Ansatzes, Assumptions and Production of $J/\Psi$-Particles: A Non-charmed Approach versus Charmed Ones

P. Guptaroy$^{1,**}$, Goutam Sau$^{2}$, S. Bhattacharyya$^{3}$

$^{1}$Department of Physics, Raghunathpur College, Raghunathpur 723133, Purulia (WB), India
$^{2}$Beramara Ram Chandrapur High School, South 24-Parganas, 743609 (WB), India
$^{3}$Physics and Applied Mathematics Unit (PAMU), Indian Statistical Institute, 203 B.T. Road, Kolkata-700108, India

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We look at some crucial aspects of $J/\Psi$-production in a few high energy nuclear collisions in the light of a non-standard model which is outlined in the text. The underlying physical ideas, assumptions and ansatzes are also enunciated in some detail. The results are in fairly good agreement with both measured data and the results obtained on the basis of other models of the standard variety. The impact and implications of this comparative study are also discussed.

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The proposed ‘suppression’ of $J/\Psi$ mesons in the high energy relativistic heavy ion collisions has been viewed all through the years as one of the most prominent diagnostics for the formation of a quark-gluon plasma (QGP), the hypothetical ‘hot and dense matter’ created in high energy collisions$^{[1,2]}$. The RHIC experiments cannot yet give any final confirmation to the formation of any clear and unambiguous quark-gluon plasma. Very recently, the ATLAS group reported the first results of $J/\Psi$ production at the LHC in Pb+Pb collisions.$^{[3]}$ The results are still rudimentary, so the group could not give any decisive view in regard to the formation of deconfined matter. Still, both speculations about and research on production-characteristics of $J/\Psi$ continue to take place.

Our objectives are: (1) to explain the major features of the latest data on $J/\Psi$-production in BNL-RHIC experiments from the proposed alternative approach called the sequential chain model (SCM), built up in a set of previous studies done in the both the remote and recent past;$^{[4]}$ and (2) to compare our model-based calculations with some other competing models.

According to this model, called the sequential chain model (SCM), high energy hadronic interactions are essentially pion-pion interactions; as the protons are conceived in this model as $p=(\pi^+\pi^0\vartheta)$,$^{[4]}$ where $\vartheta$ is a spectator particle needed for the dynamical generation of quantum numbers of the nucleons. The multiple production of $J/\Psi$-mesons in high energy proton-proton collisions is described in the following way. The secondary $\pi$-meson or the exchanged $\varphi$-meson emits a free $\omega$-meson and pi-meson; these pions at high energies could liberate another pair of free $\varphi$ and trapped $\omega$-mesons (in the multiple production chain). These so-called free $\varphi$ and $\omega$-mesons decay quite fast into photons and these photons decay into $\Psi$ or $\Psi'$ particles, which according to this alternative approach is a bound state of $\Omega\Omega'$ or $\Omega'\Omega'$ particles. In this model there is no concept for parton fragmentation and recombination as in the standard model (SM). Particles are emitted as just particles with their attributed quantum numbers. Thus ideas on evolution do not arise in this approach. The inclusive cross-section of the $\Psi$-meson produced in the $pp$ collisions given by$^{[5]}$

$$E \frac{d^3\sigma}{dp^3} |_{p+p\to J/\Psi+X} \equiv C_{J/\Psi} \frac{1}{p_T^{N_T}} \exp \left( -5.35 (p_T^2 + m_{J/\Psi}^2) \right) \cdot \exp(-1.923(n_{J/\Psi})_{pp} x),$$

(1)

where the expression for for average multiplicity for $\Psi$-particles in $pp$ scattering would be given by

$$\langle n_{J/\Psi} \rangle_{pp} = 4 \times 10^{-6} s^{1/4}. $$

(2)

In the above expression, the term $|C_{J/\Psi}|$ is a normalisation parameter and is assumed here to have a value $\sim 0.09$ of intersecting storage ring (ISR) energy, and it is different for different energies and for various collisions. The terms $p_T$, $x$ and $m_{J/\Psi}$ represent the transverse momentum, the Feynman scaling variable and the rest mass of the $J/\Psi$ particle, respectively. Moreover, by definition, $x = 2p_L/\sqrt{s}$, where $p_L$ is the longitudinal momentum of the particle. Here $s$ in Eq. (2) is the square of the c.m. energy.

The second term on the right-hand side of Eq. (1), the constituent rearrangement term arises out of the partonic rearrangements inside the proton. It is established that hadrons (baryons and mesons) are composed of few partons. In high energy interaction processes, the partons at large transverse momenta undergo some dissipation loss due to the impact and impulse of the projectile on the target and the parton inside them (both the projectile and the target), they

**Corresponding author. Email: gpradeepata@rediffmail.com
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suffer some forced shifts of their placements or configurations. These rearrangements mean an undesirable loss of energy, in so far as the production mechanism is concerned. The choice of $N_R$ would depend on the following factors: (i) the specificities of the interacting projectile and target, (ii) the particularities of the secondaries emitted from a specific hadronic or nuclear interaction and (iii) the magnitudes of the momentum transfers and of a phase factor (with a maximum value of unity) in the rearrangement process in any collision. Parametrisation is to be carried out for two physical reasons, viz., the amount of momentum transfer and the contributions from a phase factor arising from the rearrangement of the constituent partons. Sorting and combining all these, we propose the relation to be given by

$$N_R = 4 \langle N_{\text{part}} \rangle^{1/3} \theta,$$  

where $\langle N_{\text{part}} \rangle$ denotes the average number of participating nucleons and $\theta$ values are to be obtained phenomenologically from the fits to the data points.

$$E \frac{d^3 \sigma}{dp_T^3} |_{A + B \rightarrow J/\Psi + X} = a_{J/\Psi} p_T^{-N_R} \exp[-c(p_T^2 + m_{J/\Psi}^2)] \cdot \exp[-1.923(n_{J/\Psi})_{pp}], \quad (4)$$

where $a_{J/\Psi}$, $N_R$ and $c$ are the factors to be calculated under certain physical constraints. The set of relations to be used for evaluating the parameters $a_{J/\Psi}$ are obtained from Ref.[5].

As the psi-productions are generically treated as the resonance particles, standard practice is to express the measured $J/\Psi$ (total) cross-sections times branching ratio to muon or electrons, i.e. for lepton pairs, that is, by $B_{ll} \sigma_{pp \rightarrow J/\Psi + X}$. By using expression (4) we arrive at expressions for the differential cross-sections for the production of $J/\Psi$-mesons in the mid and forward-rapidities (i.e. $|y| < 0.35$ and $1.2 < |y| < 2.2$, respectively) in $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC.

$$\frac{1}{2\pi p_T} B_{ll} \frac{d^2 \sigma}{dp_T dy} |_{pp \rightarrow J/\Psi + X} = 6.1 p_T^{-1.183} \exp[-0.13(p_T^2 + 9.61)]$$

for $|y| < 0.35,$  

$$\frac{1}{2\pi p_T} B_{ll} \frac{d^2 \sigma}{dp_T dy} |_{pp \rightarrow J/\Psi + X} = 6.5 p_T^{-1.183} \exp[-0.16(p_T^2 + 9.61)]$$

for $1.2 < |y| < 2.2$.  

For deriving the expressions (5) and (6) we have used the relation $x \simeq \frac{2p_T \gamma_{cm}}{\sqrt{s}} = \frac{2m_T \sinh y_{cm}}{\sqrt{s}}$, where $m_T$ and $y_{cm}$ are the transverse mass of the produced particles and the rapidity distributions, respectively. Here $m_{J/\Psi} \simeq 3.096.9\pm 0.011$ MeV[10] and $B_{ll}$, the branching ratio is for muons or electrons, i.e. it is for lepton pairs $J/\Psi \rightarrow \mu^+ \mu^-/e^+e^-$, is taken as $5.93 \pm 0.10 \times 10^{-2}$[10] in calculating the above equations. These expressions assume slightly altered numerical values for the LHC energy of 7 TeV.

In Figs.1(a) and 1(b) we have drawn the solid lines depicting the SCM model-based results with the help of the above expressions (5) and (6) and some other changed forms of them against the experimental measurements.[11,12] respectively.

For the calculation of the rapidity distribution from the set of Eqs. (1)–(4) we can make use of a standard relation as

$$\frac{dN}{dy} = \int \frac{1}{2\pi p_T} \frac{d^2 N}{dp_T dy} dp_T. \quad (7)$$

The rapidity distributions for the $J/\Psi$-production has now been reduced to a simple relation given here below

$$\frac{dN}{dy} = a_1 \exp(-0.23 \sinh y_{cm}). \quad (8)$$

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**Fig. 1.** Plot of the invariant cross-section for $J/\Psi$ production in proton-proton collisions at (a) $\sqrt{s_{NN}} = 200$ GeV and (b) $\sqrt{s_{NN}} = 7$ TeV versus $p_T$. The data points are taken from Ref. [11] for (a) and from Ref. [12] for (b). The solid curves show the SCM-based results.
The normalization factor $a_1$ depends on the centrality of the collisions and is obvious from the nature of Eqs. (1)–(4) and (7).

**Fig. 2.** Plot of the rapidity distribution for $J/\psi$ production in proton-proton collisions at $\sqrt{s_{NN}} = 200$ GeV versus $y$. The data points are taken from Ref. [13]. The solid curves show the SCM-based results.

For $p + p$ collisions, the calculated rapidity distribution equation is given by

\[
\frac{dN}{dy}_{p+p \rightarrow J/\psi + X} = 1.215 \times 10^{-6} \exp(-0.23 \sinh y_{cm}).
\]

(9)

In Fig. 2 we have plotted the rapidity distributions for $J/\psi$-production in $p + p$ collisions. Data in the figure are taken from Ref. [13] and the line shows the SCM-based output.

**Fig. 3.** Plot of the invariant yields for $J/\psi$ production in $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV versus $p_T$. The data points are taken from Ref. [13]. The solid curves show the SCM-based results.

From expression (4), we arrive at the invariant yields for $J/\psi$-production in $d + Au \rightarrow J/\psi + X$ reactions for mid and forward-rapidities.

\[
\frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy_{cm}}_{d+Au \rightarrow J/\psi + X} = 7.25 \times 10^{-7} p_T^{-0.629} \exp[-0.13(p_T^2 + 9.61)]
\]

for $|y| < 0.35$, \hspace{1cm} (10)

\[
\frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy_{cm}}_{d+Au \rightarrow J/\psi + X} = 4.25 \times 10^{-7} p_T^{-0.629} \exp[-0.16(p_T^2 + 9.61)]
\]

for $1.2 < |y| < 2.2$. \hspace{1cm} (11)

In Fig. 3, we have drawn the solid lines depicting the SCM-based results with the help of Eqs. (10) and (11) against the experimental background. [13]

For $d + Au$ collisions, the calculated rapidity distribution equation in the light of SCM turns into a form given by

\[
\frac{dN}{dy}_{d+Au \rightarrow J/\psi + X} = 7.025 \times 10^{-6} \exp(-0.23 \sinh y_{cm}).
\]

(12)

In Fig. 4 we have plotted the rapidity distributions for $J/\psi$-production in $d + Au$ collisions. Data in figure 4 are taken from Ref. [13] and the solid line shows the SCM-based theoretical outputs.
Similar looking expressions have been worked out for Au+Au interactions with numerically changed physical parameters depending on the energy differ-
ences and the mass number differences of the target and the projectile.

To calculate the rapidity distribution for Au+Au collisions we take into account Eqs. (4) and (7). The rapidity distribution for the 0–20% central Au+Au collision is given by

$$dN/dy|_{Au+Au \rightarrow J/\Psi + X} = 0.472 \times 10^{-6} \exp(-0.23 \sinh y_{cm}).$$

Similarly, the solid lines in Fig. 6 depict the theoretical plot based on SCM (Eq. (13)) of $dN/df y$ vs $y$ for 0–20% centrality while the data for Au+Au collisions are taken from Ref. [13]. The dotted line in the same figure shows the coalescence model-based result. [14]

Now we deal with nuclear modification factor (NMF) for production of $J/\Psi$ in some nuclear collisions. Based on the standard definition of NMF and the use of Eqs. (9) and (12) of this work, the expression of NMF finally turns out to be\([13]

$$R_{AA} = \frac{dNN^{AA}/dy}{(N_{coll}(b))dNN_{AA}/dy}.\]

For numerical calculations one has to use, from Adare et al.\([13]\)

$$\langle N_{coll}(b) \rangle_{Au+Au} \approx 15.1 \pm 1.0 \text{ and } \langle N_{coll}(b) \rangle_{AA} \approx 955.4 \pm 93.6.$$.

The plots shown in Figs. 5–7 depict the results that are almost self-explanatory from the figure-captions attached. Comparisons of our SCM-based results with two other model-dependent calculations (which are generically of the standard model variety) show neither sharp disagreement, nor very good agreement with either one. Rather, our results are in better agreement with the data than either model. Thus, in our opinion, this work essentially represents a case of paradigm shift in the domain of particle theory, as we have eschewed the conventional views of $c\bar{c}$ approach to $J/\Psi$ in the ‘standard’ framework.

In summary, the “plasma” state, or the “hot and dense” state, gives no startling revelations, because when heated to very high temperatures attained by extremely energetic collisions, the microscopic matter might be converted to a liquid of unknown nature, and thus obviously of a “new” kind. [4] Our treatment of the problem rests only on hadron degrees of freedom. $J/\Psi$-production is neither suppressed nor enhanced; rather in the present scenario this is both qualitatively and quantitatively just natural, as in the case with some other hadrons like pion, kaon etc.

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