

DYSON-SCHWINGER EQUATION APPROACH TO THE QCD DECONFINEMENT TRANSITION AND J/ψ DISSOCIATION

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We consider an extension of the finite-temperature Dyson-Schwinger equation (DSE) approach to heavy mesons and quarkonia and apply it to calculate the cross section for the J/ψ breakup reaction $J/\psi + \pi \rightarrow D + \bar{D}$. We study the effects of chiral symmetry restoration in the light quark sector on this process and obtain a critical enhancement of the reaction rate at the chiral/ deconfinement transition. Implications for the kinetics of charmonium production in ultrarelativistic heavy-ion collisions are discussed with particular emphasis on the recently observed anomalous J/ψ suppression as a possible signal for quark matter formation.

1 Introduction

Recent results of the NA50 collaboration at CERN SPS on anomalous J/ψ suppression in Pb-Pb collisions at 158 A GeV^{1,2} have renewed the quest for a proper description of charmonium production in heavy-ion collisions. It has been emphasized that a threshold effect in the E_T dependence of J/ψ suppression like the one observed by NA50 could be a signal for quark-gluon plasma formation^{3,4,5}, see Fig. 1. However, up to now there is no theory for the hadroproduction of charmonium and the present approaches have to be considered as parametrizations of the data. We provide here a reparametrization of this threshold effect where we extract effective comover cross sections from the difference of the observed data points to the extrapolated nuclear absorption within a generalized Glauber model⁶, see Fig. 1, lower panel. This comover cross section shows an onset at the transverse energy of $E_T \sim 40$ GeV which we interpret as a signal for a critical phenomenon in dense mat-

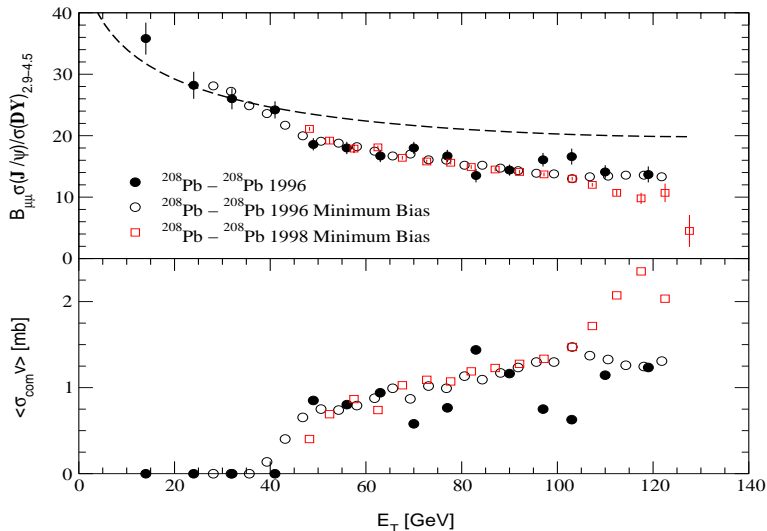


Figure 1: Upper panel: J/ψ production in Pb-Pb collisions at 158 AGeV^{1,2} compared to the extrapolation from p-A and S-U collisions using a Glauber model (dashed line) with nuclear J/ψ absorption. Lower panel: Comover absorption cross sections extracted from the difference of observed data to the nuclear absorption extrapolation.

ter due to the chiral/deconfinement transition. Within the present paper, we want to investigate the charmonium dissociation cross section within a DSE model of QCD at high temperature and density⁷ and thus go beyond previous estimates of this quantity within a nonrelativistic potential model⁸. This is particularly important since pions as quasi Goldstone bosons are involved in the dissociation process and a nonrelativistic description of these states fails to describe their wave functions accurately. The DSE approach will be applied for the description of the temperature dependence of heavy meson masses, which can lead to a dramatic increase in the J/ψ dissociation cross section, as has been demonstrated previously⁶. This behaviour could contribute to an interpretation of the still puzzling experimental situation.

2 Dyson-Schwinger equation approach to light and heavy mesons

The nonperturbative features of low energy QCD such as dynamical chiral symmetry breaking and confinement can be successfully modeled by the truncation of the full DSE for the renormalized dressed quark propagator $S(p)$, see Fig. 2, to the rainbow level^{7,9}. This approach has been systematically extended to the

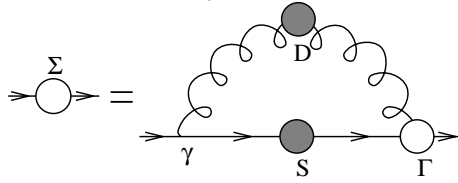


Figure 2: Self-energy diagram defining the fully dressed quark two-point function $S(p)$.

case of finite temperatures¹⁰ and chemical potentials¹¹ within the imaginary time (Matsubara) formalism, where it gives insight into the interplay between chiral symmetry restoration and deconfinement found in Lattice QCD simulations¹² and predicts the phase transition parameters in the quark matter phase diagram¹³.

Masses and decay properties of light mesons (π , ρ) have been studied using the finite-temperature Bethe-Salpeter equations (BSEs) in the corresponding channels^{10,14}. The DSE approach has also proven to be successful for the description of heavy meson observables¹⁵ which play a crucial rôle in the present work.

The approach we present in the following will employ a confining, separable model¹⁶ recently extended to finite temperatures in the low-mass sector^{17,18}. In a rank-1 truncation the model gluon propagator reads $D(p, q) = D_0 \varphi(p^2)\varphi(q^2)$, and the renormalized quark propagator takes the form

$$S(p) = -i\gamma_\mu p_\mu \sigma_V(p^2) + \sigma_S(p^2) \quad (1)$$

with $\sigma_V(p^2) = [p^2 + m^2(p^2)]^{-1}$, $\sigma_S(p^2) = m(p^2)\sigma_V(p^2)$ and the dynamical quark mass function is given by

$$m(p^2) = m_0 + \Delta m(T, \mu)\varphi(p^2). \quad (2)$$

The solution of the quark DSE reduces to that of the gap equation

$$\Delta m(T, \mu) = \frac{16D_0}{3} \int \frac{d^4q}{(2\pi)^4} \varphi(q^2)\sigma_S(q^2), \quad (3)$$

where a nonvanishing mass gap $\Delta m(T, \mu)$ in the chiral limit $m_0 = 0$ signals spontaneous chiral symmetry breaking in the T, μ -plane of the phase diagram. We choose a Gaussian formfactor $\varphi(p^2) = \exp(-p^2/\Lambda^2)$ and obtain a fit of π - and ρ - meson properties with $D_0 = 227.8 \text{ GeV}^{-2}$, $\Lambda = 0.60 \text{ GeV}$, $m_0 = 7.2 \text{ MeV}$. The temperature dependence of the solution of the mass gap equation (3) results in a chiral restoration transition temperature $T_c = 150 \text{ MeV}$, see

upper panel of Fig. 6. The model is confining for all $\Delta m(T, \mu) > \Lambda/\sqrt{2e}$ since it has then no solution of $p^2 + m^2(p^2) = 0$ for real p^2 (no quasiparticle poles). For the heavy quark propagators the limit $m(p^2) = m_Q = \text{const}$ will be used where m_Q is the current mass of the heavy quark¹⁵.

The BSE in ladder approximation for the mesonic bound states has the form

$$\lambda(P^2)\Gamma_M(q, P) = -\frac{4}{3} \int \frac{d^4p}{(2\pi)^4} D(q, p) \gamma_\mu S_{q_1}(p_+) \Gamma_M(p, P) S_{q_2}(p_-) \gamma_\mu \quad (4)$$

with $p_+ = p + \eta P$, $p_- = p - (1 - \eta)P$, where $\eta = 1/2$ for $m_{q_1} = m_{q_2}$ and $\eta = 1$ for $m_{q_1} \gg m_{q_2}$. Here we will use the one-covariant meson vertex functions $\Gamma_M = \gamma_M N_M \varphi_M(p^2)$, where for the pseudoscalar mesons $\gamma_\pi = \gamma_D = \gamma_{\bar{D}} = i\gamma_5$ and for the vector mesons $\gamma_\rho = \gamma_{D^*} = \gamma_{J/\psi} = \gamma_\mu$ with the proper normalization constants N_M . For the present study we will use the exploratory ansatz $\varphi_M(p^2) = \varphi(p^2)$. The condition $\lambda(P^2 = -M_M^2) = 1$ leads to the meson mass formulae

$$1 = \frac{8}{3} D_0 \int \frac{d^4p}{(2\pi)^4} \varphi^2(p^2) \left[V_M^{(V)}(p, P) \sigma_V^+ \sigma_V^- + V_M^{(S)}(p, P) \sigma_S^+ \sigma_S^- \right] \Big|_{P=iM_M}, \quad (5)$$

where the functions $V_M^{(V,S)}(p, P)$ can be found elsewhere¹⁸. With $m_Q = m_c = 1.844$ GeV the resulting masses for the heavy mesons (experimental value in brackets) are $M_D = 1.869$ GeV ((1.8693 \pm 0.0005) GeV), $M_{D^*} = 2.006$ GeV ((2.0067 \pm 0.0005) GeV) and $M_{J/\psi} = 3.459$ GeV ((3.09688 \pm 0.00004) GeV).

3 Triangle diagram for the $D^* \rightarrow D\pi$ decay

We consider this vector-pseudoscalar-pseudoscalar decay as a test for our relativistic quark model. In the light meson sector this process describes the $\rho\pi\pi$ decay⁹, which is an important ingredient of recent studies of dilepton production in heavy-ion collisions due to vector meson dominance. It has also been studied in the present model at finite temperature recently¹⁸. Here we calculate the $D^*D\pi$ decay process as a quark loop diagram, see Fig. 3. The decay width of this process is given by

$$\Gamma_{D^* D\pi} = \frac{g_{D^*D\pi}^2}{192\pi M_{D^*}^5} \lambda^3(M_{D^*}^2, M_D^2, M_\pi^2), \quad (6)$$

with the kinematic factor $\lambda(s, M_1^2, M_2^2) = \sqrt{[s - (M_1 + M_2)^2][s - (M_1 - M_2)^2]}$. The $D^*D\pi$ coupling constant $g_{D^*D\pi} = \frac{1}{2}(A - B)$ is given by the functions A, B ,

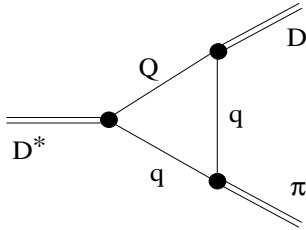


Figure 3: The quark loop diagram for $D^* \rightarrow D\pi$ decay vertex.

defined from the transition amplitude of this process

$$\begin{aligned}
T_{D^* D\pi}^\sigma &= AP_\pi^\sigma + BP_D^\sigma \\
&= N_c \int \frac{d^4p}{(2\pi)^4} \mathcal{F}(p^2) \text{tr}_D \{ [\gamma_\sigma] [-i(p_1 \cdot \gamma) \sigma_V(p_1^2) + \sigma_S(p_1^2)] [i\gamma_5] \\
&\quad [-i(p_2 \cdot \gamma) \sigma_V(p_2^2) + \sigma_S(p_2^2)] [i\gamma_5] [-i(p_3 \cdot \gamma) \sigma_V(p_3^2) + \sigma_S(p_3^2)] \} \quad (7)
\end{aligned}$$

where $\mathcal{F}(p^2) = N_{D^*} N_\pi N_D \varphi^3(p^2)$ and $p_1 = p - P_\pi/2$, $p_2 = p + P_\pi/2$, $p_3 = p + P_\pi/2 - P_D$. Our result for the coupling constant $g_{D^* D\pi} = 10.7$ agrees well with the experimental value $g_{D^* D\pi}^{exp} = 10.0 \pm 1.3$ ¹⁹. The next type of diagram to be calculated is the box diagram that occurs at fourth order in the meson field expansion.

4 J/ψ dissociation cross section as a quark exchange process

The J/ψ dissociation cross section in a hot and dense medium of correlated quarks (mesons) has been studied within a nonrelativistic potential model⁸ for quark exchange (string-flip) processes. This calculation gives large energy dependent cross sections with a threshold enhancement (peak value about 6 mb) and an exponential tail. It is, however, questionable whether the inadequate treatment of the pions in these models spoils the results. The pions which are Goldstone bosons of the broken chiral symmetry should be described within a chiral Lagrangian model. The corresponding reformulation of the charmonium dissociation process given previously²⁰ has recently been extended and improved²¹. These approaches disregard the quark substructure effects which give rise to the nonlocality of the formfactors and which are expected to become apparent at finite temperatures and densities close to the QCD phase transition.

Therefore, we consider here the formulation of the J/ψ dissociation process within a relativistic quark model at finite temperature. As a generic new

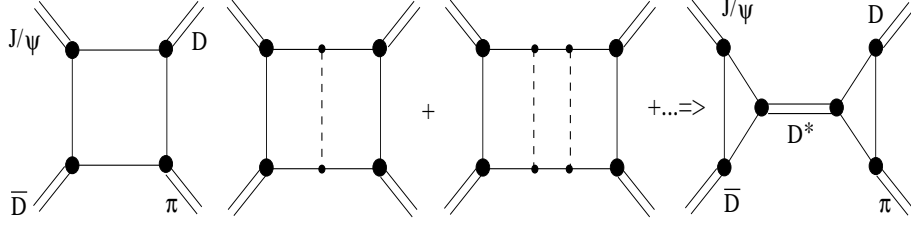


Figure 4: The (anomalous) J/ψ dissociation process in a relativistic quark model. Quark exchange (box diagram) is found to dominate over D^* exchange (ladder resummed box diagram).

mechanism on the quark level that we will study in detail is the anomalous process $J/\psi + \pi \rightarrow D + \bar{D}$ is described by the two types of diagram shown in Fig. 4. One type represents the quark exchange process (box diagram) and the other one describes the D^* exchange (ladder resummed box diagram). In the language of the effective meson Lagrangian model, the box diagram is a contact term which is found to dominate over the heavy-meson exchange. Therefore we will focus on the evaluation of the cross section for the anomalous box diagram as a function of the center of mass energy $\sqrt{s} = \sqrt{(P_{J/\psi} + P_\pi)^2}$

$$\sigma(s) = \int_{t_{min}}^{t_{max}} dt \frac{|T_{J/\psi\pi D\bar{D}}|^2}{16\pi\lambda(s, M_{J/\psi}^2, M_\pi^2)} \quad (8)$$

with the transition amplitude for this process being $T_{J/\psi\pi D\bar{D}}$ and the kinematic function λ as defined above. In our calculations we put $M_\pi = 0$, so that $\lambda = [s - M_{J/\psi}^2]$, $s \geq 4M_D^2$, and the physical region for this process is determined by

$$t_{min,max} = \frac{1}{2}(s - M_{J/\psi}^2) \left[\mp \left(1 - \frac{4M_D^2}{s} \right)^{\frac{1}{2}} - 1 \right] + M_D^2. \quad (9)$$

In the DSE quark model the transition amplitude is given by

$$\begin{aligned} T_{J/\psi\pi D\bar{D}} = e^\mu N_c \int \frac{d^4p}{(2\pi)^4} \frac{1}{[p_2^2 + m_Q^2][p_3^2 + m_Q^2]} \\ \times \text{tr}_D \left\{ [-i(p_1 \cdot \gamma)\sigma_V + \sigma_S] \Gamma_{\bar{D}} [-i(p_2 \cdot \gamma) + m_Q] \Gamma_{J/\psi}^\mu \right. \\ \left. [-i(p_3 \cdot \gamma) + m_Q] \Gamma_D [-i(p_4 \cdot \gamma)\sigma_V + \sigma_S] \Gamma_\pi \right\}, \quad (10) \end{aligned}$$

where $p_1 = p + P_\pi/2$, $p_2 = p + P_\pi/2 - P_D$, $p_3 = p - P_\pi/2 + P_D$, $p_4 = p - P_\pi/2$. Our result for the s dependence of the cross section $\sigma_{J/\psi\pi D\bar{D}}^{\text{box}}$ is shown in Fig. 5. We see a critical enhancement just above the reaction threshold. Then the cross section drops down for higher values of s . This qualitative behavior is similar to the result of a calculation within a non-relativistic potential model⁸ but the absolute value of the cross section without in-medium effects ($n = 0$) is much smaller since we have considered the anomalous process first which vanishes in the non-relativistic treatment.

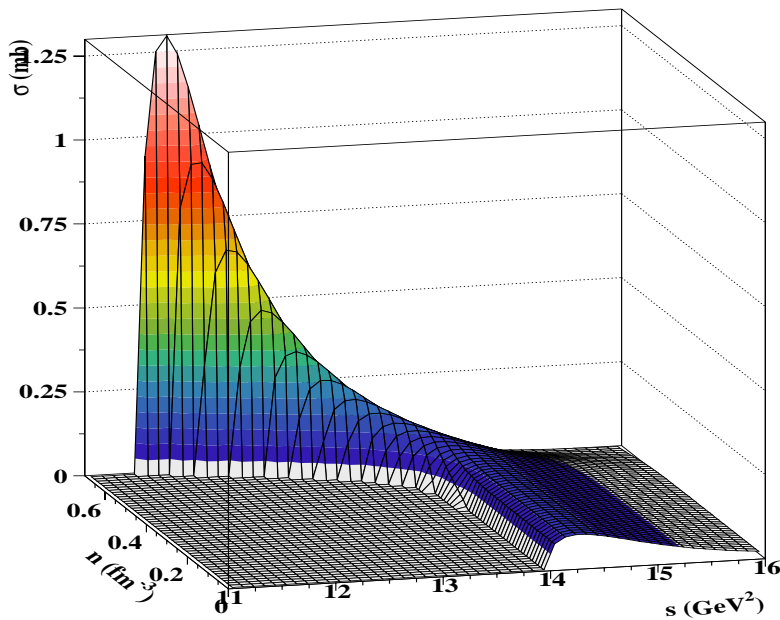


Figure 5: Dependence of the J/ψ dissociation cross section for the anomalous process (box diagram) on the squared center-of-mass energy s and on the parton density n of the medium.

Now we investigate the influence of a hot and dense medium on charmonium dissociation. A first effect is the modification of the D -meson mass $M_D(T)$ due to chiral symmetry restoration. Similar to the temperature de-

pendence of the light quark mass the D -mass is nearly constant for lower temperatures and becomes smaller in the vicinity of the critical temperature, see Fig. 6. Secondly, this effect of chiral symmetry restoration enhances the cross section for the breakup reaction $J/\psi + \pi \longrightarrow D + \bar{D}$. The enhancement of the breakup cross section has a critical temperature/density dependence at the chiral restoration transition.

5 J/ψ kinetics at chiral symmetry restoration

Aiming at a qualitative discussion of possible observable effects of the chiral restoration transition to be seen in the J/ψ production cross section in ultrarelativistic heavy-ion collisions we consider a relaxation time approximation for the evolution of the J/ψ distribution in a hot and dense pion gas with the pion distribution function $f_\pi(\vec{p}; T, \mu_\pi) = \{\exp[(\sqrt{|\vec{p}|^2 + M_\pi^2} - \mu_\pi)/T] - 1\}^{-1}$. This distribution function increases strongly near and above the critical temperature. This leads to a critical enhancement of thermally averaged charmonium dissociation cross section $\langle \sigma_{J/\psi\pi \rightarrow D\bar{D}} v_{\text{rel}} \rangle$ and to a critical drop of the relaxation time τ

$$\tau^{-1} = \langle \sigma_{J/\psi\pi \rightarrow D\bar{D}} v_{\text{rel}} \rangle n_\pi(T) = \int \frac{d\vec{p}_\pi}{(2\pi)^3} f_\pi(\vec{p}_\pi, T) \sigma(\vec{p}_\pi, \vec{p}_\psi) v_{\text{rel}} \frac{P_\psi P_\pi}{E_\psi E_\pi} \quad (11)$$

of the J/ψ distribution in a comoving dense pion (parton) gas. The result is shown in Fig. 6 lower panel. The critical enhancement of the thermally averaged dissociation cross section at the QCD phase transition temperature may lead to the result that in a heavy-ion collision above a critical energy density (E_T) threshold this additional absorption process is switched on and results in an enhanced J/ψ suppression. This pattern may serve as an explanation for the puzzling observation of anomalous J/ψ suppression in the NA50 experiment at CERN SpS, see Fig. 1.

6 Conclusions

A recently developed dynamical approach to the chiral symmetry restoration and deconfinement transition is generalized for heavy mesons and quarkonia; in-medium modifications of masses and decay constants are studied. We apply this model to calculate the cross section for charmonium dissociation by hadron impact and find that contributions from the quark exchange dominate over those from D^* resonance propagation processes. At the QCD phase transition the reaction rates for the J/ψ breakup are strongly enhanced.

The approach will be further developed in order to include the ρ -meson which catalyzes exothermic J/ψ breakup and a treatment of the normal pro-

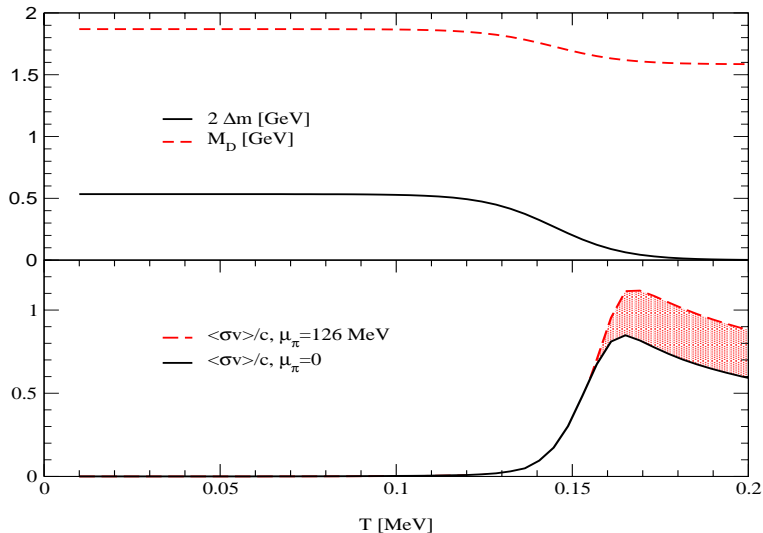


Figure 6: Upper panel: Double quark mass gap (solid line) and D meson mass (dashed line) as a function of temperature. Lower panel: Temperature dependence of the average cross section (arbitrary units) for J/ψ dissociation (anomalous process) in a hot pion gas with critical enhancement at the chiral restoration temperature $T_c = 150$ MeV. The dashed band shows the influence of a finite (nonequilibrium) pion chemical potential.

cess $J/\psi + \pi \rightarrow D\bar{D}^*, D^*\bar{D}$, which should be larger than the anomalous one considered here. On this basis, a detailed quantitative calculation of J/ψ production in the NA50 experiment can be attacked and predictions for the RHIC and LHC colliders can be made. A particularly new aspect is the occurrence of $D\bar{D}$ annihilation into $J/\psi + \pi(\rho)$ (gain process) under these conditions which modifies the charmonium kinetics^{22,23} and may lead to a saturation or even enhancement of the J/ψ abundance.

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