Charmonium Production in $\gamma$-A, p-A and A-A

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Abstract.
The data for the production of the $\psi'$ meson in pA collisions at 450 GeV at CERN-SPS (of the NA50-collaboration) [1] yields $\sigma(\psi'N) \approx 8$ mb under the assumption that the $\psi'$ is produced as a result of the space-time evolution of a point-like $c\bar{c}$ pair which expands with time to the full size of the charmonium state. However, much higher values of $\sigma(\psi'N)$ are not ruled out by the data. We show that recent CERN data confirm the suggestion of ref. [2] that color fluctuations are the major source of suppression of the $J/\psi$ yield as observed at CERN in both pA and AA collisions.

1. Introduction
The NA50-collaboration [1] observed quite different $J/\psi$ and $\psi'$-nucleon cross sections. Analogous results have been found at Fermilab [3]: Both experiments found that the charmonium-nucleon cross section is larger in the target fragmentation region than at midrapidity. This is in good agreement with models that assume that the $\psi'$ is produced as colorless, point-like $c\bar{c}$ pair, which expands with time to its full size and that there exists a relationship between the spatial distribution of color in a hadron and the cross section of its interaction with a nucleon. Such a relation is proved in pQCD (perturbative QCD) [6]. For the nonperturbative regime it is a well known experimental fact that spatially larger hadrons have larger interaction cross sections. For example, 3.5 mb for the inelastic $J/\psi$-nucleon cross section was found at SLAC [7] while the inelastic $\pi$-nucleon cross section at this energies is 20 mb. From charmonium models, e.g. in ref. [8, 9] it is known that the different charmonium states ($J/\psi$, $\chi$ and $\psi'$) have different spatial sizes. We concluded in ref. [2] that these cross sections are dominated by non-perturbative contributions.

The agreement of this scenario with the negative $x_F$ Fermilab data [3] with was first demonstrated in ref. [2]. Another attempt to describe these data with such an expansion scenario was done in ref. [4]. However, in ref. [4] 20%-50% of the suppression of charmonium states is due to a color octet state added to the model to explain also the large $x_F$ regime. This state as defined in ref. [4] is in variance with QCD, because of the following reason. The eigen life time of this state adjusted to the Fermilab data is only 0.06 fm. A gluon emitted in such a short time has to have a momentum of $1/(0.06\text{fm}) \approx 3.3$ GeV relative to the $c\bar{c}$ pair [5]. In ref. [4] this gluon was assumed to be massless.

In ref. [2] it was shown that the production of $J/\psi$'s in pA collisions can be described, if one takes into account the production and the subsequent decays of higher resonances ($\chi, \psi'$) into $J/\psi$'s. This leads to a significant increase of the absorption of
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$J/\psi$'s as compared to the propagation of genuine $J/\psi$-states. In ref. [10] it was shown also that the production of $J/\psi$'s in AA collisions is additionally suppressed by the final state interaction of charmonium states with newly produced particles like $\pi$'s, $\rho$'s and so on.

In sect. 2 the used models are introduced and in sect. 3 they are compared to the data. A more detailed description can be found in ref. [11]. We summarize in sect. 4.

2. Model Description

2.1. Semiclassical Glauber Approximation

The suppression factor $S$ for minimum bias $pA$ collisions can be evaluated within the semiclassical approximation (cf. [12]) as

$$S_A = \frac{\sigma(pA \to X)}{A \cdot \sigma(pN \to X)} = \frac{1}{A} \int d^2B dz \rho(B, z) \cdot \exp \left( - \int_z^{\infty} \sigma(XN) \rho(B, z') dz' \right).$$

Here $\rho(B, z)$ is the local nuclear ground state density (we used the standard parametrisation from [13]). $\sigma(XN)$ is the interaction cross section of the charmonium state $X$ with a nucleon and $\sigma(pA \to X)$ ($\sigma(pp \to X)$) is the production cross section of the state $X$ in a $pA$ ($pp$) collision. We want to draw attention to the fact that this cross section changes with time due to the space-time evolution of color fluctuations. Therefore, it is necessary to keep $\sigma$ under the integral. The suppression factor $S$ of $J/\psi$'s produced in the nuclear medium is calculated as:

$$S = 0.6 \cdot (0.92 \cdot S^{J/\psi} + 0.08 \cdot S^{\psi'}) + 0.4 \cdot S^X.\quad (2)$$

Here $S^X$ are the respective suppression factors of the different pure charmonium states $X$ in nuclear matter. Eq. (2) accounts for the decay of higher resonances after they left the target nucleus into $J/\psi$'s. The fractions of $J/\psi$'s that are produced in the decays of higher resonances in eq. (2) are taken from ref. [14]. However, in ref. [14] it is assumed that the different charmonium states interact with nucleons with the same cross section, which is in disagreement with the data from the refs. [1, 3].

In line with the above discussion we want to stress here that Eqs. (1) and (2) are applicable at CERN energies for central and negative rapidities, but have to be modified, if applied already at $y_{c.m.} \sim 0$ at RHIC or higher energies, because at higher energies charmonium states can be produced outside of the nucleus and the $c\bar{c}$ pairs propagate through the whole nucleus without forming a hadron. Data are often presented in the form $\alpha$ vs. $A$, where $\alpha$ is given by

$$\sigma_{pA} = \sigma_{pp} \cdot A^\alpha \text{ so that } S = A^{\alpha-1}.\quad (3)$$

In the semiclassical Glauber approximation, we take into account these color fluctuations in an effective way as described in ref. [15]. We assume that charmonium states are produced at $z$ as small $c\bar{c}$ configurations predominantly through gluon-gluon-fusion, then they evolve – during the formation time $t_f$ – to their full size. Please note that there is up to now no theoretical or experimental proof for the assumption that charmonium states are produced in point-like configurations as predicted in pQCD. A way to test this experimentally was suggested recently in ref. [16]. It’s based on the idea that the $\psi'$ and the $\psi''$ are mixed states of the $2S$ and the $1D$ charmonium states.

The names of these states comes from a comparison of nonrelativistic charmonium...
models with the nonrelativistic wave functions of the positronium (actually even the name charmonium was given to pronounce the similarity with positronium). Namely

\[ \begin{align*}
|\psi'\rangle &= \cos \theta |2S\rangle + \sin \theta |1D\rangle , \\
|\psi''\rangle &= \cos \theta |1D\rangle - \sin \theta |2S\rangle.
\end{align*} \tag{4} \]

Since only the S-wave contributes to the decay of \( \psi \) states into \( e^+e^- \)-pairs (at least in nonrelativistic charmonium models) the value of \( \theta = 19 \pm 2^\circ \) can be determined from the data on the \( e^+e^- \) decay widths of \( \psi' \) and \( \psi'' \). If the production of these charmonium states is pointlike, then only the S-wave is produced. These leads to an universal ratio of

\[ \frac{\sigma(\psi'')}{\sigma(\psi')} \approx \frac{\Gamma(\psi'' \rightarrow \ell^+\ell^-)}{\Gamma(\psi' \rightarrow \ell^+\ell^-)} \approx 0.1. \tag{5} \]

\( \sigma(\psi'') \) resp. \( \sigma(\psi') \) are here the production cross sections of the \( \psi'' \) and resp. \( \psi' \) in various processes. Predictions for different processes can be found in ref. \[16\].

If the formation length of the charmonium states, \( l_f \), becomes larger than the average internucleon distance \( (l_f > r_{NN} \approx 1.8 \text{ fm}) \), one has to take into account the evolution of the cross sections with the distance from the production point \[15\]. Here we assume motivated by quantum diffusion that the cross section increases linearly with time. The formation length of the \( J/\psi \) is given by the energy denominator \( l_f \approx \frac{2p}{m^2_{J/\psi} - m^2_e} \), where \( p \) is the momentum of the \( J/\psi \) in the rest frame of the target. With \( p = 30 \text{ GeV} \), the momentum of a \( J/\psi \) produced at midrapidity at SPS energies \( (E_{lab} = 200 \text{ AGeV}) \), this yields \( l_f \approx 3 \text{ fm} \), i.e. a proper formation time of \( \tau_f = 0.3 \text{ fm} \). As formation time of the \( \psi' \) in its rest system we use here the radius given by nonrelativistic charmonium models, e.g. see the refs. \[19\]. This radius is \( r = 0.45 \text{ fm} \) for the \( \psi' \). A larger value of \( \tau_f \) for the \( \psi' \) is supported also by the extraction of the formation time of the \( J/\psi \) \[17\]. Finally the formation time is \( \tau_f = \gamma \cdot \tau_f \), where \( \gamma \) is the the Lorentz-factor of the charmonium state relativ to the nuclear target. For higher gamma factors, i.e. at higher energies, the formation time becomes larger than the nuclear targets. In this regime a hadronic description during the formation time is questionable. A partonic model for this energy range was proposed in ref. \[18\].

2.2. Vector Dominance Model for \( \gamma A \)

The VDM (Vector Dominance Model) takes into account only the direct diffractive production of the \( J/\psi \) and the \( \psi' \), while the GVDM (Generalized Vector Dominance Model) accounts also for the non-diagonal transitions \( (\psi' + N \rightarrow J/\psi + N \text{ and } J/\psi + N \rightarrow \psi' + N) \). The later are needed, because in photoproduction the particles are produced as point like configurations and develop then to their average size. In a hadronic model like the GVDM this is taken into account in form of the interference due to the non-diagonal matrix elements. In the GVDM the photoproduction amplitudes \( f_{\gamma \psi} \) and \( f_{\gamma \psi'} \) for the \( J/\psi \) and the \( \psi' \) are given by \[19\]

\[ \begin{align*}
f_{\gamma \psi} &= e \frac{f_{\psi}}{f_{\psi'}} + e \frac{f_{\psi'}}{f_{\psi}} \frac{f_{\psi}}{f_{\psi'}} \\
f_{\gamma \psi'} &= e \frac{f_{\psi}}{f_{\psi'}} + e \frac{f_{\psi}}{f_{\psi'}} \frac{f_{\psi}}{f_{\psi'}} \tag{6} \end{align*} \]

Here \( f_{\psi} \) and \( f_{\psi'} \) are the \( J/\psi - \gamma \) and the \( \psi' - \gamma \) coupling and \( f_{VV} \), are the amplitudes for the processes \( V + N \rightarrow V' + N \), where \( V \) and \( V' \) are the \( J/\psi \) and the \( \psi' \) respectively. In the VDM the non-diagonal amplitudes with \( V \neq V' \) are neglected. The importance
of the nondiagonal transitions is evident, because the left hand side of eq. (6) is small. If it is neglected as a first approximation \[19\], then \( f^{\psi'}_{\psi} = -\frac{f_{\psi'}}{f_{\psi}} f_{\psi} \approx 1.7 \cdot f_{\psi}. \) And due to the CPT-theorem \( f^{\psi'}_{\psi} = f_{\psi}. \)

In ref. \[20\] the GVDM yields approximately \( 8 \pm 2 \) mb for the \( \psi' \)-nucleon interaction cross section at SPS-energies as can be seen in Fig. 1. \( \omega \) is the laboratory energy of the photon. The \( J/\psi \)-nucleon interaction cross section at SPS-energies approximately \( 3.5 \) - \( 4 \) mb is used as input into the analysis of ref. \[20\]. The accuracy of such GVDM in predicting the \( \psi'N \) cross sections is not clear. The above calculation demonstrates that implementing color transparency leads to significantly larger cross sections of the \( \psi'N \) interaction.

\[ \text{Figure 1: The energy dependence of the elementary charmonium-nucleon cross sections found in the GVDM. The filled areas show the variation of the cross sections due to the uncertainty of the experimental J/ψN cross section.} \]

3. Comparison with NA50 and NA51 Data

In Fig. 2 we show a comparison between calculations with different cross sections and different expansion times and the NA50 data \[11\] for pA collisions and the NA51 data \[21\] for pp and pD collisions for the cross section of \( \psi' \) interaction vs. the mass of the target. The y-axis shows \( B_{\mu\mu} \sigma_{\psi'}/A \) where \( B_{\mu\mu} \) is the branching ratio for the decay of the \( \psi' \) into dimuon pairs, and \( \sigma_{\psi'} \) is the production cross section. The ”5.1 mb, instant formation” curve in Fig. 2 is the fit of the NA50 collaboration to their data. Instant formation means that they assumed that the \( \psi' \) is produced with the full cross section and not as a point like particle as in the description of this paper. (Note the NA50 collaboration fitted \( B_{\mu\mu} \sigma_{\psi'}/\sigma_{DY} \), where \( \sigma_{DY} \) means Drell-Yan, we multiplied this fit with the \( DY \) cross section in pp collisions measured by NA51).

The ”8 mb, \( t_f = 0.45 \) fm” curve is the eye-ball fit of the model described in this paper. For the comparison with the data we need the production cross section of the \( \psi' \) in pp collisions as input. We used here the average of the pp and pD data of the NA51 collaboration. The value of 8 mb agrees well with the model parametrisations discussed in the sections \[2\]. However, we compare also with the calculation with the parameters of ref. \[2\], i.e. \( \sigma(\psi'N) = 20 \) mb and \( t_f = 0.6 \) fm. For this comparison we used the production cross section of the \( \psi' \) in pD collisions divided by two as
input. This is also close to the value of the NA50 fit. One can see in Fig. 2 that the calculation with these parameters is also in good agreement with the data. A value for $\sigma(\psi'N)$ of the size of 20 mb is favored by the nucleus-nucleus data as shown in ref. [11] and in Fig. 3. Plotted is $B_{\mu\mu}\sigma(J/\psi)/\sigma(DY)$ with the absorption cross sections from ref. [2] and the NA50 data [22] for PbPb collisions vs. the transverse energy $E_t$, a measure for the centrality of the collision. The calculation agrees well with the data. The calculation for the $\psi'$ underestimates the data. However it is not understood, if this is due to the high value of $\sigma(\psi'N) = 20$ mb, or if nondiagonal transitions like in sect. 2.2 should be taken into account in AA collisions, too.

The value of 8 mb is smaller than the theoretical estimate 20 mb of ref. [2]. This is because in ref. [2] a formation time of 0.6 fm was chosen for the $\psi'$, while we used her 0.45 fm, the radius of the $\psi'$ given by the charmonium models. The fact that the formation time is not known very well is another theoretical uncertainty. Further uncertainty comes from using diffusion model of expansion at the distances comparable to the scale of the soft interaction. Within the error bars the $\psi'$-nucleon cross section extracted from these pA data and the prediction of the GVDM, discussed in sect. 2.2 are qualitatively similar. However, further data are needed to learn more about this cross section.

![Figure 2](image-url)
4. Conclusions

The new data of the NA50-collaboration [1] and the data of the E866-collaboration [3] prove that the $\psi'$-nucleon cross section is much larger than the $J/\psi$-nucleon cross section. This is in agreement with the photoproduction data for these charmonium states as discussed in the framework of the GVDM in section 2.2. This confirms the QCD prediction that the strength of hadron-hadron interactions depends on the volume occupied by color.

Within the assumption that charmonium states are produced as point like white states, we demonstrated that the data [1] can be fitted with a $\psi'$-nucleon cross section of $\sigma(\psi'N) \approx 8$ mb. However, a much larger cross section of e.g. $\sigma(\psi'N) \approx 20$ mb is not ruled out by the data. Due to the large experimental errors we conclude that the data and the QCD-motivated models agree, but further data with higher accuracy and covering larger rapidity range are needed.

This cross section will be measured soon in proton-nucleus collisions at HERA B at an energy of $E_{\text{lab}} = 920$ GeV. The advantage of this experiment is that it covers a larger range of Feynman-$x_F$, especially in the negative $x_F$ region. In this region effects due to the formation time of the hadron will be less important and the genuine cross sections will be measured.

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