Charmonium Cross Sections and the QGP

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In this short review we summarize experimental information and theoretical results for the low-energy dissociation cross sections of charmonia by light hadrons. These cross sections are required for the simulation of charmonium absorption through collisions with comovers in heavy ion collisions, which competes with quark-gluon plasma production as a charmonium-suppression mechanism. If the cross sections are sufficiently large these dissociation reactions may be misinterpreted as an effect of quark-gluon plasma production. Theoretical predictions for these RHIC-related processes have used various methods, including a color-dipole scattering model, meson exchange models, constituent interchange models and QCD sum rules. As the results have been largely unconstrained by experiment, some of the predictions differ by orders of magnitude, notably in the near-threshold regime that is most relevant to QGP searches.

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INTRODUCTION

Many unusual subjects have been studied in the name of QCD. One of the more unusual, which has arisen in the field of heavy ion collisions, is the size of cross sections of charmonia on light hadrons. This has attracted attention because of the proposal by Matsui and Satz [1] that suppression of $J/\psi$ production could be used as a signature for the formation of a quark-gluon plasma.

This suggestion, like many signatures proposed for the quark-gluon plasma, is perhaps excessively intuitive. The idea is that a QGP will screen the linear confining action between quarks, so that a $c\bar{c}$ pair produced within a QGP will be less likely to form a bound $c\bar{c}$ charmonium resonance, as in Fig.1, but instead will more likely separate to form open-charm mesons.

Even if this simple picture of $c\bar{c}$ production in a QGP is qualitatively correct, it can only be confirmed easily if the competing direct charm production and scattering by the initial relativistic nucleons is understood [2, 3, 4] and if there is little subsequent dissociation of the charmonia by the many other “comoving” light hadrons produced in such a collision. To summarize the last point, if charmonium + light hadron “comover” dissociation cross sections are small (case 1, top of Fig.1) and the background of direct charm production from the initial nucleons is understood, one may have a useful signature of QGP formation, but if the comover dissociation cross sections are large (case 2, bottom of Fig.1) one must distinguish a QGP-reduced charmonium production amplitude from subsequent dissociative scattering, and the interpretation of this signal will therefore be ambiguous.

Thus it is of great relevance to the interpretation of RHIC physics to establish the approximate size of these low-energy $c\bar{c} +$ light hadron cross sections.

FIG. 1: We wish to distinguish between 1) weak and 2) strong $J/\psi$ absorption by light comovers.

EXPERIMENT, OR WHAT PASSES FOR IT

Unfortunately we have no charmonium beams or targets, so the experimental cross sections must be inferred indirectly and are poorly known. The earliest estimates of lower energy charmonium hadronic cross sections came from $J/\psi$ photoproduction experiments in the mid 1970s, which were interpreted in terms of a $J/\psi + N$ cross section given additional theoretical assumptions. Early Fermilab and SLAC photoproduction experiments gave rough estimates of $\sim 1$ mb for $\sigma_{J/\psi + N}$, assuming vector dominance,
for photon energies from $E_{\gamma} \approx 13$ to 200 GeV. A subsequent SLAC photoproduction experiment in 1977 used the $A$ dependence of $J/\psi$ absorption to estimate a rather larger cross section of $\sigma_{J/\psi|N} = 3.5(0.8)$ mb at $E_{\gamma} \approx 17$ GeV ($\sqrt{s} \approx 6$ GeV). The vector dominance hypothesis may have lead to an underestimate of the cross section in the earlier references.

In heavy ion collisions these cross sections may be estimated from the ratio of lepton pairs produced in the $J/\psi$ peak to “background” Drell-Yan pairs nearby in energy. Since the $J/\psi$ must reach the exterior of the nuclear target to decay into a sharp mass peak, this ratio gives us an estimate of the absorption cross section through a classical survival probability formula,

$$\sigma(J/\psi \rightarrow \mu^+\mu^-)/\sigma(\text{Drell-Yan} \mu^+\mu^-) = \exp(-\rho \sigma_{J/\psi+N}^{abs} L) \quad (1)$$

where $\rho$ is the mean nucleon density and $L$ is the estimated mean path length in the experimental nuclear system. A “naïve” interpretation of the $J/\psi$ production data from collisions of various nuclear species using this formula gives $\sigma_{J/\psi+N}^{abs} \approx 6$ mb at $\sqrt{s} \approx 10$ GeV, with a numerically similar result for the $\psi'$.

Of course one may raise many questions about the validity of this simple estimate, including the importance of shadowing in Drell-Yan, the neglect of $J/\psi$ scattering by other light hadrons formed in the collision (for example $\pi$ and $\rho$), and the assumption of a single, constant $J/\psi+N$ cross section in all circumstances.

In addition to these more or less direct measurements there have been several attempts to infer charmonium cross sections from related processes, given additional theoretical assumptions. A series of theoretical papers \[10, 11, 12, 13\] has estimated the rather weak closed-flavor cross sections such as $J/\psi + \pi \rightarrow \psi' + \pi$ near threshold from the observed dipion decays (here $\psi' \rightarrow \pi\pi J/\psi$). Redlich et al. \[14\] have used charm photoproduction data combined with a vector dominance model to estimate the $J/\psi N$ cross section, and find quite small values near threshold. Hüfner et al. \[15\] again argue however that vector dominance is not justified for this process, so that the $J/\psi + N$ cross sections estimated in this manner are inaccurate.

Recently, concerns have been expressed that the $J/\psi$ and $\psi'$ wavefunctions have not had sufficient time to form within the nucleus in these collisions, so experiment may instead be measuring the cross section for a small initial $c\bar{c}$ “premeson” on a nucleon. One can increase the time spent in the interior of the nuclear system by selecting small and even negative $x_F$ events, as has been done by E866 at Fermilab. As discussed by He, Hüfner and Kopeliovich \[16, 17\], this leads one to infer $\sigma_{J/\psi+N}^{abs} = 2.8(0.3)$ mb and $\sigma_{\psi'+N}^{abs} = 10.5(3.6)$ mb respectively, also at $\sqrt{s} \approx 10$ GeV. This is rather more satisfying to people who have an intuitive notion that the larger $\psi'$ should have a larger reaction cross section. Actually the connection between cross section and physical extent is less direct (compare KN and KN), and in any case the relative proximity of inelastic thresholds alone would suggest a larger $\psi'$ cross section. These experiments also indicate a preference for dissociation over elastic cross sections in this energy region by roughly a factor of 30 \[16, 17\].

THEORY: INTRODUCTION

To quote B. Müller in 1999, “...the state of the theory of interactions between $J/\psi$ and light hadrons is embarrassing [...]”. Only three serious calculations exist (after more than 10 years of intense discussions about this issue!) and their results differ by at least two orders of magnitude in the relevant energy range [...]. There is a lot to do for those who would like to make a serious contribution to an important topic.” \[18\].

The theoretical situation has improved considerably in recent years, at least in terms of the number of calculations if not in the understanding of the scattering mechanism. A list of $c\bar{c}$ + light hadron cross section calculations is given in Table I.

Color Dipole Model

The most cited work, albeit furthest in its predictions from a low-energy “theoretical mean”, is the color-dipole scattering calculation of Kharzeev and Satz \[19\]. This reference is basically a restatement of the color-dipole model developed in the late 1970s by Peskin and Bhanot...
TABLE I: A summary of near-threshold $c\bar{c}+\text{light hadron}$ cross section calculations.

| Method          | Init. State | Ref. |
|-----------------|-------------|------|
| color dipole    | $J/\psi+N$  | [19] |
|                 | $J/\psi + (\pi,N)$ | [20] |
|                 | $(J/\psi,\psi')+N$ | [15, 21] |
| meson ex.       | $J/\psi + \pi$ | [27] |
|                 | $J/\psi + \pi,\rho$ | [28, 29, 30, 31, 32] |
|                 | $J/\psi+N$ | [33, 34] |
|                 | $J/\psi + \pi, K,\rho,N$ | [35, 36] |
| constit. int.   | $J/\psi + \pi$ | [27, 37] |
|                 | $(J/\psi,\psi') + (\pi,\rho)$ | [38] |
|                 | $(J/\psi,\psi',\chi_J) + (\pi,\rho, K)$ | [39] |
|                 | $(J/\psi,\psi') + (\pi,\rho,\chi_J)$ | [40] |
|                 | $J/\psi+N$ | [41] |
|                 | $(J/\psi,\psi') + (\pi,N)$ | [42] |
| QCD sum rules   | $J/\psi + \pi$ | [43, 44] |

for scattering of light hadrons by Coulombic bound states of very massive quarks. According to Peskin, the criterion for validity of this approach is “...not met even for the $b\bar{b}$ system.” [23], so there may be large systematic errors at the $c\bar{c}$ mass scale. This approach certainly makes marginal approximations for charmonium, such as the use of Coulombic wavefunctions (which are far from accurate for $c\bar{c}$) and the introduction of a $QQ$ binding energy (which is hard to interpret for charmonium, and is taken to be $2 M_D - M_{J/\psi}$ by Kharzeev and Satz). These color-dipole scattering formulas also implicitly assume that charmonia are small relative to the natural QCD length scale. Since potential models actually find rms $c\bar{c}$ separations of about 0.4 fm for the $J/\psi$, 0.6 fm for the $\chi_c$ states and 0.8 fm for the $\psi'$ [20], this is also a dubious assumption.

Although this approach has problems with justification for $c\bar{c}$, the predictions are nonetheless interesting as estimates of the scale of these cross sections assuming a color-dipole scattering mechanism, and the approach could presumably be extended to lower energies by generalizing the wavefunctions and interaction. The formula for the $J/\psi+N$ cross section quoted by Kharzeev and Satz [19] is

$$\sigma_{J/\psi+N} = 2.5 \text{ mb } \left(1 - \frac{\lambda_0}{\lambda}\right)^{6.5}$$  \hspace{1cm} (2)

where $\lambda = (s - M_{J/\psi}^2 - M_N^2)/2 M_{J/\psi}$, the constant $\lambda_0$ is defined to be $\lambda \sim M_N + \epsilon_0$ according to the text following Eq.(24) of [19] (we assume the equality), and the “binding energy” $\epsilon_0$ is set to $2 M_D - M_{J/\psi}$. The result is shown in Fig.3, together with the single lower-energy SLAC experimental point [5].

Evidently the Kharzeev-Satz cross section is smaller than this SLAC point (which was an inferred cross section and certainly needs confirmation) by about two orders of magnitude, and falls precipitously as $\sqrt{s}$ is decreased. Their calculation actually has no direct information about physical thresholds, so Kharzeev et al. typically leave their curves “dangling” just below $\sqrt{s} = 5$ GeV. (See Fig.2 of [19] for example.) If we plot their formula Eq.(2) for $J/\psi+N$ at low energy (Fig.3), we find the unphysical prediction of a zero cross section near 4.5 GeV, whereas the physical $\Lambda_c + D$ threshold is at 4.15 GeV. Obviously this calculation is inapplicable at low energies, which is unfortunate because this is the regime of greatest interest for QGP searches.

Similar cross section calculations have since been reported by Arleo et al. [21] and Oh et al. [21] (also using Coulomb wavefunctions, but incorporating physical kinematical constraints) and by Hufner et al. [13], using a similar dipole scattering model with more realistic $c\bar{c}$ wavefunctions. Oh et al. [21] note that this model predicts an extremely large cross section ratio of $\sigma_{\psi'p}/\sigma_{J/\psi+p} \sim 2000$-5000 at 4.2 GeV. Hufner et al. find $J/\psi+p$ and $\psi'+p$ cross sections of $\approx 3$ mb and 10 mb respectively at $\sqrt{s} = 10$ GeV (see their Fig.10), and do not consider use of this approach justified near threshold.

**Meson Exchange Models**

Several calculations of charmonium + light hadron cross sections have been reported assuming $t$-channel charmed meson exchange. Of course this picture is also problematic, since the range of the exchanged charmed meson would be only about $1/M_D \approx 0.1$ fm, and the assumption of nonoverlapping hadrons at this separation is clearly invalid. (This is the Isgur-Maltman [13] argument as to why vector meson exchange is unjustified as the source of the short-ranged NN core interaction.) Nonetheless it is again interesting to see what scale of cross section is predicted by this type of model, since it
FIG. 4: The Matinian-Müller $t$-channel meson exchange results for $J/\psi + \pi$ and $J/\psi + \rho$ inelastic cross sections [28].

might at least incorporate the correct scales and degrees of freedom, and it assumes a different scattering mechanism from the color-dipole model advocated by Kharzeev and Satz.

The first such meson exchange calculation, due to Matinian and Müller [28], considered $t$-channel D exchange as the mechanism for the reactions $J/\psi + \pi \to D^* \bar{D} + h.c.$ and $J/\psi + \rho \to D \bar{D}$; their results are shown in Fig. 4. Note that 500 MeV above threshold these cross sections lie in the 0.5 to 1 mb range. A subsequent calculation by Haglin [35], who assumed an SU(4) invariant gauge field effective meson lagrangian, found few-mb scale results for these cross sections near threshold.

Similar meson exchange dissociation cross sections calculations for $J/\psi + N$ were reported by Haglin [35], Sibirtsev, Tsushima and Thomas [33] and Liu, Ko and Lin [34]. Haglin found a peak of about 7 mb near $\sqrt{s} = 4.3$ GeV, whereas Sibirtsev et al. found a peak cross section of about 1 mb near $\sqrt{s} = 4.6$ GeV (Fig. 5). Liu et al. found a scale similar to Sibirtsev et al. near threshold, but concluded that production of charmed meson pairs dominated at higher energies. Since Kharzeev and Satz found that the color-dipole scattering model predicts negligible $J/\psi + N$ cross sections at low energies (Fig. 3), evidently flavor-exchange processes are predicted to be dominant near threshold.

Subsequent meson-exchange studies by Lin and Ko [29], Haglin and Gale [30] and Oh et al. [31] found that the assumption of pointlike mesons in the effective lagrangian leads to unrealistically large cross sections even at moderate energies, so that hadronic form factors must be incorporated in the calculations. With plausible but rather arbitrary form factors these cross sections are greatly reduced, so that they are again found to be typically of few-mb scale (see Fig. 6 for example).

In summary, the current, rather unsatisfying state of affairs in meson exchange models of charmonium dissociation is that mb-scale cross sections are anticipated near threshold, but their precise values depend on poorly known hadronic form factors, as well as on effective meson lagrangians of unknown accuracy. Future studies that can put the effective lagrangians and form factors on a more sound theoretical basis would be an important contribution to this approach. One interesting possibility, which has recently been investigated by Navarra et al. and Mathews et al., is to derive the hadronic form factors from QCD sum rules [46, 47]. An especially attractive possibility explored very recently by Deandrea, Nardulli and Polosa [48] is that the hadronic form factors may be evaluated explicitly in terms of quark model wavefunctions.

FIG. 5: The $t$-channel meson exchange cross sections for $J/\psi + N \to \Lambda_c + D$ found by Sibirtsev, Tsushima and Thomas [33]. The smaller contribution is from D exchange and the larger is from (non-interfering) $D^*$ exchange.

FIG. 6: A strong suppression of dissociation cross sections is found on incorporating hadronic form factors in meson exchange models. This example is Fig. 4 of Lin and Ko [29].

FIG. 7: The $t$-channel meson exchange cross sections for $\rho \psi \to D \bar{D}$ [35].
Constituent Interchange Model

In this approach one uses explicit nonrelativistic quark model wavefunctions for the external hadrons and calculates the cross section assuming a constituent interchange scattering mechanism, driven by the Born-order matrix element of the standard quark model Hamiltonian. Constituent interchange $c\bar{c} + q\bar{q}$ cross sections have their strongest support just a few hundred MeV in $\sqrt{s}$ above threshold, since the overlap integrals are damped by the external meson wavefunctions at higher momenta.

This technique, which has no free parameters once quark model wavefunctions and the interquark Hamiltonian are specified, has been shown to compare reasonably well with experimental low-energy hadron-hadron scattering data near threshold for a wide range of annihilation-free reactions. There are four quark interchange diagrams in meson-meson scattering (Fig.7), each of which has an associated overlap integral of the external meson wavefunctions at higher momenta.

The difference lies mainly in the treatment of the confining interaction; Blaschke et al. treated confinement as a color-independent Gaussian potential between quark and antiquark (hence they include only diagrams C1 and C2), whereas Wong et al. used the conventional $\lambda^a \cdot \lambda^a$ form between all pairs of constituents. This leads to destructive interference between the C and T diagrams due to opposite color factors, and hence to a much reduced total cross section. Ref.40 also considers $\psi' + \pi$ scattering; the rather large cross section found for this process is shown in Fig.9. As a final example, the constituent-interchange $J/\psi + \rho$ cross section from Ref.40 is shown in Fig.10; this diverges at threshold for the simple reason that the DD channel is exothermic.

FIG. 7: The four constituent interchange scattering diagrams evaluated in $c\bar{c} + q\bar{q}$ cross section calculations (prior formalism). The “exchange” is the full quark-quark interaction Hamiltonian $H_1$.

The first charmonium cross section calculation using this approach was due to Martins, Blaschke and Quack [37], who considered the reactions $J/\psi + \pi \to D^*\bar{D} + h.c.$ and $D^*\bar{D}^*$ (The amplitude for $J/\psi + \pi \to DD$ is zero in the nonrelativistic quark model without spin-orbit forces, and has been found to be quite weak in a relativized calculation [27].) Martins et al. found that these exclusive final states have numerically rather similar cross sections (except for their different thresholds), and give a maximum total cross section of about 7 mb at $\sqrt{s} \approx 4.1$ GeV.

Wong et al. have carried out similar constituent interchange cross section calculations [38, 39, 40], using numerically determined Coulomb plus linear plus smeared hyperfine quark potential model wavefunctions, with parameters fitted to the $q\bar{q}$ and $c\bar{c}$ meson spectra. Figs.8-10 show some recent results from Ref.40. The $J/\psi + \pi$ cross section is somewhat smaller than was found by Blaschke et al., and peaks at about 1.4 mb just above 3.9 GeV.

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It is interesting that the simple two-parameter function
\[ \sigma(s) = \sigma_{\text{max}} \left( \frac{\epsilon}{\epsilon_{\text{max}}} \right)^p \exp\left( \frac{1 - \epsilon}{\epsilon_{\text{max}}} \right), \]
often provides an accurate parametrization of the constituent interchange cross sections. In this formula \( \epsilon = \sqrt{s} - M_C - M_D \) is the c.m. energy above threshold and \( \sigma_{\text{max}} \) is the cross section maximum, at \( \epsilon_{\text{max}} \). The threshold exponent \( p \) is determined by the angular quantum numbers of the hadrons, and is \( \pm 1/2 + 1_{\text{CD}} \) (for endothermic/exothermic), where \( L_{\text{min}}^{\text{CD}} \) is the lowest angular momentum allowed for the final meson pair CD.

The much more complicated problem of charmonium-nucleon scattering has also been investigated in the constituent interchange model. \( J/\psi+N \) and \( \psi'+N \) cross sections were derived by Martins \cite{42} using a simplified quark+diquark model of the nucleon; this approach gave several-mb peak cross sections not far above threshold. Black \cite{41} has carried out the full \( J/\psi+p \) constituent interchange calculation for several final states, assuming hyperfine, Coulomb and linear interactions. He finds that the final state \( D^0 \Lambda^+ \) is dominant, with a surprisingly large (ca. 12 mb) peak cross section just above threshold.

**QCD Sum Rules**

The application of QCD sum rules to the determination of charmonium dissociation cross sections, due to Navarra et al. \cite{43} and to Durães et al. \cite{44}, is a relatively recent development. This method relates the scattering amplitude to a sum of operator vacuum expected values, and gives a model independent result to the extent that these expected values are known experimentally and the set of operators chosen does indeed dominate the scattering amplitude over the chosen kinematic regime. There are also systematic uncertainties in the approach due to the details of a Borel summation and treatment of a continuum contribution to the amplitudes.

The studies published to date are a calculation of the \( J/\psi \) dissociation reactions \( J/\psi + \pi \rightarrow DD, D^*D + h.c. \) and \( D^*D^* \), followed by a more detailed investigation of the same processes \cite{44}. The sum rule results (Fig.11) appear to confirm the mb-scale of near-threshold dissociation cross sections, in qualitative agreement with both meson exchange and constituent interchange models.

**CONCLUSIONS**

We have reviewed theoretical predictions and related experimental results for the low-energy dissociation cross sections of charmonia on light hadrons, which are of great importance for QGP searches in heavy ion collisions. Four theoretical approaches have recently been applied to this problem, which are a color-dipole scattering model, meson exchange, constituent interchange, and QCD sum rules. Near threshold the color-dipole model predicts very small cross sections, whereas meson exchange, constituent interchange and QCD sum rules all predict mb-scale cross sections. At present there are no direct measurements of these dissociation cross sections near threshold. It would clearly be of great interest to measure any of these low-energy dissociation cross sections experimentally, both for the relevance to QGP searches and as a valuable test of the theoretical models of hadron scattering that have been applied to this problem.

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