + {\rm h.c.}$ could occur provided the reaction threshold

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of $\Delta E \sim 640$ MeV can be overcome by pion impact. It has been shown recently [6] that this process and its in-medium modification can play a key role in the understanding of anomalous J/ψ suppression as a deconfinement signal. Since at the deconfinement transition the D mesons enter the continuum of unbound (but strongly correlated) quark–antiquark states (Mott effect), the relevant threshold for charmonium breakup is lowered and the reaction rate for the process gets critically enhanced [8]. Thus a process which is negligible in the vacuum may give rise to additional (anomalous) J/ψ suppression when conditions of the chiral/deconfinement transition and D-meson Mott effect are reached in a heavy-ion collision, but the dissociation of the J/ψ itself still needs impact to overcome the threshold which is still present but dramatically reduced.

For this alternative scenario as outlined in [6] to work, the J/ψ breakup cross section by pion impact is required and its dependence on the masses of the final-state D mesons has to be calculated. Both, nonrelativistic potential models [13–16] and chiral Lagrangian models [10–12] have been employed to determine the cross section in the vacuum. The results of the latter models appear to be strongly dependent on the choice of form factors for the meson–meson vertices. This is considered as a basic flaw of these approaches which could only be overcome when a more fundamental approach, e.g., from a quark model, can determine these input quantities of the chiral Lagrangian approach.

In the present paper we would like to reduce the uncertainties of the chiral Lagrangian approach by constraining the form factor from comparison with results of a nonrelativistic approach which makes use of meson wave functions [16]. Finally, we will obtain a result for the off-shell J/ψ breakup cross section which can be compared to the fit formula used in [6]. This quantity is required for the calculation of the in-medium modification of the J/ψ breakup due to the Mott effect for mesonic states at the deconfinement/chiral restoration transition which has been suggested [6,7] as an explanation of the anomalous J/ψ suppression effect observed in heavy-ion collisions at the CERN-SPS [1].

1. J/ψ ABSORPTION CROSS SECTIONS

The effective Lagrangian approach allows us to study the following processes for J/ψ absorption by π and ρ mesons:

$$J/\psi + \pi \to D^* + \bar{D},\ \ J/\psi + \pi \to D + \bar{D}^*, \tag{1}$$

$$J/\psi + \rho \to D + \bar{D},\ \ J/\psi + \rho \to D^* + \bar{D}^*. \tag{2}$$

The corresponding diagrams for this process, except the process $J/\psi + \pi \longrightarrow D + \bar{D}^*$, which has the same cross section as the process $J/\psi + \pi \longrightarrow D^* + \bar{D}$, are shown in Fig. 1.

The full amplitude for the first process $J/\psi + \pi \longrightarrow D^* + \bar{D}$, without isospin factors and before summing and averaging over external spins, is given by

$$M_1 \equiv M_1^{\mu\nu}\varepsilon_{1\mu}\varepsilon_{3\nu} \quad = \quad \left(\sum_{i=a,b,c} M_{1i}^{\mu\nu}\right)\varepsilon_{1\mu}\varepsilon_{3\nu}, \tag{3}$$

with

$$M_{1a}^{\mu\nu} = -g_{\pi DD^*} g_{J/\psi DD}(-2p_2 + p_3)^\nu \left(\frac{1}{u - m_D^2}\right)(p_2 - p_3 + p_4)^\mu,$$

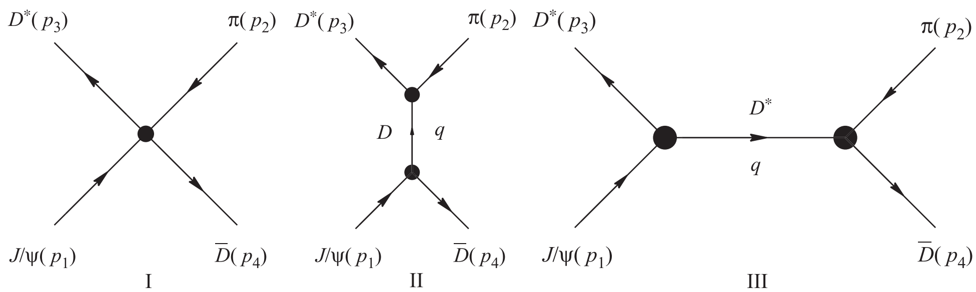

Fig. 1. Diagrams for J/ψ breakup by pion impact: $J/\psi + \pi \to D^* + \bar{D}$; I — contact term; II+III — D-meson exchange processes

$$\begin{aligned} M_{1b}^{\mu\nu} &= g_{\pi D D^*} g_{J/\psi D^* D^*} (-p_2 - p_4)^\alpha \left(\frac{1}{t - m_{D^*}^2} \right) \times \\ &\times \left[g^{\alpha\beta} - \frac{(p_2 - p_4)^\alpha (p_2 - p_4)^\beta}{m_{D^*}^2} \right] \times \\ &\times \left[(-p_1 - p_3)^\beta g^{\mu\nu} + (-p_2 + p_1 + p_4)^\nu g^{\beta\mu} + (p_2 + p_3 - p_4)^\mu g^{\beta\nu} \right], \end{aligned}$$

$$M_{1c}^{\mu\nu} = -g_{J/\psi\pi D D^*} g^{\mu\nu}. \tag{4}$$

Similarly, we calculate the full amplitudes for the processes $J/\psi + \rho \to D + \bar{D}$ and $J/\psi + \rho \to D^* + \bar{D}^*$ (for detail, see [18]).

In the above, p_j denotes the momentum of particle j. We choose the convention that particles 1 and 2 represent initial-state mesons, while particles 3 and 4 represent final-state mesons on the left and right sides of the diagrams shown in Fig. 1, respectively. The indices $\mu,\ \nu,\ \lambda$ and ω denote the polarization components of external particles, while the indices α and β denote those of the exchanged mesons.

After averaging (summing) over initial (final) spins and including isospin factors we calculate the cross sections for the processes.

2. HADRONIC FORM FACTORS

The chiral Lagrangian approach for J/ψ breakup by light meson impact makes the assumption that mesons and meson–meson interaction vertices are local (four-momentum independent) objects. This neglect of the finite extension of mesons as quark–antiquark bound states has dramatic consequences: it leads to a monotonously rising behavior of the cross sections for the corresponding processes, see the dashed lines in Fig. 2. This result, however, cannot be correct away from the reaction threshold where the tails of the mesonic wave functions determine the high-energy behavior of the quark exchange (in the nonrelativistic formulation of [13, 16]) or quark loop (in the relativistic formulation [17]) diagrams describing the micrscopic processes underlying the J/ψ breakup by meson impact. As long as the mesonic wave functions describe quark–antiquark bound states which have a finite extension

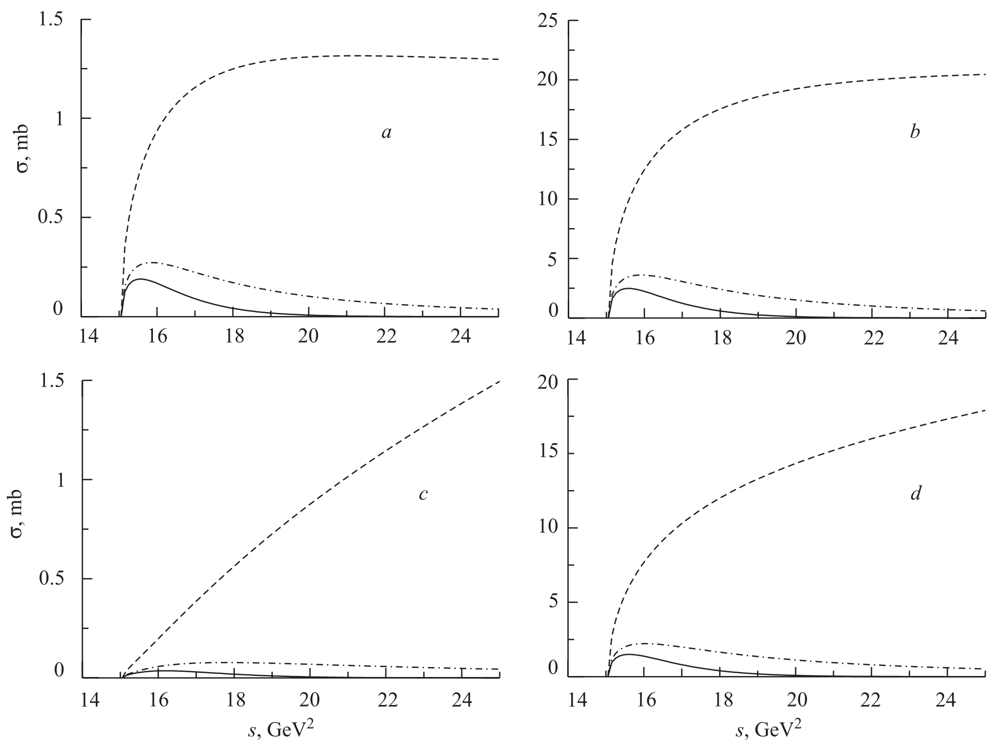

Fig. 2. *b*) Total cross section for J/ψ breakup by pion impact without form factor (dashed line), with monopole type form factor (dash-dotted line) and with Gaussian form factor (solid line) as a function of the squared c.m. energy of initial-state mesons. The partial contributions from diagrams I, II, and III of Fig. 1 are shown in panels a, c and d, respectively

in coordinate- and momentum space, the J/ψ breakup cross section is expected to be decreasing above the reaction threshold and asymptotically small at high c.m. energies. This result of the quark model approaches to meson–meson interactions [13, 16, 17] can be mimicked within chiral meson Lagrangian approaches by the use of form factors at the interaction vertices [11, 12]. We will follow here the definitions of Ref. [11], where the form factor of the four-point vertices of Fig. 1, i.e., of the box diagram (I), as well as of the meson exchange diagrams (II, III), is taken as the product of the triangle diagram form factors

$$F_4^i(\mathbf{q}^2) = \left[F_3(\mathbf{q}^2)\right]^2, \; i = \mathrm{I}, \mathrm{II}, \mathrm{III}, \tag{5}$$

with the squared three-momentum $\mathbf{q}^2$ given by the average value of the squared three-momentum transfers in the t and u channels:

$$\mathbf{q}^2 = \frac{1}{2}\left[(\mathbf{p_1} - \mathbf{p_3})^2 + (\mathbf{p_1} - \mathbf{p_4})^2\right]_{\mathrm{cm}} = p_{i,\mathrm{cm}}^2 + p_{f,\mathrm{cm}}^2. \tag{6}$$

For the triangle diagrams, we use form factors with a momentum dependence in the monopole form (M)

$$F_3^M(\mathbf{q}^2) = \frac{\Lambda^2}{\Lambda^2 + \mathbf{q}^2}, \tag{7}$$

and in the Gaussian (G) form

$$F_3^G(\mathbf{q}^2) = \exp\left(-\mathbf{q}^2/\Lambda^2\right). \tag{8}$$

At this point we have to add the comment that this choice, however, is obviously not supported by the underlying quark substructure diagrams that can provide a justification for the use of form factors: While the triangle diagram is of third order in the wave functions so that the meson exchange diagrams are suppressed at large momentum transfer by six wave functions, the box diagram appears already at fourth order, thus being less suppressed than suggested by the ansatz (5) of Ref. [11]. For the cross section of the three diagrams including the effect of hadronic form factors, we multiply the bare expressions with the form factors given above. The results are depicted in Fig. 2. In the last section, we want to discuss the results and their possible implications for phenomenological applications.

3. RESULTS AND DISCUSSION

The J/ψ breakup cross section by π- and ρ-meson impact has been formulated within a chiral $U(4)$ Lagrangian approach. Numerical results have been obtained for the pion impact processes with the result that the D-meson exchange in the t channel is the dominant subprocess contributing to the J/ψ breakup. The use of form factors at the meson–meson vertices is mandatory since otherwise the high-energy asymptotics of the processes with hadronic final states will be overestimated (see Fig. 2). From a comparison with results of a nonrelativistic potential model calculation, we can choose the shape of the form factor to be Gaussian and fix the range $\Lambda = 0.9$ GeV from the asymptotic high energy behavior (see Fig. 3). Within our semi-quantitative discussion, we do not attempt a high-accuracy description of the nonrelativistic result which accounts for another final-state D-meson pair (see [13–16]).

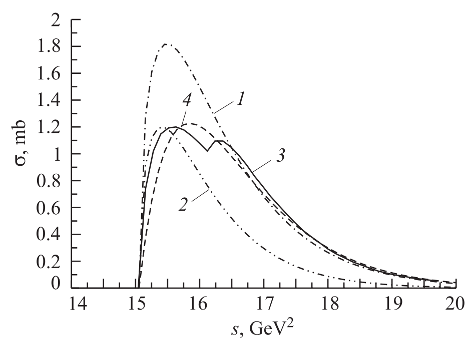

Fig. 3. Total J/ψ breakup cross section with Gaussian form factor (*1* — $\Lambda = 0.9$ GeV; *2* — $\Lambda = 0.8$ GeV) compared to the nonrelativistic quark exchange model (*3* — Wong et al. [16]) and its parametrization by Burau et al. [7] (*4*)

Finally, we want to explore the influence of a variation of the final-state D-meson masses on the effective J/ψ breakup cross section. Our motivation for considering mesonic states to be off their mass shell is their compositeness which can become apparent in a high-temperature (and density) environment at the deconfinement/chiral restoration transition, when these states change their character qualitatively, being resonant quark–antiquark scattering states in the quark plasma rather than on-shell mesonic bound states.

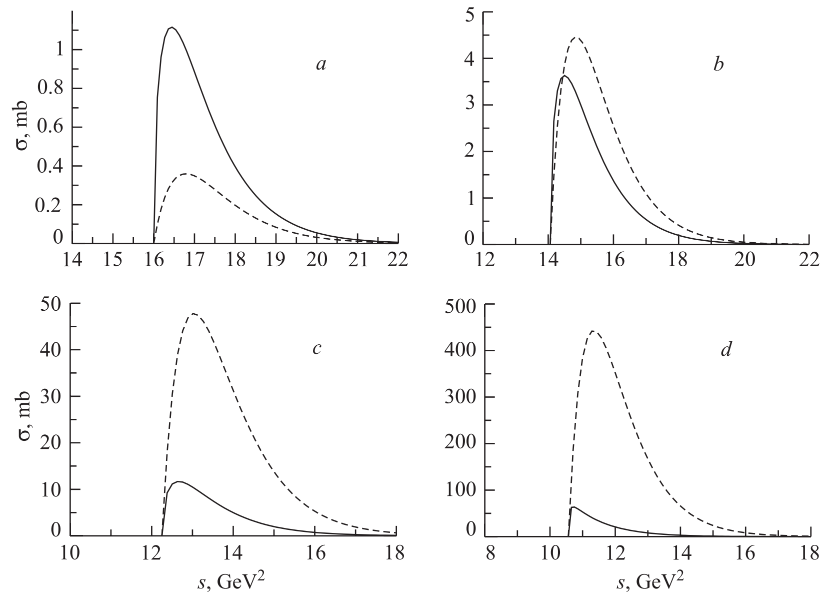

Fig. 4. Total J/ψ breakup cross section in the chiral Lagrangian model with Gaussian form factor (solid line — $\Lambda = 0.9$ GeV) compared to the parametrization of the nonrelativistic quark exchange model [16] by Burau et al. [7] (dashed line). The four panels illustrate the differences between both models when the final-state masses $M_{D_1} = M_{D_2} = M_D$ are varied: *a*) 4.0 GeV; *b*) 3.75 GeV; *c*) 3.5 GeV; *d*) 3.25 GeV

The consequence of this Mott transition from bound to resonant states for the J/ψ breakup has been explored by Burau et al. using a fit formula [6, 7] and Monte Carlo calculations [9, 19] for the D-mass dependence of the breakup cross section, which shows a strong enhancement when the process becomes subthreshold ($M_D < M_D^{\text{vac}}$). This behavior is qualitatively approved within the present chiral $U(4)$ Lagrangian + form factor model, although the subthreshold enhancement is more moderate (see Fig. 4). A more consistent description should include a quark model derivation of the form factors for the meson–meson vertices and their possible medium dependence. Such an investigation is in progress.

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