Suppression of ψ' and J/ψ in High-Energy Heavy-Ion Collisions

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The experimental ratio of ψ' to J/ψ is approximately a constant in pA collisions, but decreases as the transverse energy increases in nucleus-nucleus collisions. These peculiar features can be explained as arising from approximately the same $c\overline{c}$-baryon absorption cross section for ψ' and J/ψ but greater disruption probabilities for ψ' than for J/ψ due to the interaction of the $c\overline{c}$ system with soft particles produced in baryon-baryon collisions.

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High-energy heavy-ion collisions have become the focus of intense research because of the possibility of producing a deconfined quark-gluon plasma during such collisions [1,2]. The J/ψ suppression has been suggested as a way to probe the screening between a charm quark with its antiquark partner in the plasma [3]. While the J/ψ suppression has been observed [4,5] as predicted, the phenomenon can be explained by the absorption model [6–8], which was actually introduced earlier [9] to measure the total ψ-N cross section using J/ψ suppression. In the model of Gerschel and Hüfner [6], the collision of a J/ψ particle with baryons of the colliding nuclei may lead to the breakup of the J/ψ into an open-charm pair. One can alternatively describe J/ψ suppression in terms of the interaction of the J/ψ particle with produced hadrons (comovers) [7,8]. A comparison of the production of ψ' with J/ψ has been suggested to distinguish between deconfinement and absorption [10].

The NA38 experimental measurements using protons and heavy ions at 200*A* and 450*A* GeV reveal three features [11,12]: (1) ψ'/ψ is approximately a constant in pA collisions, independent of energies, (2) ψ'/ψ decreases as the transverse energy E_T^0 increases in SU collisions, and (3) ψ'/ψ for SU collisions is about 0.5 of that for pA collisions. The first feature, further supported by other pA experiments [13], implies that in pA collisions ψ' is suppressed in the same way as ψ. We would like to describe an absorption model with $\sigma_{\rm abs}(\psi' N) = \sigma_{\rm abs}(\psi N)$ and with additional soft-particle disruption to explain all three features of the phenomenon.

The production of J/ψ or ψ' occurs by the interaction of the partons of one baryon with the partons of the other baryon. The incipient $c\overline{c}$ pair is created with a radial dimension of the order of $\sim$0.06 fm at $t_{c\overline{c}}$. It is necessary for the incipient $c\overline{c}$ system to evolve to the bound state rms radius of 0.24 fm for ψ at t_ψ and 0.47 fm for ψ' at $t_{\psi'}$ [14,15]. Because J/ψ is produced predominantly in the central rapidity region [16], the incipient $c\overline{c}$ pair is produced predominantly in the central rapidity region.

In soft-particle production in a baryon-baryon collision, we envisage Bjorken's inside-outside cascade picture [17] or Webber's picture of gluon branching [18] as a q and a $\overline{q}$ (or a diquark) pull apart. After the collision, the diquark of one nucleon and the valence quark of the other nucleon pull apart and the gauge field between them is polarized. Gluons are emitted at t_g, and the system hadronizes at t_h. The shape of the rapidity distribution of produced gluons should be close to that of the produced hadrons. Thus, produced gluons are found predominantly in the central rapidity region. Because we shall use the J/ψ (or ψ') production rate in a nucleon-nucleon collision as a unit of reference, it is not necessary to include explicitly the interaction of the incipient $c\overline{c}$ system with gluons and their hadronized products in the same nucleon-nucleon collision, when we study pA and nucleus-nucleus (AB) collisions.

The space-time diagram for a typical pA collision is depicted schematically in Fig. 1(a). The trajectory of an incipient $c\overline{c}$ pair, which is produced predominantly in the central rapidity region of the colliding baryons, does not cross the trajectories of soft particles produced in earlier or later collisions. Therefore, there is little interaction between the produced $c\overline{c}$ system and these soft particles. However, the $c\overline{c}$ system collides with baryons crossing its trajectory to lead to the breakup of the $c\overline{c}$ system into $D\overline{D}X$. Such a reaction requires the production of at least one light-quark pair and is an inelastic process. In the collision at 200*A* GeV, the $c\overline{c}$ rapidities are separated from the baryon rapidities by about two units and the reaction cross section can be calculated in the additive

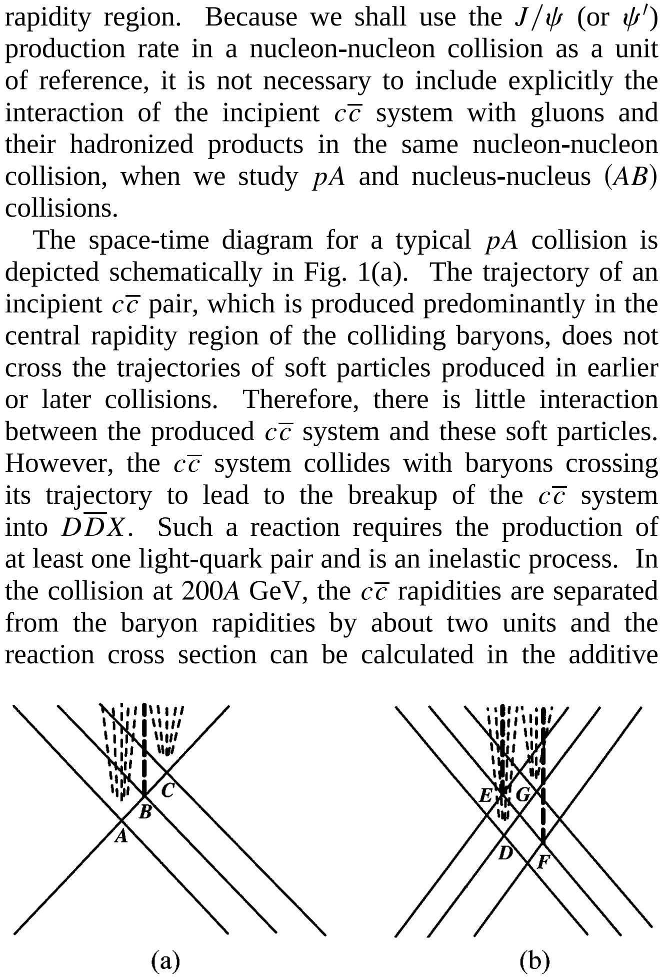

FIG. 1. Schematic space-time diagram in the nucleon-nucleon center-of-mass system, with the time axis pointing upward. (a) pA collision and (b) an AB collision. The trajectories of the baryons are given as solid lines, the trajectories of an incipient $c\overline{c}$ system produced in some of the collisions are represented by thick dashed lines and the trajectories of soft particles produce in some of the baryon-baryon collisions by thin dashed lines.

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quark model (AQM) [19], whose approximate validity and connection with soft Pomeron exchanges have been reassessed recently [20]. Using the Glauber theory and a Gaussian thickness function, the total $c\bar{c}$-baryon inelastic cross section in the AQM is given by Eq. (12.27) of Ref. [2]:

$$\sigma_{\rm abs}(c\bar{c} - N) = -2\pi\beta^2 \sum_{n=1}^{6} \binom{6}{n} (-f)^n/n\,, \qquad (1)$$

where $f = \sigma_{cq}/\beta^2 = \sigma_{cq}/2\pi(\beta_{c\bar{c}}^2 + \beta_N^2 + \beta_{cq}^2)$, σ_{cq} is the inelastic cross section for the collision of c (or $\bar{c}$) and a constituent q of the baryon, $\sqrt{3}\beta_{c\bar{c}}$ and $\sqrt{3}\beta_N$ are the rms radii of the $c\bar{c}$ and the baryon, respectively, and β_{cq} is the c-q interaction range. We find below that $\sigma_{\rm abs}(\psi N) = 4.2$ mb. Taking $\sqrt{3}\beta_N = 0.74$ fm [21] and neglecting β_{cq}, we obtain from Eq. (1) $\sigma_{cq} = 0.753$ mb, which leads to $\sigma_{\rm abs}(\psi' N) = 4.27$ mb, and $\sigma_{\rm abs}(c\bar{c} - N) = 4.17$ mb for the initial $c\bar{c}$ at $\sqrt{3}\beta_{c\bar{c}} = 0.06$ fm. Thus, the absorption cross section is approximately the same for any $c\bar{c}$ state during all stages of its evolution because $6\sigma_{cq} \ll 2\pi\beta^2$. Consequently, in pA collisions, ψ' is suppressed in the same way as ψ and ψ'/ψ is a constant independent of A and collision energies, in agreement with experimental observations.

The approximate equality of the absorption cross sections for different $c\bar{c}$ states is supported by the experimental ratio $\sigma_{\rm total}(\psi' N)/\sigma_{\rm total}(\psi N) \sim 0.75$ to 0.86 ± 0.15, for $\sqrt{s}$ ranging from 6.4 to 21.7 GeV, as deduced from the photoproduction of vector mesons [22,23]. It implies that a small incipient $c\bar{c}$ system is not transparent to the hadron medium, in agreement with the absence of color transparency for small hadron systems as indicated by experimental data in $A(e, e'p)$ reactions at high Q^2 [24].

To study AB collisions, we adopt a row-on-row picture and consider a typical row with a cross section of the size of the nucleon-nucleon inelastic cross section, $\sigma_{\rm in} = 29.4$ mb. The space-time diagram of the collision can be depicted schematically in Fig. 1(b). The trajectories of the $c\bar{c}$ system cross the trajectories of colliding baryons, and the process of absorption due to the $c\bar{c}$-baryon interaction is the same in pA as in AB collisions. However, there are collisions, such as the ones at E and F in Fig. 1(b), where the trajectories of incipient $c\bar{c}$ systems produced there cross the trajectories of the produced soft particles. It is necessary to consider the additional interaction of the $c\bar{c}$ systems with soft particles in AB collisions but not in pA collisions. Because the $c\bar{c}$ systems and the gluons (or their hadronized products) are produced predominantly in the central rapidity region, their rapidities are not much separated and their relative kinetic energies are not large. At these low energies, the absorption of a produced gluon by the $c\bar{c}$ system, the screening of c from $\bar{c}$ by gluons, and the inelastic gluon scattering which excites the $c\bar{c}$ system to higher levels will contribute to the breakup of the $c\bar{c}$ system. As gluons carry color, the cross sections for these breakup processes increase with the color dipole moment of $c\bar{c}$, which is proportional to the separation between c and $\bar{c}$. Furthermore, the threshold for ψ' breakup is small compared to those for ψ and $\chi_{1,2}$. Thus, the breakup probability for a $c\bar{c}(\psi')$ system due to $c\bar{c}$-gluon interactions at low energies is greater than those for J/ψ and χ.

The hadronized product (comovers) of the produced gluons can interact with J/ψ and ψ' to lead to their breakup [7,8]. The breakup of ψ', $\chi_{1,2}$, and J/ψ into $D\bar{D}$ require the threshold energy of 52, $\sim$200, and 640 MeV, respectively. In $c\bar{c}$-hadron interactions at low energies below thresholds, J/ψ and χ cannot be broken up by low energy pions. Above the thresholds, the interaction is mediated by a color gluon exchange which probes the color dipole moment of the $c\bar{c}$ system. Thus, the breakup probability due to $c\bar{c}$-hadron interactions at low energies is also larger for the ψ' system than those for the J/ψ and χ systems. This is different from the higher-energy (Pomeron-exchange dominated) Glauber case discussed earlier where ψ' and J/ψ have about the same inelastic baryon cross sections.

Assuming straight-line space-time trajectories and uniform distribution of baryons in nuclei, we find

$$\frac{d\sigma_{\psi N}^{AB}(\boldsymbol{b})}{\sigma_{\psi N}^{NN}\,d\boldsymbol{b}} = \int \frac{d\boldsymbol{b}_A}{\sigma_{\rm abs}^2(\psi N)} \{1 - [1 - T_A(\boldsymbol{b}_A)\sigma_{\rm abs}(\psi N)]^A\}\{1 - [1 - T_B(\boldsymbol{b} - \boldsymbol{b}_A)\sigma_{\rm abs}(\psi N)]^B\}F(\boldsymbol{b}_A)\,, \qquad (2)$$

where $T_A(\boldsymbol{b}_A)$ is the thickness function of A and the disruption factor $F(\boldsymbol{b}_A)$ is

$$F(\boldsymbol{b}_A) = \frac{1}{N_> N_<} \sum_{n=1}^{N_<} a(n) \times \sum_{i=1}^{n} \exp\left\{-\theta \sum_{j=1, j\neq i}^{n} (k_{\psi g} t_{ij}^t + k_{\psi h} t_{ij}^h)\right\}. \qquad (3)$$

Here, $N_>(\boldsymbol{b}_A)$ and $N_<(\boldsymbol{b}_A)$ are the greater and the smaller of the (rounded-off) numbers of target nucleons $AT_A(\boldsymbol{b}_A)\sigma_{\rm in}$ and projectile nucleons $BT_B(\boldsymbol{b} - \boldsymbol{b}_A)\sigma_{\rm in}$ in the row at $\boldsymbol{b}_A$ with the cross section of $\sigma_{\rm in}$, and $a(n)$ is obtained by simple counting to be

$$a(n) = 2 \quad \text{for } n = 1, 2, \ldots, N_< - 1, \quad \text{and}$$
$$a(n_<) = N_> - N_< + 1\,. \qquad (4)$$

In Eq. (3), we have assumed that when a $c\bar{c}(\psi)$ system is produced in the jth collision and soft particles are produced at the same spatial location in the ith collision, the bound state survival probability is related to the $c\bar{c}$-gluon interaction time t_{ij}^g by $e^{-\theta(k_{\psi g} t_{ij}^g + k_{\psi h} t_{ij}^h)}$, where $k_{\psi g}$ and $k_{\psi h}$ are rate constants, averaged over the interaction history of the $c\bar{c}(\psi)$ system. The interaction times, which must be non-negative, are

$$t_{ij}^{g} = t_i + t_h - \mathrm{Max}(t_i + t_g, t_j + t_{c\bar{c}}), \qquad (5)$$

$$t_{ij}^{h} = t_n + t_f - \mathrm{Max}(t_i + t_h, t_j + t_{c\bar{c}}), \qquad (6)$$

where $t_i = t_1 + (i - 1)2m_N d/\sqrt{s}$, m_N is the nucleon mass, d ($= 1.93$ fm) is the internucleon separation in a nucleus, $\sqrt{s}$ the nucleon-nucleon center-of-mass energy, and t_f is the freeze-out time. In Eq. (3), the step function $\theta = \Theta(AT_A(\boldsymbol{b}_A)\sigma_{\rm in} - 1)\Theta(BT_B(\boldsymbol{b} - \boldsymbol{b}_A)\sigma_{\rm in} - 1)\Theta(A - 1)\Theta(B - 1)$ is introduced to ensure that there is no soft-particle disruption in pA collisions. The expressions for the production of ψ' can be obtained from Eqs. (2)–(6) above by changing ψ into ψ'. For simplicity, we do not treat $\chi_{1,2}$ separately so that the extracted parameters are actually for a "J/ψ" system with the observed ψ:χ = 62:30 mixture [25].

It is not yet possible to ascertain the exact nature of all suppression mechanisms in AB collisions because of the uncertainties in the reaction cross sections (see below) and the characteristics of produced gluons. Besides the $c\bar{c}$-baryon absorption, the suppression can be attributed to (A) produced gluons, (B) both produced gluons and hadrons, (C) produced hadrons (as in the comover model [7,8]), or deconfined matter with no baryon absorption [26]. In our model, with $\sigma_{\rm abs}(\psi N) = \sigma_{\rm abs}(\psi' N) = 4.2$ mb fixed by pA data and a set of plausible time parameters $t_g = 0.1$, $t_h = 1.2$, $t_f = 3$, and $t_{c\bar{c}} = 0.06$ (in units of fm/c), we obtain results calculated with rate constants (in c/fm) (A) $k_{\psi g} = 0.2$, $k_{\psi' g} = 3$, $k_{\psi h} = k_{\psi' h} = 0$ (gluon disruption only), (B) $k_{\psi g} = 0.2$, $k_{\psi' g} = 1$, $k_{\psi h} = 0$, $k_{\psi' h} = 1$ (gluon disruption for J/ψ but gluon and hadron disruption for ψ'), and (C) $k_{\psi g} = k_{\psi' g} = 0.2$, $k_{\psi h} = 0.12$, $k_{\psi' h} = 3$ (hadron disruption only). For the case when all impact parameters are summed over, the quantity $\mathcal{B}\sigma_{J/\psi}^{AB}/AB$ is plotted as a function of $A^{1/3} + B^{1/3}$ in Fig. 2 for the three cases considered. The presence of additional soft-particle disruption in AB collisions relative to pA collisions is consistent with the experimental data in Fig. 2. To study ψ'/ψ data for SU collisions at 200A GeV, we relate the transverse energy E_T^0 approximately to the impact parameter as given in Refs. [28] and [11], and the ratio ψ'/ψ is corrected for the feeding of J/ψ by ψ'. The theoretical results for $\mathcal{B}'\sigma(\psi')/\mathcal{B}\sigma(\psi)$ as a function of E_T^0 for the cases of (A), (B), and (C) differ by about 1% and are represented for simplicity by a single solid curve in Fig. 3. The theoretical ratio decreases with increasing E_T^0 and coincides with the pA limit, in good agreement with data. When we include all impact parameters, we obtain theoretically $[\mathcal{B}'\sigma(\psi')/\mathcal{B}\sigma(J/\psi)]^{\rm SU}/[\mathcal{B}'\sigma(\psi')/\mathcal{B}\sigma(J/\psi)]^{pA} = 0.62$ for the three sets of parameters, approximately consistent with the experimental ratio $[\mathcal{B}'\sigma(\psi')/\mathcal{B}\sigma(J/\psi)]^{\rm SU}/[\mathcal{B}'\sigma(\psi')/\mathcal{B}\sigma(J/\psi)]^{pA} = 0.52 \pm 0.07$ [11].

The parameter sets in (A)–(C) suggest greater disruption for ψ' than J/ψ due to their interaction with soft particles. To resolve the ambiguities, it is interesting to note that while heavy-quark production by hadron-hadron collisions is inhibited by the Okubo-Zweig-Iizuka rule, there is no such inhibition in gluon-gluon collisions. The fusion of energetic gluons produced in different baryon-baryon collisions can lead to additional charm and strangeness production [29] and may explain the enhanced charm and dilepton production in AB collisions relative to pA collisions observed in [30].

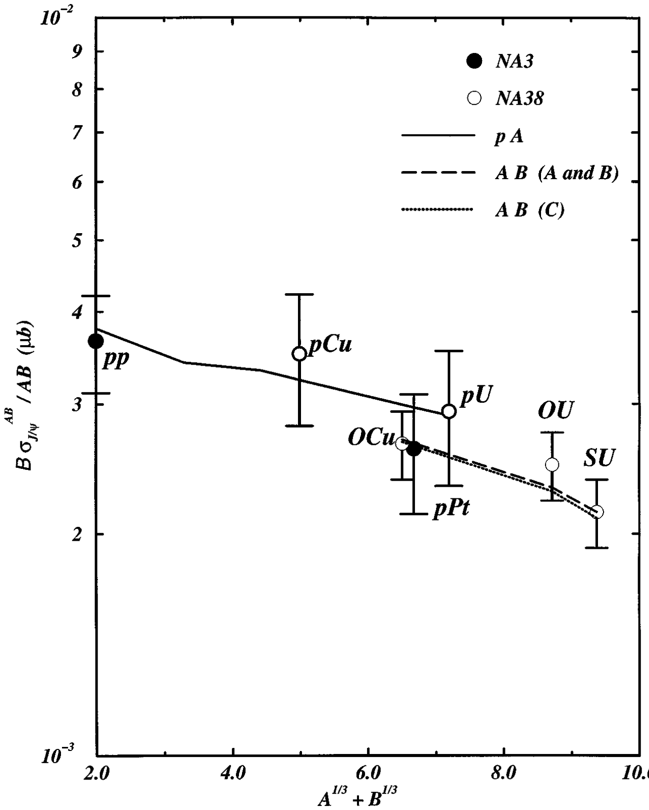

FIG. 2. The quantity $\mathcal{B}\sigma_{J/\psi}^{AB}/AB$ as a function of $A^{1/3} + B^{1/3}$ for pA and AB collisions. The data points are from the NA3 Collaboration [27] and the NA38 Collaboration [5]. The solid curve gives theoretical results for pA collisions. For ABcollisions, the theoretical results are shown as the long-dashed curve for cases (A) and (B) and as the dotted curve for case (C).

For a medium m whose constituents move with an average velocity v_m with respect to $c\bar{c}(\psi_i)$, the rate constant $k_{\psi_i m}$ is $\rho_m v_m \sigma_{\psi_i m}$, where $\rho_m = (dN_m/dy)/\pi R_0^2 t_0$ is the contribution to the medium number density from a single NN collision and $\sigma_{\psi_i m}$ is the ψ_i-m breakup cross section. The time t_0 is the mean point in the time when the medium exists in the specified form; $t_0 = (t_g + t_h)/2 = 0.65$ fm/c for gluons and $t_0 = (t_h + t_f)/2 = 2.1$ fm/c for hadrons. We can estimate ρ_m by taking $dN_h/dy = 2dN_g/dy = 2.3$ and $R_0 = 0.5$ fm. We can estimate v_m by assuming that a produce gluon has a mass $M \sim 1$ GeV [29]. At a temperature $T = 200$ MeV, which is often found in these nuclear collisions, the most probably velocity is $v_m = \sqrt{2kT/M} = 0.6$ for gluons and $v_m \sim 1$ for hadrons. Then, the rate constant $k_{\psi_i m}$ suggest approximate

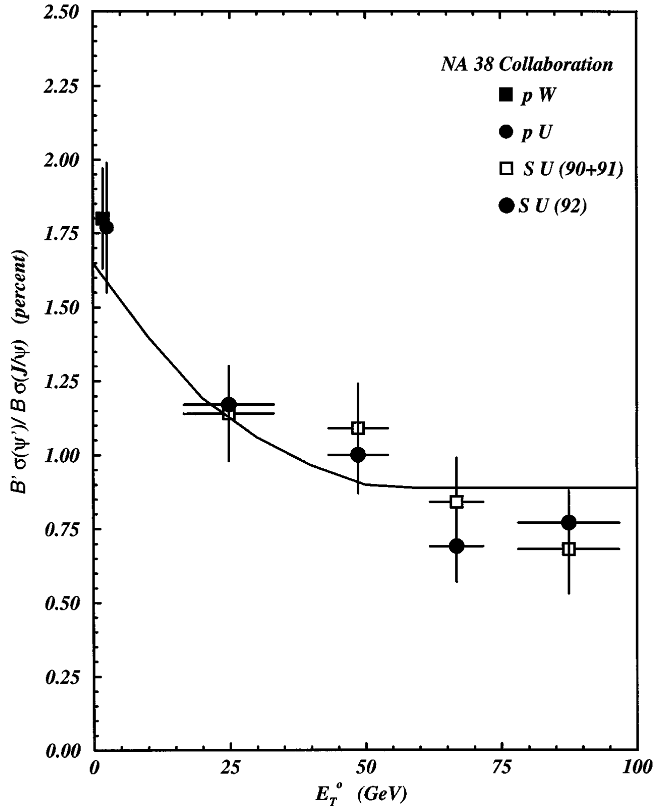

FIG. 3. The ratio $\mathcal{B}'\sigma(\psi')/\mathcal{B}\sigma(\psi)$ as a function of the transverse energy in SU collisions at 200*A* GeV. Data points are from Ref. [11]. The theoretical results are shown as the solid curve.

orders of magnitude of $\sigma_{\psi g} \sim 1.4$ mb, $\sigma_{\psi' g} \sim 20$ mb for case (A), $\sigma_{\psi g} \sim 1.4$ mb, $\sigma_{\psi' g} \sim \sigma_{\psi' h} \sim 7$ mb for case (B), and $\sigma_{\psi h} \sim 0.9$ mb, $\sigma_{\psi' h} \sim 21$ mb for case (C). The excessively large ψ' cross sections required to explain the ψ' suppression in cases (A) and (C) may make the scenario (B) tentatively a more attractive description.

The geometrical model [31] predicts the total hadron-N cross section at high energies proportional to the rms hadron radius and suggests $\sigma_{\rm abs}(\psi' N)$ much larger than $\sigma_{\rm abs}(\psi N)$, which is also assumed in the comover model [8]. Using perturbative QCD, Karzeev and Satz [26] claim that ψN total cross section for $\sqrt{s} = 6$ GeV is about 0.3 mb. The geometrical model results and perturbative QCD results differ from those obtained here. A recent calculation using an exchange potential J/ψ-hadron dissociation cross section about 7 mb at 0.8 GeV kinetic energy [32]. Much work remains to be done to resolve the differences.

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