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Charmonium + Light Hadron Cross Sections

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ABSTRACT: In this contribution we summarize experimental information and theoretical results for the dissociation cross sections of charmonium by light hadrons. Theoretical predictions for these RHIC-related processes differ by orders of magnitude over the physically relevant energy range. The results found by the author and collaborators using a constituent interchange model, which predicts cross sections in the mb region near threshold, are discussed in more detail.

1. 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/ψ 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 interaction 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.

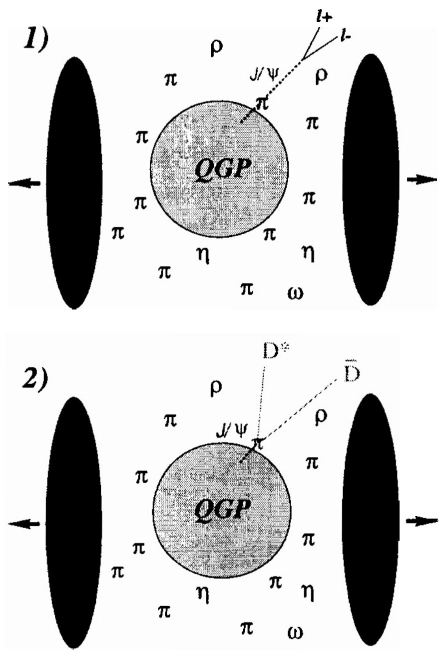

Figure 1: The two scenarios we wish to distinguish for the external evolution of a J/ψ produced (purportedly with reduced probability) within a quark-gluon plasma: 1) weak, versus *2)* strong J/ψ absorption by comoving light hadrons.

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] 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" disso-

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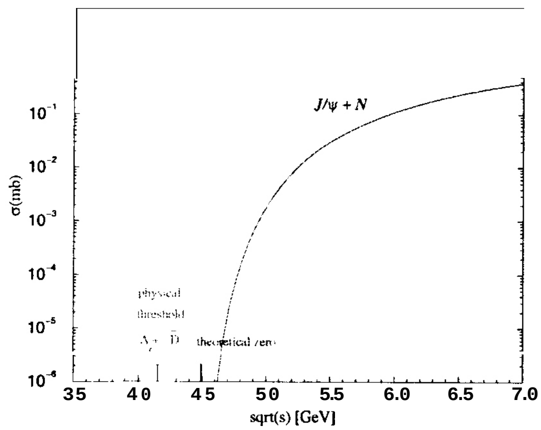

Figure 3: The Kharzeev-Satz $J/\psi + N$ total cross section Eq.(3.1) and the 1977 SLAC result [5].

duction. Cross section calculations using this a p proach with more realistic $c\bar{c}$ wavefunctions are currently being carried out by Kopeliovich *et al.* [23].

4. Theory: meson exchange

Recently, 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 [24] argument as to why vector meson exchange is unjustifed 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 might at least incorporate the correct scales and degrees of freedom, and it assumes a different scattering mechanism from the pQCD color-dipole model advocated by Kharzeev and Satz.

The first such meson exchange calculation, due to Matinyan and Muller [15], considered t-channel D exchange as the mechanism for the reactions $J/\psi + \pi \rightarrow D^* \bar{D} + h.c.$ and $J/\psi + \rho \rightarrow D\bar{D}$. The cross sections found by this reference are shown in Fig.4 below. Note that 500 MeV son exchange calculation of $J/\psi + N \rightarrow$ A, $+ D$ by Sibirtsev, Tsushima and Thomas [17] finds a peak cross section of about **2** mb near $\sqrt{s} = 4.6$ GeV. (An earlier calculation of $J/\psi + N \rightarrow \Lambda_c +$ D by Haglin [18], assuming D exchange but no hadronic form factors, found a somewhat larger peak of about 7 mb near $\sqrt{s} = \mathbf{4.3}$ GeV.) In comparison, Kharzeev and Satz predict nanobarn-scale J/ψ + **N** cross sections **500** MeV above threshold, *six orders of magnitude smaller!* The scatter of theoretical predictions for these processes is remarkably wide.

This discrepancy between theoretical cross sections may appear discouraging. One can instead consider it an opportunity to learn something important about QCD: the predictions differ because they come from very different assumptions regarding the scattering mechanism, and as they are so far apart, for once we have a clear possibility of distinguishing between different hadron-hadron scattering models.

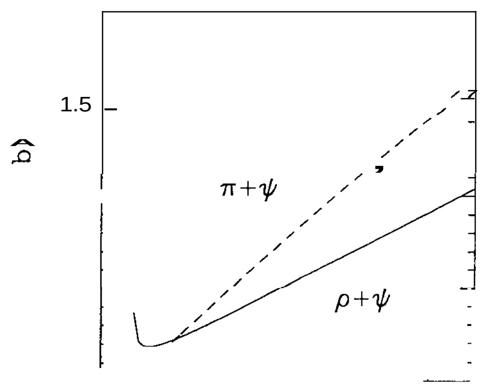

Figure 4: The Matinyan-Müller t-channel meson exchange results for $J/\psi + \pi$ and $J/\psi + \rho$ inelastic cross sections [15].

Meson exchange calculations of $c\bar{c} + q\bar{q}$ dissociation cross sections have since been reported by Lin and Ko [16] and Haglin and Gale [18, 19]. The models differ considerably in detail, due to different choices for the diagrams included, the

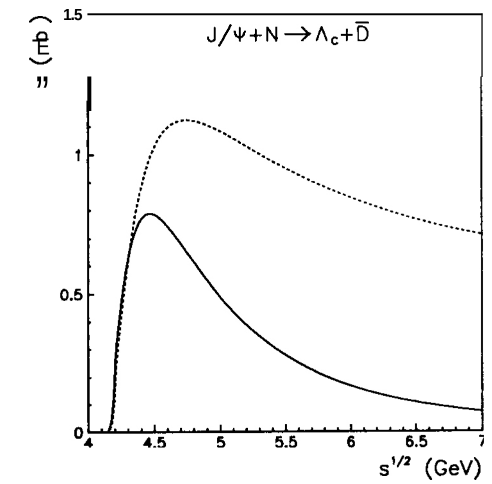

Figure 5: The t-channel meson exchange cross sections for $J/\psi + N \rightarrow$ A, $+ \bar{D}$ found by Sibirtsev, Tsushima and Thomas [17]. The smaller contribution is from D exchange and the larger is from (non-interfering) D^* exchange.

pointlike "hard" vertices, $J/\psi + \pi$ cross sections in the 10s of mb not far above threshold are typical. After introducing plausible hadronic form factors, these are usually reduced to peak values of 1-10 mb near $\sqrt{s} \approx$ 4.0-4.2 GeV. Unfortunately there is considerable "guessing" regarding hadronic couplings constants, which may be unnecessary because these can be calculated using well established quark model techniques, for example the $^3P_0$ meson decay model. Similarly, hadronic form factors can be derived from the $^3P_0$ model, presumably with sufficient accuracy for these purposes.

5. Theory: constituent interchange

We advocate an approach which uses nonrelativistic quark model wavefunctions and calculates these cross sections assuming a constituent interchange scattering mechanism, driven by the Born-order matrix element of the standard quark model Hamiltonian. 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 in a wide range of annihilation-free reactions [25, 26]. In meson-meson scattering there are four distinct diagrams (see Fig.6), each of which has an associated overlap integral of the nonrelativistic quark model external meson wavefunctions convolved with the interquark Hamiltonian. Constituent interchange is forced at Born-order because $H_I \propto$ A" . A" changes each initial color-singlet $q\bar{q}$ meson into a color octet, which has overlap with color-singlet final state mesons only after quark line interchange. The Feynman rules for these diagrams were given by Barnes and Swanson [25].

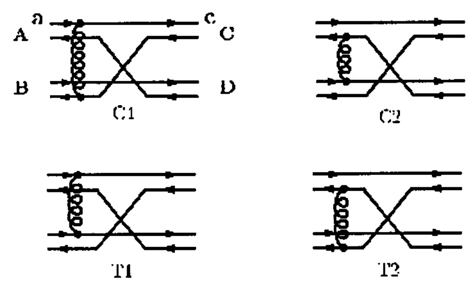

Figure 6: The four constituent interchange scattering diagrams evaluated in the $J/\psi + q\bar{q}$ cross section calculation [20, 21, 22]. The "exchange" is the full **quark-quark** interaction Hamiltonian H_I.

The first quark model calculation using this approach was reported by Martins, Blaschke and Quack [20], who considered the reactions $J/\psi + \pi \rightarrow D^* \bar{D} + h.c.$ and $D^* \bar{D}^*$ (The amplitude for $J/\psi + \pi \rightarrow D\bar{D}$ is zero in the nonrelativistic quark model without spin-orbit forces, and has been found to be quite weak in a relativized calculation [14].) 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. **A** constituent interchange calculation of J/ψ + N and ψ' + N cross sections using a simplified quark+diquark model of the nucleon [22] also found several-mb peak cross sections not far above threshold.

Our collaboration recently carried out quite similar constituent interchange quark model calculations (Wong *et* al. [21]). We used numerically determined Coulomb plus linear plus hyperfine quark potential model wavefunctions, and evaluated the Born-order meson-meson scattering amplitude, which is the matrix element of the interquark Hamiltonian between scattering states with quark interchange (Fig.6). We included smeared OGE spin-spin, OGE color Coulomb and linear confining interactions, with parameters chosen to give a good fit to the $q\bar{q}$ and $c\bar{c}$ meson spectra. We find a somewhat smaller cross section (peaking at about 1 mb at $\sqrt{s} \approx 4.0$ GeV) for the sum of these inelastic $J/\psi + \pi$ reactions. The difference between our work and that of Blaschke *et al.* lies mainly in the treatment of the confining interaction; for simplicity, Blaschke *et al.* treated confinement as a color-independent Gaussian potential that acts only between quark and antiquark (hence they include only diagrams C1 and C2), whereas we used the standard $\lambda^a \cdot \lambda^a$ linear confining potential between all pairs of constituents.

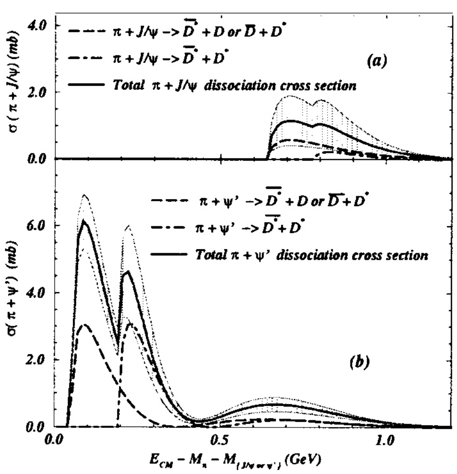

Figure 7: Constituent interchange model predictions for $J/\psi + \pi$ and $\psi' + \pi$ cross sections [21]. A band of estimated systematic uncertainty is also shown.

We find destructive interference between the C and T diagrams, leading to a much reduced total cross section. In [21] we also treated $\psi' + \pi$ scattering, which involved a simple change to a 2S $c\bar{c}$ wavefunction and a change of phase space, and found a rather large, *ca.* 5 mb maximum cross section (see Fig.7). Our $c\bar{c} + q\bar{q}$ cross sections have their strongest support just a few hundred MeV in $\sqrt{s}$ above threshold, since the overlap integrals are damped by the tails of the wavefunctions at higher energies.

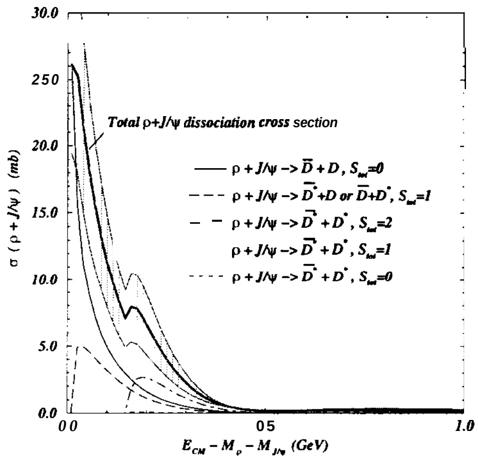

Figure 8: Constituent interchange model predictions for $J/\psi + \rho$ exothermic reactions [21], as in Fig.7.

We also consider $J/\psi + \rho$ (Fig.8) and $\psi' + \rho$, which are predicted to be much larger near threshold for the simple reason that they are exothermic; there is a $1/v_{AB}$ divergence in these cross sections as we approach threshold.

Although our scattering amplitudes and cross sections are evaluated numerically, it is interesting that a simple two-parameter function gives a useful approximation to our (single channel) cross sections. This function is

$$\sigma(s) = \sigma_{max}\ (\epsilon/\epsilon_{max})^p\ e^{p(1-\epsilon/\epsilon_{max})}\ , \qquad (5.1)$$

where $\epsilon = \sqrt{s} - M_C - M_D$, and σ_{max} (mb) is the maximum value of the cross section, at ϵ_{max} (MeV). The threshold exponent p is fixed by the angular quantum numbers of the hadrons, and is $\pm 1/2 + L^{CD}_{min}$ (for endothermic/exothermic), where L^{CD}_{min} is the lowest angular momentum allowed for the final meson pair CD. **As** an example, in Fig.9 we show our numerical results for the reaction $\eta_c + \pi^+ \rightarrow D^+\bar{D}^o$ and a fit using the function (5.1) with $p = 1/2$, **as** appropriate for an S-wave-allowed final state. The masses and parameters assumed for this example were $M_{\pi^+} = 0.140$ GeV, $M_{\eta_c} = 2.98$ GeV, $M_{D^+} = 1.869$GeV, $M_{D^o} = 1.865$GeV, $a, = 0.6$, b (string tension) $= 0.18$ GeV^2, $m_{u,d} = 0.33$ GeV, $m_c = 1.6$ GeV, and the OGE contact hyperfine smearing distance was 0.25 fm. These are all reasonably well established nonrelativistic quark model parameters. The Schrodinger equation was solved with these parameters to generate numerical wavefunctions, which were then used in a nine-dimensional Monte Carlo integration to evaluate the scattering amplitudes in the CM frame. The Monte Carlo amplitude evaluation in Fig.9 used **4M** points for each diagram at each energy and each final $D^+(\hat{\Omega})$ direction; amplitudes along three final directions were evaluated, which were then projected into S-, P- and D-moments to separate the different partial waves. Cancellation of diagram sums in certain channels as well as evaluation of known exact results with SHO wavefunctions provided nontrivial checks of the numerical work.

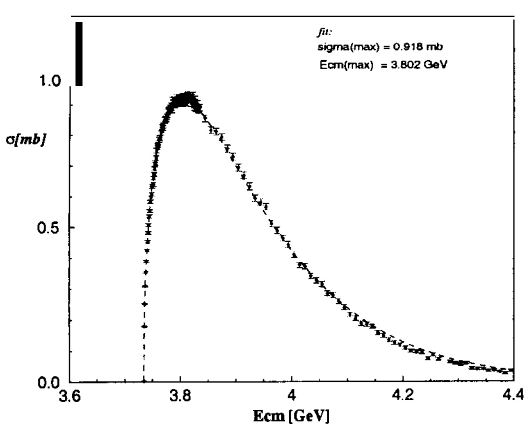

Figure 9: Monte Carlo evaluation of the cross section for $\eta_c + \pi^+ \rightarrow D^+\bar{D}^o$ in the constituent interchange model. **A** fit to the function **(5.1)** is also shown.

6. Conculsions

We have reviewed the recent theoretical predictions and experimental status of the cross sections of $c\bar{c}$ on light hadrons, which is of great interest for the interpretation of heavy ion collisions. There are three scattering mechanisms currently being investigated, which are color-dipole pQCD, t-channel meson exchange, and constituent interchange. The pQCD approach gives very small cross sections at low energies, whereas the meson exchange and constituent interchange models both predict peak cross sections near threshold of $\approx$ 1-10 mb. If it is possible to establish these cross sections experimentally, we may achieve a much better understanding of the mechanisms of low energy hadron-hadron scattering.

7. Acknowledgements

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