A New Approach of $J/\psi$ suppression in pA and AA Collisions

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Abstract

When the cross section of $J/\psi$ production is considered varying with the energy of the nucleon-nucleon interaction the production of $J/\psi$ in pA and AA collisions has been studied using FRITIOF Model. The calculation shows that the cross section of $J/\psi$ production "per nucleon-nucleon collision" decreases with increasing mass number and centrality as a consequence of continuous energy loss of the projectile nucleons to the target nucleons in their successive binary nucleon-nucleon collisions. We have compared our model predictions with the experimental data of $J/\psi$ production.

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Suppression of $J/\psi$ production in high energy heavy ion collisions was proposed as an effective signature of QGP formation ten years ago [1]. The ensuing experimental data confirmed a significant suppression of $J/\psi$ production in both pA and AA collisions [2]. However, alternative explanations of the $J/\psi$ suppression exist based on the absorption of $J/\psi$ in nuclear matter [3]. The overall set of extensive data collected and analysed by NA38 seems to support the absorption mechanism in p+B\text{target}, O+B\text{target} and S+U collisions. Nevertheless a rather large absorption cross section ($\sim 6.2$ mb) has to be used in order to fit the experimental data, about three times larger than the total $J/\psi$-N cross section from the EMC Collaboration [4]. Such a difference was already noted long time ago in [5]. Recent calculations based on the colour octet model show that this phenomenological cross section could be understood by the absorption of pre-resonance states ($ccg$) in nuclear matter [6].

Other sources of $J/\psi$ suppression in nuclear collisions, such as the interaction of $J/\psi$ particles with the produced mesons (called comover) [7], gluon shadowing in nuclei, intrinsic charm component, energy degradation of produced $c\bar{c}$ pair, etc. [8], have been introduced besides the absorption due to the $J/\psi$-N interaction to explain the data.

We in this paper propose a simple model to investigate $J/\psi$ suppression in pA and AA collisions focusing on the decrease of the cross section of $J/\psi$ production with increasing mass number and centrality due to the continuous energy loss of the projectile nucleons to the target nucleons in their successive binary nucleon-nucleon collisions, not on its later absorption in nuclear matter. From the calculations of this model, we conclude that the absorption of $J/\psi$ particles in nuclear matter is only part of the sources of $J/\psi$ suppression seen in pA and AA collisions so far.

Since the probability for a nucleon-nucleon collision leading to $J/\psi$ production is very small it is generally accepted that multiple $J/\psi$ production processes in pA and AA collisions can be neglected. The studies of $J/\psi$ suppression based on the absorption mechanism actually assume that the probability of $J/\psi$ production “per nucleon-nucleon collision” is the same independent of the masses of the colliding nuclei at a given energy. However, each binary nucleon-nucleon collision experienced by a projectile nucleon on its way out of the target in pA and AA collisions may not be the same if the projectile nucleon loses a fraction of its energy in each binary collision to the target nucleon such that the cms energy of each binary collision of this incoming nucleon with a target nucleon is different. For the cross sections of the hard QCD parton-parton scatterings, which is responsible for $J/\psi$ production, increase with increasing energy it is conceivable that the probability of $J/\psi$ production would also depend on the energy of a nucleon-nucleon collision in a similar way. It is confirmed both theoretically and experimentally that $J/\psi$ photoproduction cross section exhibits a strong threshold behaviour at the low energy region and then increases with energy at the higher energy region [9].

In a participant-spectator model of nucleus-nucleus collisions, like FRITIOF, each projectile nucleon may collide several times with the target nucleons. If momentum transfers are assumed to take place in each binary nucleon-nucleon collision, then the cms energy of these binary collisions will decrease with time, thereby the probability to produce $J/\psi$ in each binary collision going down.

We in this paper have calculated how the cross section of $J/\psi$ production varies with increasing mass number of colliding nuclei and centrality using FRITIOF model. The calculations show that $J/\psi$ production is suppressed in pA and AA collisions in comparison with the nucleon-nucleon collision, and the larger the mass number of colliding nuclei and the centrality, the greater the suppression, as a result that probability of finding a QCD hard process in a binary nucleon-nucleon decreases with increasing mass number of colliding nuclei and centrality. Taking into account the $J/\psi$ absorption by $J/\psi$-N interaction our results are in good agreement with experimental data with the exception.
of the latest data of Pb+Pb collisions at 158 AGeV/c, which show a further $J/\psi$ suppression \[9\]. The absorption cross section $\sigma_{\text{abs}}$ needed to explain the data from p+B target, O+B target and S+U collisions is about 1.4 mb in this paper, which is consistent with the experiments (EMC Collaboration \[1\] gives a total $J/\psi$-N cross section 2.2 $\pm$ 0.7 mb and the $J/\psi$-N quasi-elastic cross section is given in \[1\] as 0.79 $\pm$ 0.012 mb). Furthermore, our results also imply that some new mechanism of $J/\psi$ suppression seems to be needed particularly for understanding Pb+Pb data. The authors in \[12\] have attributed the further $J/\psi$ suppression in Pb+Pb data to the formation of a QGP state.

As we have mentioned before the cross section of $J/\psi$ production will be different in each binary nucleon-nucleon collision in pA and AA collisions if the energy loss of the projectile nucleons to the target nucleons in the successive binary collisions is taken into account. Assume that $<\sigma_{J/\psi}>$ is the mean cross section for the production of a $J/\psi$ particle in a binary nucleon-nucleon collision (here the average is done over all the binary collisions at an impact parameter $b$), then the total probability for producing a $J/\psi$ particle in the collisions of A + B at an impact parameter $b$ is the sum

$$P_{J/\psi}^{AB} = \sum_{n=1}^{AB} \left( \frac{AB}{n} \right) \left( T(b) <\sigma_{J/\psi}^N > \right)^n \left[ 1 - T(b) <\sigma_{J/\psi}^N > \right]^{AB-n},$$  \[1\]

where $T(b)$ is the thickness function. Because $T(b) <\sigma_{J/\psi}^N >$ is a very small quantity ($<\sigma_{J/\psi}^N > \sim 10^{-4}$ fm$^2$ \[3\], $T(b) \sim 10^{-2}$fm$^{-2}$ for central S+U collisions, for instance), the summation given by Eq.\[1\] is dominated by the first term with $n=1$. The terms with $n>1$ represent multiple $J/\psi$ production processes and shadowing corrections, which are very small and can be neglected. Then the probability for $J/\psi$ production in A+B collisions can be approximated to be

$$P_{J/\psi}^{AB} = AB[R(b) <\sigma_{J/\psi}^N >].$$  \[2\]

Therefore, the cross section of $J/\psi$ production corresponding to a centrality bin, $\Delta b$, is given by the following formula

$$\sigma_{J/\psi,\Delta b}^{AB} = AB <\sigma_{J/\psi}^N >_{\Delta b} \int_{\Delta b} T(b) db,$$  \[3\]

where $<\sigma_{J/\psi}^N >_{\Delta b}$ is the mean cross section of $J/\psi$ production “per nucleon-nucleon collision” within the centrality bin $\Delta b$. We know that QCD hard scatterings (the gluon fusion and quark-antiquark annihilation) between partons are the main source of $J/\psi$ production. Let $P_h$ be the probability to have a hard scattering in a nucleon-nucleon collision and $P_{h,J/\psi}$ the probability to produce a $J/\psi$ from the hard scattering, then we can write out $<\sigma_{J/\psi}^N >$ to be

$$<\sigma_{J/\psi}^N > = <\sigma_T P_{h,J/\psi}^P_h > = <\sigma_T P_{h,J/\psi}^P_h > = <\sigma_T P_{h,J/\psi}^P_h >,$$  \[4\]

where $\sigma_T$ is the total cross section of a nucleon-nucleon collision. We have assumed that $\sigma_T P_{h,J/\psi}^P$ is approximately a constant in the energy span that we are concerning, so the product is the same for all the binary collisions. Combining Eq.\[4\] with Eq.\[3\] and replacing $<\sigma_T P_{h,J/\psi}^P_h >$ by the ratio $\frac{n_h}{n_{\text{bin}}(b)}$ ($n_{\text{bin}}(b)$ is the number of binary collisions in an A+B collision and $n_h^{b}$ the number of binary collisions with a hard scattering. Both of them are the function of the impact parameter $b$) we finally obtain

$$\sigma_{J/\psi,\Delta b}^{AB} = AB\sigma_T P_{h,J/\psi}^P_h <\frac{n_h^{b}}{n_{\text{bin}}(b)} >_{\Delta b} \int_{\Delta b} T(b) db$$  \[5\]

and for the minimum bias events we have

$$\frac{\sigma_{J/\psi}^{AB}}{AB} = \sigma_T P_{h,J/\psi}^P_h \frac{n_h^{b}}{n_{\text{bin}}},$$  \[6\]
We see from Eq. (6) that the dependence of the quantity \( \frac{\sigma_{AB}}{A_{c}} \) on the masses of colliding nuclei or centrality is solely determined by how the mean probability of having a hard scattering in a binary nucleon-nucleon collision varies with the masses of colliding nuclei or centrality. Before calculating \( \frac{n_{h}}{n_{br}}(b) \) in pA and AA collisions we will give a brief introduction of FRITIOF dynamics focusing on how a hard parton-parton scattering is distinguished from a soft one.

FRITIOF is a string model based on the concepts of the Lund String Model [16], which started from the modeling of inelastic hadron-hadron collisions and it has been successful in describing many experimental data from the low energies at the ISR-regime all the way to the top SPS energies [17] [18]. This has been achieved by the introduction of a particular longitudinal momentum transfer scenario, gluon bremsstrahlung radiation (The Dipole Cascade Model, DCM [19], and the Soft Radiation Model, SRM [20], — this is implemented by the use of ARIADNE [21]) as well as hard parton scattering (Rutherford Parton Scattering, RPS — this is implemented by the PYTHIA routines [22]). In FRITIOF, during the collision two hadrons are excited due to longitudinal momentum transfers and/or a RPS. It is further assumed that there is no net color exchange between the hadrons. The highly excited states will emit bremsstrahlung gluons according to the SRM. They are afterwards treated as excitations or the Lund Strings and the string states are allowed to decay into final state hadrons according to the Lund prescription as implemented by JETSET [23].

In the FRITIOF model a hadron is assumed to behave like a massless relativistic string (MRS) corresponding to a confined color force field of a vortex line character embedded in a type II color superconducting vacuum. A hadron-hadron collision is pictured as the multi-scatterings of the partons inside the two colliding hadrons. This includes both the hard and the soft components depending on the four-momentum transfers \( Q^2 \), or equivalently the transverse momentum transfers involved. The soft part is described by a simple phenomenological model. The hard scatterings can however be calculated from perturbative QCD, and correspond to the Rutherford parton-parton scattering (RPS). The divergence problem in RPS is handled by introducing the Sudakov factor.

There will be color separation in the model, i.e. there will for each hadron be a color \( \bar{3} \) (a “diquark”) continuing forward along the beam direction and a valence quark, a color \( 3 \), moving in the opposite direction due to the longitudinal momentum transfer. This will lead to bremsstrahlung of a dipole character.

A procedure therefore is adopted in FRITIOF that compares the “hardness” of the Rutherford partons to that of the bremsstrahlung gluons. The RPS is accepted only if it is harder than the associated radiation. If the RPS is “drowned”, which is to say that it is softer than the radiation, then the RPS is not acceptable and the collision proceeds as a purely soft collision. With this prescription the RPS spectrum is suppressed smoothly at small to medium transverse momentum region.

For the hadron-nucleus and nucleus-nucleus collisions, the process has in the FRITIOF model been treated as a set of incoherent collisions on the nucleons. Thus a nucleon from the projectile interacts independently with the encountered target nucleons as it passes through the nucleus. The probability distribution for the number of inelastic collisions \( \nu \) is taken from geometric calculations. Each of the sub-collisions is treated in the same way as an ordinary hadron-hadron collision, although the momentum transfers will again be additive and every encounter will make the projectile more excited. If it interacts with \( \nu \) nucleons in the target, \( \nu + 1 \) excited string states will be formed as a result. These string states will then independently emit associated bremsstrahlung radiation and
then fragment into hadrons in the same way as individual strings. This picture is supported by the fact that the global features of heavy ion collisions are satisfactorily explained by the collision geometry together with the independent hadron-hadron collisions.

Using FRITIOF it is straightforward to calculate the number of binary nucleon-nucleon collisions, \( n_{\text{bin}}(b) \), and the number of the binary collisions with a hard scattering, \( n_{\text{bin}}^h(b) \), in pA and AA collisions at a given impact parameter \( b \), so that the mean probability to have a hard scattering in a binary nucleon-nucleon collision, \( \langle P_h \rangle = \frac{n_{\text{bin}}^h(b)}{n_{\text{bin}}(b)} \), can be obtained. Since we are mainly interested in \( J/\psi \) production in pA and AA collisions relative to that in the pp collision we do not need to know how a \( J/\psi \) is actually formed from the hard scatterings in order to investigate the dependence of \( J/\psi \) production cross sections on mass number and centrality.

We have calculated the quantity \( \frac{n_{\text{bin}}^h(b)}{n_{\text{bin}}(b)} \) for various pA and AA collisions (and \( \frac{n_{\text{bin}}^h(b)}{n_{\text{bin}}(b)} \Delta b \) for different centrality bins in S+U and Pb+Pb collisions) at \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \) using FRITIOF. After determining \( \sigma_T^J/\psi \) by the data of the pp collision we plot our results of \( B_{\mu \mu} \frac{\sigma_{AB}^J/\psi}{\sigma_{\text{DY}}} \cdot A_{\text{proj.}} \cdot B_{\text{targ.}} \) as a function of \( A_{\text{proj.}} \cdot B_{\text{targ.}} \) in Figure 1 for the minimum bias events. For the cross section of \( J/\psi \) production in different centrality bins we plot the results of \( B_{\mu \mu} \frac{\sigma_{AB}^J/\psi}{\sigma_{\text{DY}}} \cdot A_{\text{proj.}} \cdot B_{\text{targ.}} \) as a function of \( N_p \cdot N_t \) in Figure 2, where \( N_p \) is the number of participants from the projectile and \( N_t \) the number of participants from the target, since the Drell-Yan cross section in a given centrality bin is found in experiments proportional to an effective \( A_{\text{proj.}} \cdot B_{\text{targ.}} = A_{\text{proj.}} \cdot B_{\text{targ.}} \int_{\Delta b} T(b) \Omega \). In the same way, a constant has to be determined by the corresponding data of the pp collision. The impact parameter bins are taken to be the same as those extracted by NA38 and NA50 [10]. We decided not to use the absorption length \( L \) to be the longitudinal axis as used by NA50 because \( L \) calculated from the geometry model is not sensitive to the change of impact parameter for very central Pb+Pb collisions. The results of our calculations show that the decrease of quantity, \( B_{\mu \mu} \frac{\sigma_{AB}^J/\psi}{\sigma_{\text{DY}}} \cdot A_{\text{proj.}} \cdot B_{\text{targ.}} \) or \( B_{\mu \mu} \frac{\sigma_{AB}^J/\psi}{\sigma_{\text{DY}}} \) (the cross section of \( J/\psi \) production “per nucleon-nucleon collision”), is due to the fact that the probability of the QCD hard scattering per binary nucleon-nucleon collision decreases with the increasing mass number and centrality.

When the absorption of \( J/\psi \) by \( J/\psi \)-N interaction is also taken into account, i.e. the previous results are multiplied by \( \exp(-\rho L \sigma_{\text{abs}}) \) with \( \rho = 0.14 \text{ fm}^3 \) \( \sigma_{\text{abs}} = 1.4 \text{ mb} \) and \( L \) taken to be the same as those in [10], our model reproduces the data of \( J/\psi \) suppression with the exception of the latest data from Pb+Pb collisions at 158 GeV/c, which clearly show a further suppression.

One possibility which will bring about a further suppression of \( J/\psi \) production is that \( P_h^J/\psi \), the probability to produce a \( J/\psi \) from a hard process, drops down suddenly under certain conditions. This is equivalent to say that the \( c\bar{c} \) produced from the hard processes can not form a bound state. However at the moment our simple model can not estimate when this would happen.

However, there are still other possible mechanisms of \( J/\psi \) suppression, which are not included in our simple model. The \( x_F \) dependence of \( J/\psi \) suppression is not investigated yet. Therefore, it is hard to make any conclusion now whether this further suppression in Pb+Pb collision is due to QGP formation.

It is known that there is no unique criterion to distinguish a hard process from a soft one in a nucleon-nucleon collision. Usually a \( q_{T_{\text{min}}} \) is introduced to be the minimum transverse momentum of the
produced partons from a hard process. A dynamic criterion is applied in FRITIOF to chose a hard process by comparing the hardness of a RPS parton with the hardness of the bremsstrahlung gluons as mentioned before. However, the cross section of $J/\psi$ production should not depend on which criterion is actually used in the calculation. We have thus calculated all the results of this paper using the conventional $q_{T_{\text{min}}}$ criterion in Pythia ($q_{T_{\text{min}}} = 1\text{GeV/c}$), just to check if our conclusion relies on the specific criterion in FRITIOF. The calculations show that the results in these two cases are in agreement with each other.

We have also checked if the quantity $\sigma_{T_{\text{h}}} P_{J/\psi}^{T_{\text{h}}}$ is energy-independent as we have assumed. A parametrization form of the $J/\psi$ cross section is given as

$$\sigma_{J/\psi} = \sigma_{0}(1 - \frac{M_{J/\psi}}{\sqrt{s}})^{12},$$

(7)

where $\sqrt{s}$ stands for the cms energy per nucleon. Therefore, if $\sigma_{T_{\text{h}}} P_{J/\psi}^{T_{\text{h}}}$ in Eq.(6) is energy-independent then we should have a ratio

$$\frac{(1 - \frac{M_{J/\psi}}{\sqrt{s}})^{12}}{n_{b_{\text{bin}}}} = C = \text{constant}. \quad (8)$$

We have calculated $\frac{n_{b_{\text{h}}}}{n_{b_{\text{bin}}}}$ and the ratio at various energies from $P_{\text{lab}}=60\text{ GeV/c}$ to $P_{\text{lab}}= 450\text{ GeV/c}$ for pp collisions ($n_{b_{\text{bin}}} = 1$ for a pp collision) and the results are listed in Tab.1, which show that this ratio in this energy region is not sensitive to the change of energy in comparison with $\frac{n_{b_{\text{h}}}}{n_{b_{\text{bin}}}}$. But a threshold behaviour may exist at lower energies, which can be seen from the value at $P_{\text{lab}}=60\text{ GeV/c}$.

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Figure Captions

Figure1: $J/\psi$ cross sections divided by $A_{\text{proj.}} \cdot B_{\text{targ.}}$ as a function of $A_{\text{proj.}} \cdot B_{\text{targ.}}$. Our results are compared with the experimental data from NA51, NA38 and NA50 [10].

Figure2: $J/\psi$ cross sections divided by Drell-Yan cross sections as a function of $N_p \cdot N_t$. Our results are compared with the experimental data from NA38 and NA50 [10].
Table 1. The energy dependence of the probability to have a hard scattering per binary collision and the assumed constant $C$ in Eq.(8)

| $P_{lab}$ GeV/c | $\frac{n_{bin}}{n_{lim}}$ | $C$    |
|-----------------|-----------------|-------|
| 60              | $1.17 \times 10^{-2}$ | 1.84  |
| 100             | $2.82 \times 10^{-2}$ | 2.03  |
| 150             | $4.76 \times 10^{-2}$ | 2.14  |
| 200             | $6.40 \times 10^{-2}$ | 2.22  |
| 300             | $9.17 \times 10^{-2}$ | 2.27  |
| 450             | $12.2 \times 10^{-2}$ | 2.30  |
\[ B_{\mu\mu} \sigma(J/\Psi)/(A_{\text{projectile}} B_{\text{target}}) \text{(nb/nucleon)}^2 \]

- \( p (450\text{GeV/c}) - A (A = \text{P, d, Cu, W}) \) (NA51, NA38)
- \( p (200\text{GeV/c}) - A (A = \text{Cu, W, U}) \) (NA38)
- \( ^{16}\text{O} (16 \times 200\text{GeV/c}) - A (A = \text{Cu, U}) \) (NA38)
- \( ^{32}\text{S} (32 \times 200\text{GeV/c}) - \text{U} \) (NA38)
- \( ^{208}\text{Pb} (208 \times 158\text{GeV/c}) - \text{Pb} \) (NA50)

Results of this work without absorption
Results of this work with absorption
results of this work without absorption

results of this work with absorption