Model of charmonium absorption by light mesons

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We calculate the cross sections for dissociation of J/ψ by pions and ρ mesons within the framework of a meson exchange model. We find that these cross sections are small at center-of-mass energies less than 1 GeV above threshold, and that dissociation rates are less than 0.01 fm/c in a thermal meson gas at temperatures where such a description makes sense. [S0556-2813(98)01511-8]

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A pronounced suppression of the production of strongly bound heavy quarkonium states ($J/\psi,\Upsilon$) is considered as a signature for the formation of a new, deconfined phase of strongly interacting matter in collisions of heavy nuclei at high energy, the quark-gluon plasma [1]. Experimental investigations of charmonium production in nuclear reactions have been carried out for over a decade at the CERN-SPS (p+A,O+U,S+U,Pb+Pb) and the Fermilab Tevatron (p+A) [2–5]. These studies have shown that the J/ψ and ψ' production on nuclear targets is, indeed suppressed relative to expectations from nucleon-nucleon reactions.

For p+A collisions the observed suppression of J/ψ and ψ' can be explained as absorption of a common precursor, probably a nonresonant, color-octet $(c\bar{c})$ state, on nucleons [6]. This systematics extends to O+U and S+U reactions for the J/ψ, but not for the ψ', where additional suppression is observed [4]. This effect can be quantitatively described as absorption of the ψ' on comoving secondary hadrons (''comovers''), mostly light mesons [7–10]. Recently, measurements of charmonium production in the Pb+Pb system [5] have revealed the presence of an additional ''anomalous'' suppression mechanism also for the J/ψ. It is presently under debate whether this mechanism can be absorption of the J/ψ or the down-feeding χ_c on hadronic comovers, or whether a more drastic explanation, such as quark deconfinement, is required [11–13].

In spite of the obvious need to understand the physics of charmonium absorption on comoving hadrons, only very few quantitative predictions for J/ψ absorption cross sections on light mesons have been published [14,15] and these predictions differ by several orders of magnitude. We hope that the results presented below will help clarify this situation. Our calculation is based on an effective hadronic Lagrangian describing the interactions among π, ρ, J/ψ, D, and D^* and, for the sake of simplicity, on the assumption of thermal equilibrium among the light hadrons.

The most abundant mesons in a hot hadronic gas are π, K, and ρ. In addition, nucleons may be abundant at high baryon chemical potential. In the following, we will not consider kaon-induced reactions, but the framework presented here can be easily extended to include this absorption channel. At low energy, π and ρ mesons, as well as nucleons, can induce dissociation processes when encountering a J/ψ particle (we list only the reactions with the lowest energy thresholds):

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

$$\rho+J/\psi\to D+\bar{D}; \tag{2}$$

$$N+J/\psi\to\Lambda_c+\bar{D}. \tag{3}$$

The kinematic thresholds for these reactions are (1) 640 MeV, (2) −135 MeV, and (3) 115 MeV, respectively. The reaction $\rho+J/\psi\to D+\bar{D}$ has the lowest total invariant mass threshold and is, in fact, exothermic. At thermal equilibrium it is only suppressed due to the relatively high mass of the ρ meson which causes ρ mesons to be less abundant than pions in a thermal hadron gas. Reaction (3) is mostly of interest in the fragmentation region, where the nucleon density is high. We will not consider it further here, because it is expected to be of less importance for J/ψ suppression at central rapidity

There are two possible approaches to the J/ψ dissociation problem: one at the quark level where the large mass of the c quark is used to separate perturbative from nonperturbative aspects of the problem, and another one that makes use of effective hadronic interactions. The former approach is based on the pioneering work of Peskin [16] and Bhanot and Peskin [17], who realized that interactions between heavy quark bound states and light hadrons can be described perturbatively, if the heavy quark mass m_Q is sufficiently large. The small size of the $(Q\bar{Q})$ state allows for a systematic multipole expansion of its interaction with external glue fields, where the color-dipole interaction dominates at long range.

In the Bhanot-Peskin framework, light hadrons interact with the J/ψ only via their glue content. Kharzeev and Satz [14] applied this formalism to inelastic $\pi-J/\psi$ scattering and showed that the absorptive cross section is proportional to the component of the gluon structure function $G_h(x)$ of the interacting hadron which is sufficiently energetic to dissociate the J/ψ. Because of this requirement of rather hard gluons, only highly energetic hadrons are capable of exciting a J/ψ above the dissociation threshold. The pion momentum must reach 5 GeV/c before attaining an absorption cross section in excess of 1 mb. The thermally averaged cross section, in this framework, remains less than 0.1 mb for a pion gas within any realistic temperature range.

One limitation of the Bhanot-Peskin approach lies in the fact that the J/ψ is not truly a Coulombic bound state but probes also the confining part of the $c\bar{c}$ potential. Although these nonperturbative contributions to J/ψ absorption by light mesons can be estimated [18], the reliability of such estimates is difficult to assess.

From a microscopic point of view, the reactions (1),(2) can be viewed as quark exchanges, where the J/ψ transmits a charm quark to the light meson and picks up a light (u, d, or s) quark. Since similar reactions among light hadrons typically have large cross sections at moderate energies, one may suspect that these reactions also proceed with significant strength above their respective kinematic thresholds. It is therefore of interest to calculate the dissociation cross sections in the framework of an essentially nonperturbative approach based on a hadronic model that incorporates quark confinement. The cross section for the reaction (1) was calculated in the nonrelativistic quark model by Martins, Blaschke, and Quack [15] in the first Born approximation. Including $D^*\bar{D}$, $D\bar{D}^*$, and $D^*\bar{D}^*$ final states, the total cross section was found to peak around 1 GeV energy above threshold (in the center-of-mass system) at a value of about 7 mb. However, the large magnitude of their result is due to the action of the long-ranged, confining interaction between the quarks, which is modeled as a "color-blind" attractive interaction between the quarks with a Gaussian momentum dependence. Because this interaction is taken as attractive independent of the color quantum numbers of the affected quark pair, it does not cancel in the interaction of a light quark with a pointlike $(c\bar{c})$ pair in a color-singlet state, in contrast to the one-gluon exchange interaction.

Since the results obtained within the constituent quark model differ by orders of magnitude from those obtained in the Bhanot-Peskin approach, and because they depend critically on the particular implementation of the confining quark-quark interaction, it seems prudent to calculate the charm-exchange cross sections in a second, entirely different framework of hadronic reactions. In the effective meson theory, the exchange of a $(c\bar{q})$ or $(\bar{c}q)$ pair, where $q,\bar{q}$ stands for any light quark, can be described as the exchange of a D or D^* meson between the J/ψ and the incident light meson.

At the hadronic level, the charm exchange reaction between the J/ψ and a light hadron can proceed either by exchange of a D or a D^* meson. In fact, Regge theory dictates that the charm exchange reaction is dominated by the exchange of the D^* trajectory in the high-energy limit. However, here we are not interested in charm exchange at high energies but near the kinematical threshold, because the relative motion of the hadrons is limited to thermal momenta. We shall only consider the D-exchange reactions. (The D^*-exchange reaction cross sections exhibit an unphysical rise with energy due to the exchange of longitudinally polarized D^* mesons, which would need to be eliminated with the help of form factors.)

In order to calculate the various Feynman diagrams for the reactions (1),(2) we need to construct the effective three-meson vertices. We can do so by invoking a strongly broken local U(4) flavor symmetry with the vector mesons playing the role of quasigauge bosons. Denoting the 16-plet of pseudoscalar mesons $(\pi,\eta,\eta',K,D,D_s,\eta_c)$ by $\Phi=\phi_i T_i$, where the T_i are the U(4) generators, and the vector meson 16-plet $(\omega,\rho,\phi,K^*,D^*,D_s^*,\psi)$ by $\mathcal{V}^\mu = V_i^\mu T_i$, the free meson Lagrangian reads

$$\mathcal{L}_0 = \mathrm{tr}(\partial^\mu\Phi^\dagger\partial_\mu\Phi) - \mathrm{tr}(\partial^\mu\mathcal{V}^{\dagger,\nu})(\partial_\mu\mathcal{V}_\nu - \partial_\nu\mathcal{V}_\mu) - \mathrm{tr}(\Phi^\dagger M_\mathrm{P}\Phi) + \tfrac{1}{2}\,\mathrm{tr}(\mathcal{V}^{\mu\dagger}M_\mathrm{V}\mathcal{V}_\mu). \quad (4)$$

Here M_P and M_V denote the mass matrices for the pseudoscalar and vector mesons, respectively. Because of the heavy mass of the charm quark, M_P and M_V break the U(4) symmetry strongly down to U(3), the mass of the strange quark introduces a weaker breaking to U(2), and the axial anomaly further breaks the U(2) symmetry to SU(2) in the case of the pseudoscalar mesons. All these symmetry breakings are embodied in the physical mass matrices. It is convenient, in the following, to work with the mass eigenstates.

The meson couplings are obtained by replacing the derivatives ∂_μ by the "gauge covariant" derivatives $D_\mu = \partial_\mu - ig\mathcal{V}_\mu$. In first order in the coupling constant g this procedure leads to the following interactions:

$$\mathcal{L}_\mathrm{int} = ig\ \mathrm{tr}(\Phi^\dagger\mathcal{V}^{\mu\dagger}\partial_\mu\Phi - \partial^\mu\Phi^\dagger\mathcal{V}_\mu\Phi) + ig\ \mathrm{tr}(\partial^\mu\mathcal{V}^{\dagger\nu}[\mathcal{V}_\mu,\mathcal{V}_\nu] - [\mathcal{V}^{\dagger\mu},\mathcal{V}^{\dagger\nu}]\partial_\mu\mathcal{V}_\nu). \quad (5)$$

If the U(4) flavor symmetry were exact, we would expect all couplings given by the same constant g. In view of the significant breaking of the flavor symmetry we anticipate that the effective coupling constants for different three-meson vertices will have different values. However, we will see below that the couplings have remarkably similar values.

In order to describe π- and ρ-induced J/ψ dissociation, we need the ψDD, πDD^*, and ρDD vertices. From Eq. (5) we derive the following interactions:

$$\mathcal{L}_{\pi DD^*} = \frac{i}{2} g_{\pi DD^*}(\bar{D}\tau_i D^{*\mu}\partial_\mu\pi_i - \partial^\mu D\tau_i D_\mu^*\pi_i - \mathrm{H.c.}),$$

$$\mathcal{L}_{\rho DD} = \frac{i}{2} g_{\rho DD}\rho_i^\mu(\bar{D}\tau_i\partial_\mu D - \partial_\mu\bar{D}\tau_i D),$$

$$\mathcal{L}_{\psi DD} = ig_{\psi DD}\psi^\mu[\bar{D}\partial_\mu D - (\partial_\mu\bar{D})D]. \quad (6)$$

Here the τ_i denote the generators of SU(2)-isospin symmetry in the fundamental representation (Pauli matrices). The coupling constants $g_{\psi DD}$, and $g_{\rho DD}$ can be derived from the D-meson electric form factor in the standard framework of the vector meson dominance model [19]. If γ_V denotes the photon-vector meson $\mathcal{V}$ mixing amplitude, the usual analysis yields the relations

$$\gamma_\rho g_{\rho DD} = em_\rho^2, \quad \gamma_\psi g_{\psi DD} = \tfrac{2}{3}\,em_\psi^2. \quad (7)$$

The photon mixing amplitudes γ_V can be determined from the leptonic vector meson decay widths: $\Gamma_\mathrm{Vee} = \alpha\gamma_\mathrm{V}^2/(3m_\mathrm{V}^3)$. Inserting the experimental numbers, one finds

$$g_{\rho DD} \approx 5.6, \quad g_{\psi DD} \approx 7.7. \quad (8)$$

As is well known, different ways of deriving the value of the ρ-meson coupling yield values differing by about 20%. The

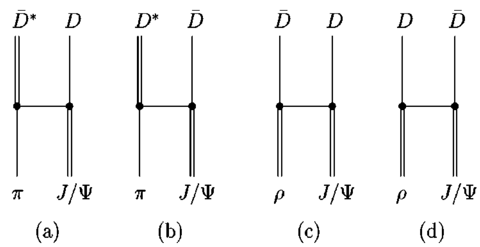

FIG. 1. Lowest-order Feynman diagrams contributing to the charm exchange reactions (1) and (2). Single lines represent pseudoscalar mesons; double lines denote vector mesons.

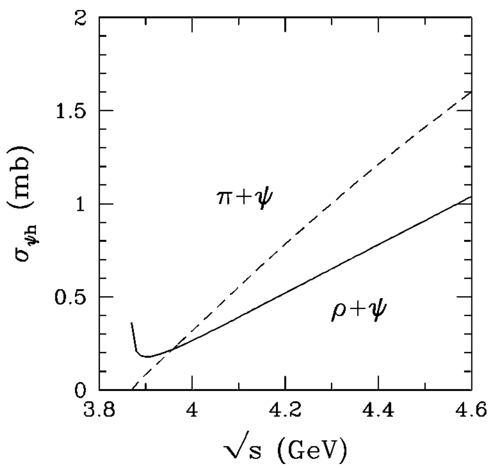

FIG. 2. Cross sections for the charm exchange reactions described by the diagrams of Fig. 1, as functions of c.m. energy. Dashed line: pions, solid line: ρ mesons.

coupling constants (8) must therefore be considered to be given with an error of this order of magnitude.

The π-meson coupling between D and D^* can be obtained from the decay width of the D^* meson: $D^* \to D\pi$. Unfortunately, only an upper bound for this decay rate is known at present [20], corresponding to $g_{\pi DD^*} < 15$. A theoretical estimate for this decay rate, based on QCD sum rules [21], gives

$$g_{\pi DD^*} \approx 8.8. \tag{9}$$

For lack of an experimentally determined value of $g_{\pi DD^*}$ we adopt this value here.

Analytical expressions for the amplitudes and cross sections for the processes corresponding to the Feynman diagrams in Fig. 1 are easily derived. We begin with the two diagrams 1(a) and 1(b) for absorption by pions. Averaging over initial and summing over final isospin and spin states, one obtains

$$\overline{|M_a|^2} = \frac{1}{6} g_{\psi DD}^2 g_{\pi DD^*}^2 \frac{1}{t'^2} \left(4m_\pi^2 - \frac{(t - m_{D^*}^2 - m_\pi^2)^2}{m_{D^*}^2} \right) \times \left(4m_D^2 - \frac{(t - m_D^2 - m_\psi^2)^2}{m_\psi^2} \right) = \overline{|M_b|^2}. \tag{10}$$

Here s, t, and u are the Mandelstam variables and we have introduced the notation $t' = t - m_D^2$, $u' = u - m_D^2$. The contributions of the diagrams 1(c) and 1(d) need to be added coherently, because they lead to identical final states. However, their results are related by crossing symmetry ($t \leftrightarrow u$). After some algebra one finds

$$\overline{|M_c + M_d|^2} = \frac{1}{18} g_{\psi DD}^2 g_{\rho DD}^2 \left[\frac{1}{t'^2} \left(4m_D^2 - \frac{(m_\rho^2 - t')^2}{m_\rho^2} \right) \times \left(4m_D^2 - \frac{(m_\psi^2 - t')^2}{m_\psi^2} \right) + \frac{1}{u't'} \left(2s - 4m_D^2 - \frac{(m_\rho^2 - t')(m_\rho^2 - u')}{m_\rho^2} \right) \left(2s - 4m_D^2 - \frac{(m_\psi^2 - t')(m_\psi^2 - u')}{m_\psi^2} \right) + (t' \leftrightarrow u') \right]. \tag{11}$$

The charm exchange cross sections are plotted in Fig. 2 as functions of the center-of-mass energy $\sqrt{s}$. The $\pi + J/\psi$ cross section (dashed line) starts at zero, because the reaction is endothermic, whereas the $\rho + J/\psi$ cross section (solid line) is finite at the threshold because of its exothermic nature. Note that the cross sections for these two J/ψ absorption reactions are of similar magnitude over the energy range relevant to a thermal meson environment.

Although pions are far more abundant than ρ mesons in the temperature range where a hadronic gas is likely to exist, most of these pions do not have sufficient energy to dissociate a J/ψ. If one counts only those pions having energy above the kinematical threshold for J/ψ dissociation, π and ρ mesons are about equally rare, because their effective density does not exceed 0.1 fm^{-3} even at $T = 200$ MeV, where the hadron picture of a thermal environment probably already breaks down. As a consequence, we expect dissociation rates of similar size for π and ρ mesons at thermal

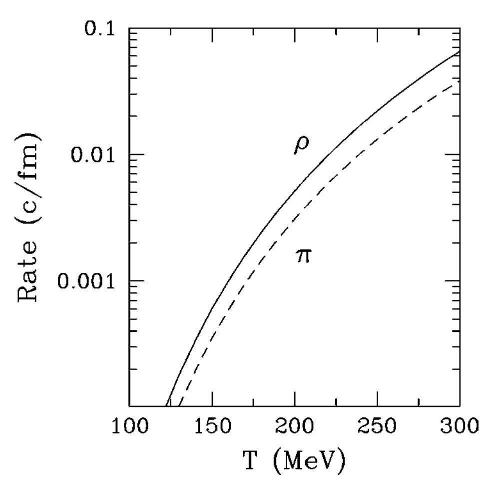

FIG. 3. Thermal J/ψ absorption rates as function of temperature. The pion and ρ-meson rates are shown separately.

equilibrium. Figure 3 shows these J/ψ absorption rates as a function of temperature. Even at the (unrealistically) high temperature $T=300$ MeV, the thermal dissociation rates are still so small that a J/ψ continues to have a lifetime around 10 fm/c. For $T\leqslant 200$ MeV, dissociation by hadrons is completely negligible on the time scale of the lifetime of a hot hadronic gas state in nuclear collisions.

The inclusion of a form factor in the meson vertices of the Feynman diagrams (1) would further reduce the dissociation rates. E.g., a Gaussian form factor $\exp(-Q^2/Q_0^2)$ with $Q_0=1.5$ GeV would reduce the absorption rates by slightly more than one order of magnitude. This implies that our result represents an upper limit for the hadronic dissociation rate. As we noted above, our analysis remains incomplete because of the neglect of D^*-exchange reactions. It would be most interesting to include these reactions in the framework of a complete effective Lagrangian describing the interactions of the pseudoscalar and vector mesons with quark content $(q\overline{q})$, $(Q\overline{q})$, $(q\overline{Q})$, and $(Q\overline{Q})$, where q stands for any light quark flavor and Q denotes a heavy quark. Such a Lagrangian embodying chiral symmetry for the light quarks has recently been given by Chan [22]. Loop corrections to the tree diagrams would permit the study of form-factor effects in this approach, as well.

In conclusion, we have calculated the dissociation cross sections and thermal absorption rates of J/ψ mesons on pions and ρ mesons in the framework of an effective meson exchange model. We find that the dissociation rates in a thermal meson gas, at temperatures where such a gas is expected to exist, are very small corresponding to a survival time of the J/ψ in excess of 100 fm/c. Our results are in line with those recently obtained for other absorption channels, such as $\pi+J/\psi\rightarrow\pi+\psi'$ [23] and $\rho+J/\psi\rightarrow\pi+\eta_c$ [24]. Taken together, these results indicate that a thermal hadronic environment in the confined phase of QCD cannot be the cause of significant absorption of J/ψ mesons.

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