

## Charmonium dissociation in hadronic matter

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Production of  $J/\psi$  from nucleus-nucleus reactions depends sensitively on the dissociation cross section with light hadrons. Effective Lagrangian methods are used to describe the hadronic degrees of freedom, including strangeness and charm. Cross sections with pions, rho mesons, kaons, and nucleons having magnitudes 4–8 mb are found, and with steep thresholds. This, folded with thermal momentum distributions for the scattering partners, suggests a mean dissociation lifetime  $\approx 20$  fm/ $c$ . Therefore, the “abnormal”  $J/\psi$  suppression seen in recent Pb+Pb experiments seems to owe a debt to expected hadron kinetics.

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Response of nuclear matter to high energy densities affords the possibility of creating in the laboratory a system of quantum chromodynamic (QCD) matter, the so-called quark gluon plasma. Among the signatures for creation of the mesoscopic colored volume is an idea put forward in 1986 by Matsui and Satz [1] to look at electromagnetic spectra for evidence of charmonium—bound states of charm-anticharm. They are very tightly bound and consequently relatively small hadrons which ought to effectively probe superdense hadronic matter. Their utility in this context comes from the fact that Debye [color] screening in the plasma would so strongly suppress  $c\bar{c}$  binding in favor of charm propagating decoupled from anticharm to later join with more abundant light antiquark species forming  $D$  mesons, that suppression of  $J/\psi$  would indicate plasma formation. Above some critical temperature, the screening radius becomes smaller than the binding radius offering this possibility.  $J/\psi$  suppression has since been regarded as a promising signature of quark gluon plasma formation.

Charmonium production cross sections from proton-induced reactions that are directly proportional to the target mass number  $A$ , are said to be normal. And yet, proton-nucleus and nucleus-nucleus experiments performed over the past several years have exhibited a common  $A^\alpha$  dependence, with  $\alpha \approx 0.92$  [2–4]. This suppression is now understood as being due to absorption of the precursor state to  $J/\psi$  on nucleons and so is in some sense of normal hadronic consequences. Additional suppression of  $\psi'$  production revealed in nucleus-nucleus experiments has been attributed to absorption on produced comoving hadrons [5,6]. However, recent experimental studies at CERN have investigated  $J/\psi$  production in Pb+Pb reactions at 158 GeV/nucleon and have reported a dramatic “abnormal” suppression compared to lighter systems’  $(AB)^\alpha$  behavior [7]. It is reasonable to begin discussing the possibility of deconfinement being responsible. But first, all conventional suppression mechanisms must be under control.

Absorption of  $J/\psi$  or  $\psi'$  on comovers has been proposed as the dominant dissociating effect. One mechanism owes to deconfinement; if the plasma were present, charmonium

states would not form at all, due to screening. This is simply a restatement of the signature idea of Matsui and Satz. Another mechanism discussed in the literature is prethermal dissociation, where the charmonium is excited above the  $(D\bar{D})$  threshold either by a partonic medium which has not had sufficient time to equilibrate [8], or by color flux tubes in the infant QCD medium [9,10]. The effectiveness of prethermal suppression mechanisms rests on separation of time scales: the first mechanism requires that dissociation proceeds faster than thermalization and the second requires that color flux tubes decay more slowly than dissociation. Finally, we come to thermal dissociation where the  $(c\bar{c})$  is absorbed through one of the myriad processes involving a light hadron.

The crucial question is the magnitudes of cross sections for  $J/\psi+h$ , where  $h$  is one of the set  $(\pi, \rho, K, N, \dots)$ . Estimates up to now have included (1) a perturbative approach at the quark level where light hadrons interact with  $J/\psi$  solely through gluonic content effects [11,12], (2) a nonperturbative study with quark exchange including a confining potential [13], and finally (3) an effective Lagrangian approach [14]. When the perturbative approach of Peskin and Bhanot was applied by Kharzeev and Satz to pions interacting with  $J/\psi$ , a cross section  $\approx 0.1$  mb was found for  $\sqrt{s}$  roughly 1 GeV above threshold [15]. Results for the nonperturbative calculation of Martins, Blaschke, and Quack applied to pions revealed cross sections peaking at several mb also about 1 GeV above threshold. The hadronic field theory calculation of Matinyan and Müller resulted in cross sections with pions and rho mesons of order 1 mb for similar energies. This situation is unsettling as there is roughly two orders of magnitude discrepancy in these estimates. The aim of this Rapid Communication is to report on further investigation of the issue using effective Lagrangian methods quantifying cross sections within a consistent gauge invariant treatment (including contact terms which are missing in previous analyses) and including a more complete hadronic medium as input to kinetic theory for a baseline estimate of the dissociation rate in hadronic matter.

Hot hadronic matter is populated most abundantly by  $\pi$ ,  $K$ , and  $\rho$  [16]. If circumstances of an appreciable baryon chemical potential arise, the nucleons become important as well. Each species can induce charmonium dissociation with respective final states governed by conservation laws. A con-

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sistent treatment of light mesons, heavy mesons, and possibly baryons is needed to work toward a reasonably reliable description for hadronic matter. We begin with an  $SU(4)$  symmetry so as to include charm, and we introduce pseudoscalar ( $P = \varphi_a \lambda_a$ ) and vector ( $V^\mu = v_a^\mu \lambda_a$ ) meson matrices, where  $\varphi_a$  and  $v_a^\mu$  are pseudoscalar and vector multiplets and the  $\lambda_s$  are  $SU(4)$  generators [17]. The symmetry is severely broken due to the large charm quark mass, so we use physical mass eigenstates and matrices, and incorporate constraints where possible.

The free meson Lagrangian reads

$$L_0 = \text{Tr}(\partial^\mu P^\dagger \partial_\mu P) - \frac{1}{2} \text{Tr}(\partial^\mu V^{\dagger \cdot \nu} - \partial^\nu V^{\dagger \cdot \mu})(\partial_\mu V_\nu - \partial_\nu V_\mu) + \text{mass terms.} \quad (1)$$

Interactions are generated by replacing the spacetime derivative with a gauge covariant one  $\partial_\mu f \rightarrow D_\mu f = \partial_\mu f + [A_\mu, f]$ , where  $A_\mu = -ig/2V_\mu$ . The vector mesons are recognizable as playing roles of gauge bosons. As is usual in effective field theory strategies, to keep gauge consistency, we must collect terms of order  $g^2$ . They are (using  $P^\dagger = P$  and  $V^\dagger = V$ )

$$L_{\text{int}} = ig \text{Tr}(PV^\mu \partial_\mu P - \partial^\mu PV_\mu P) + \frac{1}{2} g^2 \text{Tr}(PV^\mu V_\mu P - PV^\mu PV_\mu) + ig \text{Tr}(\partial^\mu V^\nu [V_\mu, V_\nu] + [V^\mu, V^\nu] \partial_\mu V_\nu) + g^2 \text{Tr}(V^\mu V^\nu [V_\mu, V_\nu]). \quad (2)$$

The order  $g$  terms deliver three-point vertices and the order  $g^2$  terms are responsible for so-called contact terms, or four-point couplings which are necessary for a gauge invariant theory. The interactions of interest for this study are the following (using  $\psi$  as shorthand for  $J/\psi$ ):

$$\begin{aligned} L_{\pi DD^*} &= \frac{i}{2} g_{\pi DD^*} (\bar{D} \tau_i D^* \partial_\mu \pi_i - \partial^\mu \bar{D} \tau_i D_\mu^* \pi_i - \text{H.c.}), \\ L_{\rho DD} &= \frac{i}{2} g_{\rho DD} \rho_i^\mu (\bar{D} \tau_i \partial_\mu D - \partial_\mu \bar{D} \tau_i D), \\ L_{\rho D^* D^*} &= -\frac{i}{2} g_{\rho D^* D^*} \rho_i^\mu (\bar{D}^{*\nu} \tau_i (\partial_\mu D_\nu^*) - (\partial_\mu \bar{D}^{*\nu}) \tau_i D_\nu^* \\ &\quad - (\partial_\nu D_\mu^*) \tau_i \bar{D}^{*\nu} + (\partial_\nu \bar{D}_\mu^*) \tau_i D^{*\nu}), \\ L_{\psi DD} &= ig_{\psi DD} \psi^\mu (\bar{D} \partial_\mu D - (\partial_\mu \bar{D}) D), \\ L_{\psi D^* D^*} &= -ig_{\psi D^* D^*} \psi^\mu (\bar{D}^{*\nu} (\partial_\mu D_\nu^*) - (\partial_\mu \bar{D}^{*\nu}) D_\nu^* \\ &\quad - (\partial_\nu D_\mu^*) \bar{D}^{*\nu} + (\partial_\nu \bar{D}_\mu^*) D^{*\nu}), \end{aligned} \quad (3)$$

and

$$\begin{aligned} L_{\psi \pi DD^*} &= -g_{\psi DD} g_{\pi DD^*} \psi^\mu D_\mu^* \tau_i \bar{D} \pi_i, \\ L_{\psi \rho DD} &= -g_{\rho DD} g_{\psi DD} \psi^\mu \rho_{\mu,i} \bar{D} \tau_i D, \end{aligned}$$

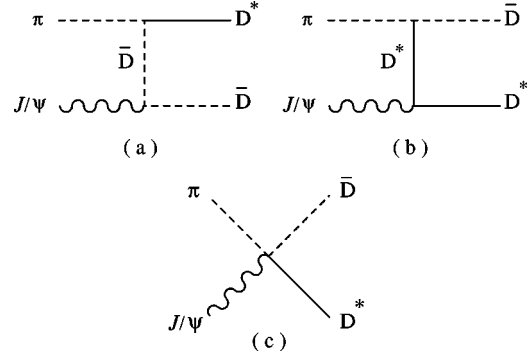


FIG. 1. Feynman graphs for the process  $J/\psi + \pi \rightarrow \bar{D} + D^*$ .

$$L_{\psi \rho D^* D^*} = \frac{1}{2} g_{\psi D^* D^*} g_{\rho D^* D^*} \psi^\mu (2\rho_{\mu,i} \bar{D}^{*\nu} \tau_i D_\nu^* - \rho_i^\nu \bar{D}_\mu^* \tau_i D_\nu^* - \rho_i^\nu \bar{D}_\nu^* \tau_i D_\mu^*). \quad (4)$$

The  $K-D_s-D^*$  interaction has the same structure as the  $\pi-D-D^*$  interaction, complete with contact terms.

In this approach there are several coupling constants in Eqs. (3) and (4). Methods for constraining them will be discussed below. The  $\mathcal{O}(g^2)$  terms carry one power of coupling constant for each three-point vertices from which the contact term collapses. As a specific example, the direct, exchange, and contact graphs for reaction  $J/\psi + \pi \rightarrow D^* + \bar{D}$  are shown in Figs. 1 (a), 1(b), and 1(c), respectively. Contribution to the amplitude from each graph is proportional to  $g_{\pi DD^*} g_{\psi DD}$ .

Appealing to measured hadronic decays to constrain the coupling constants gains very little in this case as the best measurement of the  $D^{*\pm}$  width has an upper limit of 131 keV [18]. Model calculations based on relativistic potential approaches suggest  $\Gamma_{D^{*\pm}} = 46$  keV [19]. This corresponds to a value for  $g_{\pi DD^*}$  of 8.8, which will be used here. In the absence of empirical constraints, all other coupling constants are obtained from vector meson dominance or flavor symmetry arguments. Vector dominance gives [14]

$$g_{\rho DD} = g_{\rho D^* D^*} = 5.6, \quad g_{\psi DD} = g_{\psi D^* D^*} = 7.7. \quad (5)$$

For the kaons, we use  $SU(4)$  symmetry to relate  $g_{KD_s D^*} = \sqrt{2} g_{\rho \pi \pi} = 8.5$ , and the  $\rho \pi \pi$  coupling is adjusted to give a  $\rho$  width of 151 MeV.

The following absorption reactions are considered:

$$\pi + J/\psi \rightarrow D + \bar{D}^*, \quad \bar{D} + D^*, \quad (6)$$

$$\rho + J/\psi \rightarrow D + \bar{D}, \quad \bar{D}^* + D^*, \quad (7)$$

$$K + J/\psi \rightarrow D_s + \bar{D}, \quad \bar{D}_s + D, \quad \bar{D} + D_s^*, \quad D + \bar{D}_s^*. \quad (8)$$

Just as in Fig. 1, for a reaction of type (6), each of the reactions listed in Eqs. (6)–(8) has a direct, exchange, and ‘‘seagull’’ graph contributing to the amplitude. Full expressions for the amplitudes and other details will be published elsewhere [20].

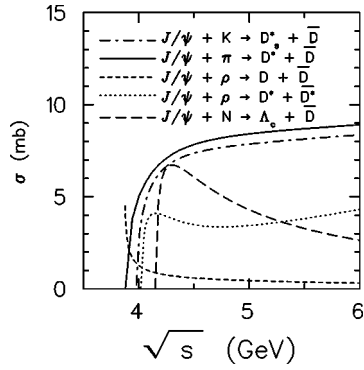


FIG. 2. Dissociation cross sections for  $\pi$ ,  $\rho$ , and kaon. Nucleon-induced dissociation is also included. See text for details.

Results for cross sections as functions of  $\sqrt{s}$  are presented in Fig. 2. A startling feature in the endothermic reactions is the sharp rise just above threshold. The cross sections reach maximum strength a few hundred MeV above their respective thresholds. We note the significant difference between these results and the  $\pi$ - and  $\rho$ -induced reactions from Ref. [14], which are due to the inclusion of contact terms and interference effects. Further, we note the relatively large kaon cross section.

Next we turn to the baryons and begin by writing an effective Lagrangian describing the interaction with pseudoscalars. The full  $SU(4)$  expression is quite lengthy [21], so we concentrate on the particular term allowing analysis of the reaction  $J/\psi + N \rightarrow \Lambda_c + \bar{D}$ . The Lagrangian bearing pseudoscalar coupling is [22]

$$L_{DNA_c} = g_{DNA_c} (\bar{N} \gamma_5 \Lambda_c \bar{D} + \bar{\Lambda}_c \gamma_5 N D). \quad (9)$$

The coupling constant is constrained by QCD sum rules which predicts a value  $g_{DNA_c} = 6.7 \pm 2.1$  [23]. There are two Feynman graphs, a direct and exchange contribution, which when added together once again produce an amplitude respecting gauge invariance. The cross section is presented also in Fig. 2. It rises sharply at threshold to  $\approx 7$  mb and falls with rising energy.

After the early stages of a high-energy heavy-ion reaction, the produced hot and dense system rapidly expands and cools leaving a kinetically thermal and probably even chemically equilibrated hadronic fireball. The fireball quickly cools, and most likely falls out of chemical equilibrium [24,25], until it eventually freezes out. Therefore, charmonium kinetics over a range of temperatures are needed for establishing predictions for  $J/\psi$  production. Relativistic kinetic theory allows for simple estimates of rates. Nonequilibrium effects are of course important, and will be discussed elsewhere [20]. In general, the invariant four rate for  $a+b$  scattering assuming Boltzmann distributions is

$$dR = \frac{gT^2}{(2\pi)^4} \int_{z_{\min}}^{\infty} dz \lambda(z^2 T^2, m_a^2, m_b^2) d\sigma K_1(z), \quad (10)$$

where  $g$  is an overall degeneracy factor,  $z = \sqrt{s}/T$ ,  $z_{\min} = \max(m_a + m_b, M)/T$ , with  $M$  being the sum of all final state

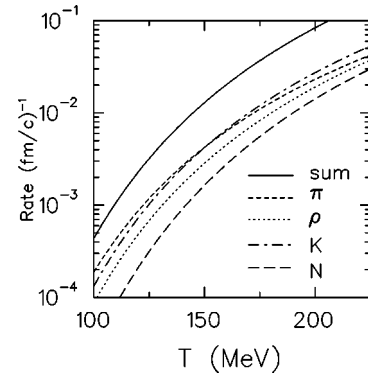


FIG. 3. The thermal rates for  $J/\psi$  dissociation induced by  $\pi$  (short-dashed curve),  $\rho$  mesons (dotted curve), kaons (dot-dashed curve), and nucleons (long-dashed curve), and the sum (solid curve).

particles' masses, and  $K_1$  is a modified Bessel function. The number of times particle  $a$  scatters with a particle of type  $b$  per unit time is then

$$\text{Rate} = \frac{dR}{dN_b}, \quad (11)$$

where  $dN_b$  is the number density of  $b$  particles,

$$dN_b = \frac{g_b}{2\pi^2} T m_b^2 K_2(m_b/T). \quad (12)$$

Again,  $K_2$  is a modified Bessel function.

The number of  $J/\psi$  dissociations per unit time induced by each light hadronic species are shown separately in Fig. 3 as well as a combined sum.  $J/\psi$  dissociation rate in resonance matter is  $\approx 0.03$   $(\text{fm}/c)^{-1}$ . If we look toward temperatures approaching 200 MeV, the rate approaches  $0.1$   $(\text{fm}/c)^{-1}$ . It was previously thought that thermal hadronic dissociation rates were so small as to be insignificant on the time scale of the fireball created in heavy ion reactions. Figure 3 indicates that reactions with light hadrons will indeed be an important hindrance for charmonium production.

There are of course error bars to discuss associated with these calculations. First, the coupling constants are uncertain to a level of ten percent or so. Form factors, which would tend to reduce the cross sections, have not been included. On the other hand, a long list of reactions involving other mesons could be imagined, and some of these reactions might be important. For instance, axial vector charm mesons  $D_1(2420)$  [26] have relatively large widths and could therefore play an important role in dissociating  $J/\psi$  through such reactions as

$$\pi + J/\psi \rightarrow D_1 + \bar{D}^*, \quad \bar{D}_1 + D^*. \quad (13)$$

Another candidate likely affecting  $J/\psi$  dissociation in the medium is  $\chi_c$ .

Finally, the rate estimates made here would be increased dramatically if phase space were overpopulated, interpretable

as finite chemical potentials. As the fireball expands isentropically, pion and kaon chemical potentials of order 50–100 MeV develop in model calculations [25]. This would easily buy back a significant factor in the rates. All these effects are currently under investigation and will be reported upon separately [20].

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