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## $\psi'$ and $J/\psi$ Suppression in High-Energy Nucleon-Nucleus and Nucleus-Nucleus Collisions

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# $\psi'$ and $J/\psi$ Suppression in High-Energy Nucleon-Nucleus and Nucleus-Nucleus Collisions

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The observed features of  $\psi'$  to  $J/\psi$  suppression in  $pA$  and nucleus-nucleus collisions can be explained in terms of a two-component absorption model. For the hard component of the absorption due to the interaction of the produced  $c\bar{c}$  systems with baryons at high relative energies, the absorption cross sections are insensitive to the radii of the  $c\bar{c}$  systems, as described by the Additive Quark Model. For the soft component due to the low energy  $c\bar{c}$  interactions with soft particles produced by other baryon-baryon collisions, the absorption cross sections are greater for  $\psi'$  than for  $J/\psi$ , because the breakup threshold for  $\psi'$  is much smaller than for  $\psi$ .

The occurrence of  $J/\psi$  suppression has been suggested as a way to probe the screening between a charm quark-antiquark pair in the quark-gluon plasma<sup>1</sup>. While the  $J/\psi$  suppression has been observed<sup>2</sup>, the phenomenon can be explained by absorption models<sup>3,4,5</sup>, in which  $J/\psi$ -hadron collisions lead to the breakup of the  $J/\psi$  into  $D\bar{D}X$ . A comparison of the production of  $\psi'$  with  $J/\psi$  has been suggested to distinguish between absorption and deconfinement<sup>6</sup>.

Recent NA38 experiments<sup>7,8</sup> using protons and heavy ions at high energies reveal that  $\psi'/\psi$  is approximately a constant in  $pA$  collisions<sup>9</sup>, but in SU collisions it decreases as the transverse energy  $E_T^0$  increases (or equivalently, as the impact parameter decreases). These features cannot be explained by the conventional absorption models. We would like to describe a two-component absorption model (TCAM) which can explain the phenomenon.

The  $J/\psi$  or  $\psi'$  particles are produced by the interaction of partons of one baryon with partons of the other baryon. The incipient  $c\bar{c}$  pair is created with a radial dimension of the order of  $\sim 0.06$  fm which evolves to the bound state rms radius of 0.24 fm for  $\psi$  and 0.47 fm for  $\psi'$ <sup>10,11</sup>. Because  $J/\psi$  is produced predominantly in the central rapidity region, the incipient  $c\bar{c}$  pair must have been produced predominantly in the same rapidity region.

In soft particle production in a baryon-baryon collision, we envisage Bjorken's inside-outside cascade picture<sup>12</sup> or Webber's picture of gluon branching<sup>13</sup> as a quark and a diquark pull apart after the collision, with the emission of gluons which later hadronize. 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.

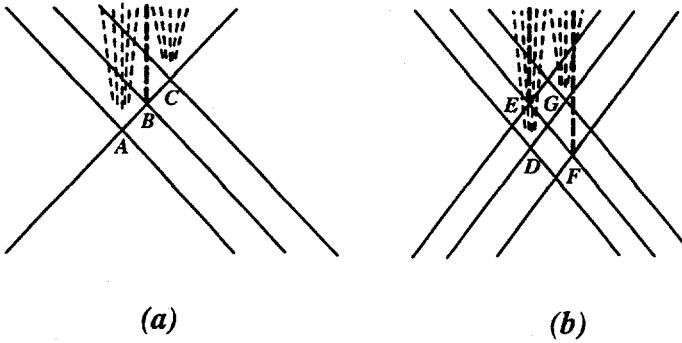


Figure 1: Schematic space-time diagram in the nucleon-nucleon center-of-mass system, with the time axis pointing upward. (a) is for a  $pA$  collision and (b) is for an  $AB$  collision. The trajectories of the baryons are given as solid lines, the trajectories of an incipient  $c\bar{c}$  system produced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

The space-time diagram for a typical  $pA$  collision is depicted schematically in Fig. 1a where the average trajectory of an incipient  $c\bar{c}$  pair does not cross the average trajectories of soft particles produced in earlier or later collisions. Therefore, there is little interaction between the produced  $c\bar{c}$  system and these soft particles. However, the  $c\bar{c}$  system collides with baryons crossing its trajectory to lead to the breakup of the  $c\bar{c}$  system into  $D\bar{D}X$ . In the collision at 200A GeV, the rapidity of a  $c\bar{c}$  system is separated from the baryon rapidities by about two units and the reaction cross section at these relative energies can be calculated in the Additive Quark Model (AQM)<sup>14</sup>. 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. [16]:

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

where  $f = \sigma_{cq}/\beta^2 = \sigma_{cq}/2\pi(\beta_{c\bar{c}}^2 + \beta_N^2 + \beta_{cq}^2)$ ,  $\sigma_{cq}$  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  $\beta_{cq}$  is the  $c$ - $q$  interaction range. For a  $\psi$ - $N$  absorption cross section in the range of 5 to 7 mb<sup>4,15</sup>, we find that  $\sigma_{\text{abs}}(\psi N) \sim \sigma_{\text{abs}}(\psi' N) \sim \sigma_{\text{abs}}(c\bar{c}-N)$ . Thus, the absorption cross section is approximately the same for a  $c\bar{c}$  state during all stages of its evolution because  $6\sigma_{cq} \ll 2\pi\beta^2$ . We ascribe the absorption due to the  $(c\bar{c})$ - $N$  collisions at these high relative energies as the hard component of the absorption model. Because of the presence of only this hard component in  $pA$  collisions,  $\psi'$  is suppressed in the same way as  $\psi$  and  $\psi'/\psi$  is a constant in  $pA$  collisions, as observed experimentally. The approximate equality of  $\sigma_{\text{abs}}(\psi N) \sim \sigma_{\text{abs}}(\psi' N)$  at high relative energies is further supported by the experimental ratio  $\sigma_{\text{total}}(\psi' N)/\sigma_{\text{total}}(\psi N) \sim 0.75$  to  $0.86 \pm 0.15$ , for  $\sqrt{s}$  ranging from 6.4 GeV to 21.7 GeV<sup>16,17</sup>.

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. The space-time diagram of the collision can be depicted schematically in Fig. 1b. The trajectories of the  $c\bar{c}$  systems cross the trajectories of colliding baryons, and the process of absorption due to the  $c\bar{c}$ -baryon interaction (the hard component) is the same in  $pA$  as in  $AB$  collisions. However, in  $AB$  collisions, many trajectories of the produced incipient  $c\bar{c}$  systems cross the trajectories of the produced soft particles (Fig. 1b). It is necessary to consider additional interaction of  $c\bar{c}$  systems with soft particles in  $AB$  collisions but not in  $pA$  collisions. These interactions occur at low relative energies and constitute the soft component of the two-component absorption model. At these low relative energies, the reaction thresholds make great differences in the cross sections. The breakup of  $\psi'$ ,  $\chi_{1,2}$  and  $J/\psi$  into  $D\bar{D}$  requires threshold energies of 52,  $\sim 200$ , and 640 MeV respectively. The breakup threshold for  $\psi'$  is much smaller than for  $\psi$  and  $\chi_{1,2}$ . Thus, the breakup probability due to soft particle interactions at low energies for a  $c\bar{c}(\psi')$  system is greater than those for  $J/\psi$  and  $\chi$ . Because of this additional soft component, in  $AB$  collisions  $\psi'$  is more suppressed than  $\psi$ , and the suppression becomes greater as the impact parameter decreases, as observed experimentally.

The above description of the  $\psi'$  and  $J/\psi$  suppression explains the qualitative features of the suppression phenomenon. For a quantitative description, it is necessary to provide a description of the produced soft particles. It is not yet possible to ascertain the exact nature of the soft component of the suppression mechanisms in  $AB$  collisions because of the uncertainties in the reaction cross sections and the characteristics of produced gluons. The soft component of the suppression phenomenon can be attributed to (A) produced gluons, (B) both produced gluons and hadrons, (C) produced hadrons (as in the comover model<sup>5</sup>), or (D) deconfined matter with no baryon absorption<sup>18</sup>. In our model, with  $\sigma_{\text{abs}}(\psi N) = \sigma_{\text{abs}}(\psi' N) = 4.2$  mb fixed by  $pA$  data and a set of plausible soft particle densities and parameters (which can be uncertain), we obtain the  $\psi'/\psi$  ratio as shown in Fig. 2 for different scenarios with different parameters. Our results for the cases of (A), (B), and (C) differ by about one percent and are represented for simplicity by a single solid curve in Fig. 2. For case (A), where we assume that the soft particles are only gluons, the solid curve in Fig. 2 can be obtained with a  $\psi$ -gluon absorption cross section  $\sigma_{\psi g} \sim 1.4$  mb, and a  $\psi'$ -gluon absorption cross section  $\sigma_{\psi' g} \sim 20$  mb. For case (B) where we assume that gluons disrupt the formation of  $\psi$  and  $\psi'$  while produced hadrons break up only  $\psi'$ , the solid curve can be obtained with  $\sigma_{\psi g} \sim 1.4$  mb,  $\sigma_{\psi' g} \sim 7$  mb and a  $\psi'$ -hadron absorption cross section  $\sigma_{\psi' h} \sim 7$  mb. For case (C), where only produced hadrons disrupt the formation of  $\psi$  and  $\psi'$ , the solid curve can be obtained with  $\sigma_{\psi h} \sim 0.9$  mb, and  $\sigma_{\psi' h} \sim 21$  mb. To explain the data of  $\psi'/\psi$ , the parameter sets in (A)-(C) suggest greater disruption for  $\psi'$  than for  $J/\psi$ , due to their interaction

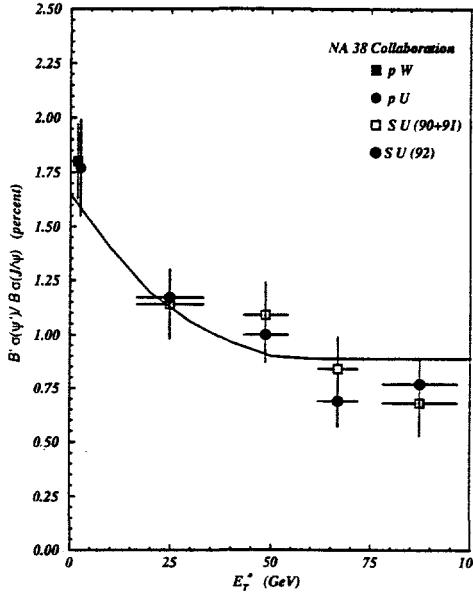


Figure 2: The ratio  $B'\sigma(\psi')/B\sigma(\psi)$  as a function of the transverse energy in SU collisions at 200A GeV. Data points are from Ref. [7]. The theoretical results are shown as the solid curve.

with soft particles. The excessively large  $\psi'$  cross sections required to explain the  $\psi'$  suppression in cases (A) and (C) may make the (B) scenario tentatively a more attractive description. To resolve the ambiguities concerning gluons or hadrons, it is interesting to note that while heavy quark production by hadron-hadron collisions is inhibited by the OZI 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<sup>19</sup> and may explain the enhanced charm and dilepton production in  $AB$  collisions relative to  $pA$  collisions observed in [21].

In conclusion, the observed features of  $\psi'$  to  $J/\psi$  suppression in  $pA$  and  $AB$  collisions can be explained in terms of a two-component absorption model. For the hard component of the absorption due to the interaction of the produced  $c\bar{c}$  systems with nucleons at high relative energies, the absorption cross sections are approximately the same for  $\psi'$  and  $J/\psi$ . However, for the soft component of the absorption (which is due to the interaction of the  $c\bar{c}$  system at low relative energies with soft particles produced by other nucleon-nucleon collisions), the absorption cross sections are greater for  $\psi'$  than for  $J/\psi$  because the breakup threshold for  $\psi'$  is much smaller than for  $\psi$ .

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