J/ψ Production by Charm Quark Coalescence

Abstract.

Production of $c\bar{c}$ pairs in elementary hadron-hadron collisions is introduced in a simulation of relativistic heavy ion collisions. Coalescence of charmed quarks and antiquarks into various charmonium states is performed and the results are compared to PHENIX J/ψ Au+Au data. The $\chi$ and $\psi'$ bound states must be included as well as the ground state $J/\psi$, given the appreciable feeding from the excited states down to the $J/\psi$ via gamma decays. Charmonium coalescence is found to take place at relatively late times: generally after $c(\bar{c})$-medium interactions have ceased. Direct production of charmonia through hadron-hadron interactions, ie. without explicit presence of charm quarks, occurring only at early times, is suppressed by collisions with comoving particles and accounts for some $\sim 5\%$ of the total J/ψ production. Coalescence is especially sensitive to the level of open charm production, scaling naively as $n_{c\bar{c}}^2$. The $J/\psi$ transverse momentum distribution is dependent on the charm quark transverse momentum distribution and early charm quark-medium interaction, thus providing a glimpse of the initial collision history.

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1. Introduction

A consistent and successful theoretical description of Au+Au and D+Au, collisions at RHIC ($s^{1/2} = 200$ A GeV), including pseudorapidity and $p_\perp$ spectra, as well as transverse momentum suppression and elliptical flow, has been developed with the simulation LUCIFER [1,2]. LUCIFER models ion-ion collisions by the early production – immediately after the completion of an initial phase of high energy interactions – and subsequent interaction of a fluid of pre-hadrons, having properties not unlike those of the $q\bar{q}$ dipoles used by many authors [3]. In the present work, we introduce charmed quarks explicitly into the picture, produced via hadronic collisions in the initial phase. Coalescence of charm quarks and anti-quarks into charmonia, which can also be viewed as heavy pre-hadrons, is calculated in a model we first used for deuteron production in Au+Au collisions at the AGS [4], adapted here to treat $c\bar{c} \rightarrow$ charmonium. Only a small percentage of charm quarks are found to coalesce into bound charmonia $J/\psi, \chi$ and $\psi'$; the remainder of such quarks appear ultimately as open charm mesons.

We find that the situation with respect to charmonium production present at the SPS is very much altered by the higher energy available at RHIC. Coalescence of $c, \bar{c}$ pairs into charmonium increases in importance, occurs later and coalesced charmonia are not subject to comover suppression. At SPS, comover suppression was sufficient to explain the observed suppression of $J/\psi$ yields relative to the expected direct production. At RHIC energies comover suppression of directly produced charmonia is found to be even larger, due to the increased particle numbers and densities. This will be spelled out in more detail in what follows.

In elementary hadronic interactions open charm and charmonium production are constrained by existing data at a variety of energies [5-9] including the data taken at RHIC [10-13]. Such cross-section information is used as a basic input for the LUCIFER simulation of A+A collisions and of course does not invoke adjustable parameters; there is little dependence on the explicit functional forms chosen to describe the input data. Indeed, for the purposes of studying charmonium production the detailed simulation can be viewed as providing only a background for the coalescence calculation, which to a large extent then stands on its own. The generation of free quarks and the wave functions for the charmonium states into which they coalesce are taken, respectively, from measured open charm production cross-sections and from phenomenological analyses of charmonium electromagnetic decays.

2. Simulation Dynamics

The simulation dynamics has already been extensively discussed in earlier publications, most recently in References [1,2], and will only be briefly outlined here. LUCIFER is a two stage simulation [14,15]. In stage I the incoming target and projectile nucleon interactions are tracked, while in stage II the produced pre-hadrons interact and decay in a standard relativistic cascade model. The time history of all the collisions recorded
in stage I sets up the geometry and initial conditions for stage II. Basic inputs for the simulation are measured hadron-hadron cross-sections \[16\]–\[18\], and rapidity, transverse momentum and particle multiplicity distributions, with the last taken to conform to KNO \[19\] scaling. Wherever hadronic cross-sections are unknown we employ quark counting to estimate their magnitudes, implying, for example, that the pre-meson/pre-meson cross-section would be \(\sim \frac{4}{9}\) the nucleon/nucleon cross-section at the equivalent center of momentum energy, i.e. \(\sim 20 – 25\) mb numerically.

Pre-hadrons, being in principle off shell, do not correspond directly to hadron resonances listed in the particle data book. We choose their masses from a Gaussian distribution, centered at \(m_0\) with width \(m_0/4\), where \(m_0\) is dependent on the particular type of pre-hadron, that is to say, \(\rho\)-like (non-strange), or \(K^*\)-like (strange). For non-strange (strange) pre-hadrons we take \(m_0 \sim 700(950)\) MeV. Small changes in these masses do not alter results since one must always readjust multiplicities and momentum distributions to fit known two body data.

All produced pre-hadrons are placed, at the end of stage I, uniformly inside the overlap region of the colliding nuclei. The pre-hadrons are then allowed to evolve longitudinally with the already assigned momenta, for a fixed time, numerically on the order of 0.30 fm/c. The total multiplicity of pre-hadrons is limited so that, given normal mesonic sizes \(\sim 0.55\) fm/c appropriate to meson-meson cross-sections, pre-hadrons do not overlap physically. The implied limitation in density is consonant with pre-hadrons existing as distinct objects only after becoming separated spatially \[20\]–\[21\]. One may conclude from this that the pre-hadronic matter is, when first created, something like an incompressible fluid, as in earlier calculations with LUCIFER \[14\].

Stage II is a straightforward two body cascade with collisions among the pre-hadrons taking place at considerably lower energy than stage I. Pre-hadrons collide, resulting in the production of more pre-hadrons and changes in momentum distributions. In addition pre-hadrons are allowed to decay by the emission of pions, the decay chains ending at stable mesons and baryons. The pre-hadron decay time at rest \(\sim 1.0\) fm/c., could also be viewed as a hadronisation time. Final state interactions in stage II are the principal agent suppressing the production of high \(p_\perp\) particles (jet suppression) \[1\]–\[22\] in Au+Au and D+Au collisions.

Central to the dynamics are the two time scales \(t_p, t_f\) defined in the rest frame of the two colliding nuclei. These times are the production and hadronisation times for pre-mesons. This has been described in detail in previous works \[1\]–\[2\]. For clarity we repeat and condense those arguments here. Colour neutral pre-hadrons are produced perturbatively at time \(t_p\), by a process that can be viewed as the coalescence of a target quark struck by a gluon with an anti-quark that was generated in a slightly later an separate pair creation event. Integrating over soft gluon radiation from the initial quark, with an accompanying hard scale \(Q\) yields \[3\] a pQCD estimate for the production time:

\[
t_p \sim \frac{E_q}{Q^2} (1 - z_h),
\]

where \(z_h = E_h/E_q\) is the fraction of energy imparted to the hadron, and \(E_q\) and \(E_h\) are
the quark and pre-hadron energies. The hadronisation time $t_f$, which is approximated as

$$t_f \sim \frac{E_h}{\Lambda_{\text{QCD}}^2},$$  \hspace{1cm} (2)$$
is far longer than the production time $t_p$, given that the $\Lambda_{\text{QCD}}$ is about 200 GeV.

In the center of mass frame these times translate to $\tau_{p,f} \sim \gamma^{-1}t_{p,f}$. This implies that the pre-hadrons are produced early on and interact for an extended period before decaying. These times, which are the main free parameters in the simulation, have already been determined in earlier work [1] and were not altered for the purposes of the present calculation.

We have previously noted the suggestion of Molnar and Voloshin [23–25] that coalescence of $q\bar{q}$ pairs could help to explain elliptical flow in ion-ion collisions. Pre-hadrons, in our simulation, have interaction cross-sections sufficiently large to explain the surprisingly large observed flow [2]: flow being the only truly collective variable observed at RHIC. The production mechanism of pre-hadrons, in view of their $q\bar{q}$ pair structure, is also akin to coalescence.

3. Coalescence of Charmed Quarks.

Due to the strong energy dependence of open charm production cross-sections, charmed quarks are mainly produced early, in the high energy collisions occurring in stage I of the simulation, and to a much lesser extent, early in stage II. In our treatment charmed quarks then propagate and interact with pre-hadrons in stage II. Stage II of the simulation then runs to its natural conclusion, which occurs when no more two-body collisions with CM energy above a minimum cutoff are detected.

Coalescence of charmed quarks and antiquarks into charmonium states is then accomplished by an afterburner algorithm which searches through the final set of particles for $c\bar{c}$ pairs and joins them, or not, on the basis of an estimate of the quantum mechanical overlap probability of the $c\bar{c}$ pair with the charmonium final state. Pairs which coalesce are therefore necessarily closely correlated in relative position and momentum. This approach to coalescence was used successfully, as stated above, to calculate deuteron yields in much lower energy Au+Au collisions at the AGS [4]. We find at RHIC, as was the case for $J/\psi$ production at CERN SPS [6,26–30], that the early, direct charmonium production is strongly suppressed by the interaction with baryons in stage I, as well as collisions with co-moving pre-mesons in stage II. In our picture, most observable charmonia at RHIC arise from coalescence of $c\bar{c}$ pairs at late times during the ion-ion collision.

The coalescence “afterburner” tests each $c\bar{c}$ pair for possible merging using recorded information about the history of the position and momentum of the $c$ and the $\bar{c}$ to estimate wavepacket sizes for each. For every $c\bar{c}$ pair considered, the distance of closest approach is determined, assuming the closest approach time occurs in the future. At the time of closest approach for most pairs interactions with the medium have virtually
ceased, due to a rapid drop in the density of comoving particles. We call the procedure of following the pair in their passage through the interacting medium and the use of that history to determine initial $c\bar{c}$ wave packets dynamic coalescence. The overlap integral is then constructed between the $c$ and $\bar{c}$ wavefunctions and an appropriately defined bound state charmonium wavefunction. The overlap generates a probability for coalescence which is used in the calculation, by Monte-Carlo, of the charmonium yield.

It’s also possible to calculate separately direct production of charmonium in our model, using the known elementary hadron-hadron production cross-sections, where these are available, or being guided by quark counting, where they are not available. At RHIC we find that the ensuing breakup of charmonia, if produced directly and early during ion-ion collisions, is very significant, even greater than at SPS. The mechanism of direct production followed by co-mover suppression successfully described the $J/\psi$ suppression as a function of $E_\perp$, observed at the SPS \[26,27\]. Interestingly it was also necessary, at SPS, to include all bound charmonia in the theory.

At RHIC we find that the number of bound charmonia formed by coalescence rises rapidly with the initially produced number of charmed quarks. Charmonium production scales with $\sim n_{c\bar{c}}^{2.5}$ where $n_{c\bar{c}}$ is the number of charm quarks produced per ion-ion collision: but the suppression of direct charmonium production at the same time increases relative to the SPS. In fact in the RHIC environment we find that the direct production mechanism results in considerably less (about a factor of 20) charmonium than coalescence. Since the two processes are to a large extent independent, sufficient accuracy can be obtained by simply adding the two contributions.

4. Coalescence: Details of Calculation

Coalescence of $c\bar{c}$ into charmonia is achieved by calculating the overlap integral between wavepackets composed of plane waves for the incoming $c$ and $\bar{c}$, with a wavefunction for the outgoing charmonium bound state, which is the product of a wavepacket consisting of plane waves in the center of momentum coordinates, and a bound state wavefunction in the relative coordinates. The assumption is made that the center of mass 3-momentum is conserved. Explicitly, we write for the wavefunctions of the $c$ and $\bar{c}$:

$$\psi_{c,\bar{c}}(x_{c,\bar{c}}) = \left(\frac{1}{\pi\sigma^2}\right)^{3/4} \exp\left(-\frac{(x_{c,\bar{c}} - \bar{x}_{c,\bar{c}})^2}{2\sigma_{c,\bar{c}}^2}\right) \exp(i\bar{P}_{c,\bar{c}} \cdot x_{c,\bar{c}}).$$  \hspace{1cm} (3)

And for the wavefunction of the charmonium we write:

$$\Psi_{c\bar{c}}(x_c, x_{\bar{c}}) = \Phi_{P,R}(R)\phi_{c\bar{c}}(r),$$  \hspace{1cm} (4)

where

$$\Phi_{P,R}(R) = \left(\frac{1}{\pi\Sigma^2}\right)^{3/4} \exp\left(-\frac{(R - \bar{R})^2}{2\Sigma^2}\right) \exp(i\bar{P} \cdot R),$$  \hspace{1cm} (5)

For the sake of simplicity, we employ three-dimensional oscillator states for the relative wavefunctions, with radius parameters selected to agree with the rms radii
extracted from Eichten et al. The Cornell wave functions for the 0s, 0p and 1s states are to a fairly good approximation harmonic oscillator states, originating, as they do, from a coulomb+linear model potential:

$$V(r) = -\frac{\kappa}{r} + \frac{r}{a^2},$$

(6)

with $\kappa$ dimensionless and $a$ possessing the dimensions of $[L]$. The strength of the Coulomb coupling $\kappa$ is related to the strong coupling at short distances, while the strength of the linear coupling $a$, is proportional to the Gaussian radius parameter and the linear potential, of course, is confining. So, for the $(0s) J/\psi$ we use

$$\phi_{cc}^{0s}(r) = (\pi \alpha^2)^{-3/4} \exp(-r^2/2\alpha^2),$$

(7)

as the relative wavefunction, with $\alpha$ chosen appropriately.

The approach to charmonium wavefunctions based on the Cornell potential is of course non-relativistic, but may still be reasonably accurate, given the large charm quark mass $\sim 1.5 - 1.6$ GeV. The same charm quark mass is used in the LUCIFER simulation. For the incoming wave packets the total and relative momenta are related by:

$$\bar{P} = (\bar{p}_c + \bar{p}_{\bar{c}}),$$

(8)

$$\bar{p} = \frac{(\bar{p}_c - \bar{p}_{\bar{c}})}{2},$$

(9)

while the relative separation between $c$ and $\bar{c}$ wavepacket centers is

$$\bar{r} = (\bar{x}_c - \bar{x}_{\bar{c}}).$$

(10)

and for completeness, the total (CM) position is given by:

$$\bar{R} = \frac{(\bar{x}_c + \bar{x}_{\bar{c}})}{2}.$$  

(11)

The final CM wave function is taken identical to its incoming form, i.e. total 3-momentum is preserved and we take $2\Sigma^2 = \sigma_c^2 = \sigma_{\bar{c}}^2$. The overlap integral

$$P = \left| \langle \psi_c \psi_{\bar{c}} | \Phi_{\bar{P},\bar{R}} \phi_{cc} \rangle \right|^2,$$

(12)

is constructed. After evaluation, the explicit probability for formation of 0s-state, i.e. the $J/\psi$ is found to be:

$$P^{0s} = A \exp(-B),$$

(13)

where

$$A = \left[ \frac{4\alpha \sigma}{\sqrt{2}(\alpha^2 + 2\sigma^2)} \right]^3 \text{ and } B = \left[ \left( \frac{2\alpha^2}{\alpha^2 + 2\sigma^2} \right) \bar{p}^2 + \left( \frac{1}{\alpha^2 + 2\sigma^2} \right) \bar{r}^2 \right].$$

(14)

Here $\alpha$ is the size parameter for the $J/\psi(0s)$ and $\sigma$ is that for the incoming free charm wave packets.

Coalescence probabilities for the $\chi(0p)$ and $\psi'(1s)$ charmonium states can be generated from $P^{0s}$ by taking appropriate derivatives with respect to momentum and
position, since we are using harmonic oscillator wavefunctions as approximations to the Cornell group wavefunctions \[31,32\], and thus have, ultimately, Gaussian integrals to perform. After some algebra, one obtains for the p-state:

\[
P^{0p} = \left(\frac{2}{3}\right) P^{0s} \left[\bar{p}^2\sigma^2 + \frac{r^2}{4\sigma^2}\right] \left(\frac{2\alpha\sigma}{\alpha^2 + 2\sigma^2}\right)^2,
\]

and for the 1s-state (with one node):

\[
P^{1s} = \left(\frac{2}{3}\right) P^{0s} \left\{2 \left[\bar{p}^2(\sigma)^2 - \frac{r^2}{4(\sigma)^2}\right] \left(\frac{\alpha\sigma}{(\alpha^2 + 2\sigma^2)}\right)^2 + 3 \left(\frac{\alpha^2 - 2\sigma^2}{\alpha^2 + 2\sigma^2}\right)^2 \right\} + \left(\frac{2\alpha\sigma}{\alpha^2 + 2\sigma^2}\right)^4 (\vec{p} \cdot \vec{r})^2.
\]

The Cornell group \[32\] determined properties of the J/ψ, χ and ψ′ from the decays of these states, electromagnetic and otherwise. In particular, the rms radii were found to be 0.47 fm, 0.74 fm and 0.96 fm respectively, the latter two being somewhat larger than expected for oscillator wavefunctions with a common radius parameter \(r_0\). To better approximate the Cornell wavefunctions using simple oscillator wavefunctions, we chose different radius parameters for the different states: \(r_0(\psi) = 0.384\) fm, \(r_0(\chi) = 0.49\) fm and \(r_0(\psi′) = 0.51\) fm.

The enhancement of the spatial size of the higher states over pure oscillators, suggests that coalescence will populate these states at a higher rate, and this is indeed found to be the case. However, the increased relative momentum dependence is somewhat quenched, since the average \(p_\perp\) in Au+Au collisions is generally larger than the bound state relative momentum content \(|\vec{p}| \leq 1/r_0 \sim 500\) MeV. We expect to find successful coalescence in charm pairs for a distribution decidedly cutoff at higher \(|\vec{p}|\) and hence higher \(p_\perp\). The χ and ψ states feed down to the J/ψ by their gamma decays, so that the yield of J/ψ due to coalescence is enhanced by the use of larger oscillator radii for these states. The overall production of J/ψ is more than doubled by feeding from the higher states.

5. Results

The measured \(NN \rightarrow c\bar{c}\) cross-section over a range of energies is a necessary input to the coalescence calculation. We fitted existing data at several energies, using in particular the PHENIX \[10,11\] measurements at 200 GeV. STAR \[12,13\] and PHENIX results for \(\sigma^{pp}_{c\bar{c}}\) differ significantly, with little room for convergence, even within the rather large experimental errors quoted. Our calculation of the charmonium yields uses the most recent PHENIX \(pp\) cross-section \(\sigma^{pp}_{c\bar{c}} = 0.57 \pm 0.21\) mb \[11\]. STAR reports \[12\] a somewhat higher cross-section \(\sigma^{pp}_{c\bar{c}}\), for minimum bias, inferred from the D+Au measurement of \(\sigma^{NN}_{c\bar{c}} = 1.40 \pm 0.22\) mb, while extracting \(\sigma^{NN}_{c\bar{c}} = 1.11 \pm 0.43\) mb, from the Au+Au \[13\] measurement. The STAR value obtained from Au+Au is, however, sensitive to theoretical input, so that this result should probably not be used to minimise the discrepancy between the collaborations.
For consistency we compare our calculations, for the most part, to PHENIX data, and use their estimated cross-section for elementary charm production. On occasion though, we make use of the STAR results: their $p_\perp$ dependence for open charm importantly confirms the conclusion drawn from the PHENIX $J/\psi$ data, ie. that charm production and interaction with the dense medium in heavy ion collisions takes place early on.

Future experiments hopefully will settle the apparent discrepancy \cite{33} between PHENIX and STAR measurements of open charm production, which is likely the largest potential source of error in our calculation of the charmonium yield due to $c\bar{c}$ coalescence, considering the great sensitivity of coalescence to the number of $c\bar{c}$ pairs. Naively coalescence is expected to vary with the square of $n_{cc}$; in fact an even more rapid dependence results from the considerably less than 3-dimensional emission of plasma in A+A collisions, since in general $p_\perp \ll p_t$.

Employing the formation probabilities shown in the last section and applying the measured branching ratios for the decay into $J/\psi$ of the higher charmonium states, we obtain in a straightforward manner the overall yield of $J/\psi$. These results are presented in a series of figures, beginning with global rapidity and transverse momentum distributions and their dependences on centrality. Figure (1) compares rapidity distributions from the simulation, for both $J/\psi$ and open charm to those from PHENIX \cite{34}. Figure (2) is a similar comparison for $p_\perp$ dependent invariant cross-sections. Both figures are for central collisions of Au+Au.

Figure (3) displays the centrality dependence of the mid-rapidity yield of $J/\psi$ in Au+Au collisions, again comparing LUCIFER results to PHENIX measurements \cite{34}. The simulated yields parallel the experimental results well and of course these variations arise directly from the underlying geometry of ion-ion collisions.

The STAR collaboration reconstructed $D^0$ mesons from their mesonic decays and thus directly measured \cite{13} open charm production, rather than using ‘non-photonic leptons’ as a proxy for open charm. They measured the variation for low $p_\perp$ open charm. Figure (4) compares STAR results to the LUCIFER calculations using an appropriate branching ratio $r = 0.52$ for $D^0$ decay.

We alluded above to the significant dependence of the overall coalescence probability for $J/\psi$ on the distributions of relative momentum and $p_\perp$ in the theoretical simulation. This is nicely illustrated in Figure (5) where the $|\vec{p}|$ distributions for all $c\bar{c}$ pairs and separately for coalesced pairs are shown. Clearly, $c\bar{c}$ pairs with $|\vec{p}| \geq 500$ MeV/c are hindered from merging.

The rapidity distribution of directly produced $J/\psi$‘s, as calculated in LUCIFER, is shown in Figure (6). This calculation proceeds simply given known cross-sections for charmonium production in $NN$ collisions. The various charmonium states are directly and promptly created – for the most part in initial $NN$ collisions in stage I of the cascade due to the high energies available and the rapid energy loss – but charmonia can also be created to some extent by the most energetic pre-hadron collisions that take place in stage II. These directly produced charmonia are then allowed to interact and
potentially be broken up in both stages of the simulation. This approach was employed and extensively described in our earlier work on $J/\psi$ suppression [26] at the SPS, where the production of open (as well as hidden) charm was appreciably smaller and $c\bar{c}$ coalescence far less important.

Direct production turns out to be a minor contribution at RHIC energy: direct yield is only some 5% of coalescent yield, for central collisions. This is because of the very efficient breakup in collisions with comovers, of any promptly produced charmonia given the higher particle densities existing at RHIC energy relative to the SPS. The rapidity distribution of directly produced charmonia differs very little from that of coalescence and we show the summed rapidity distributions in Figure (1). It seems that the present simulation describes the known RHIC data adequately, both for open charm and for $J/\psi$, with coalescence as the major mechanism of charmonium production.

5.1. Charm Quark Interactions

Introduction of charm quarks into the simulation opens a theoretical window on the early collision environment. The interaction of free charm quarks with the dense medium, initially with nucleons in stage I, thereafter with pre-hadrons in stage II of the simulation, is another input into the coalescence calculation. Once again we employed quark-counting to obtain an estimate of pre-hadron/quark interaction cross-sections, as a starting point. That is, we took the interaction cross-section for charm quarks ($c$) with pre-hadrons ($h$) to be $\sigma(ch) = \frac{1}{2} \sigma(\pi h)$.

One might expect, considering the lore on colour transparency, that a free quark interacting with a colourless pre-hadron would be subject to greater screening, suggesting that the quark-counting estimate invoked for hadron-hadron interactions might over-estimate the magnitude of the interaction, with the heaviness of the charm quark being a further variable. Perturbative QCD might offer some guidance, but for this exploratory calculation we explored the effects of differing $c(\bar{c})$-hadron interaction strengths characterized by a dimensionless parameter $s (\sigma(ch) = \frac{1}{2} s \sigma(\pi h))$. Specifically we show results for $s \in [0, 1]$, where the limit $s=1$ corresponds to the quark counting estimate of the cross-section, and $s=0$ corresponds to free-streaming charmed quarks. Figure (1) displays one such comparison. Within the errors permitted by direct measurements of $J/\psi$. [34] and certainly within the much larger range of uncertainty allowed by PHENIX and STAR [11,12] measurements of $\sigma_{pp}$, pure quark counting $s = 1$, appears to give a more than adequate description, perhaps validating the overall approach.

The coalescence yield in Figure (7) shows an interesting transverse momentum variation with the charm quark/medium interaction strength $s$. If the charm quarks are allowed to free stream, then the $J/\psi$ $p_{\perp}$ distribution falls too quickly with $p_{\perp}$, while for $s \neq 0$ the interaction adds significant transverse momentum to the $c$-quarks, thus increasing the $p_{\perp}$ of the coalesced $J/\psi$ and leading to reasonable agreement with the measure $p_{\perp}$. Open charm in A+A collisions at RHIC apparently is mostly produced
early on in the ion collisions, during the initial full energy nucleon-nucleon collisions of stage I. To a lesser extent there is also production of open charm from the few higher energy pre-hadron/pre-hadron collisions that occur early in stage II. So the actual $p_\perp$ variation in the PHENIX [34] charmonium data provides information on the initial state of the heavy ion collisions.

6. Conclusions and Discussion

All in all the simulation represents known RHIC data well, and the results suggest that coalescence of $c\bar{c}$ pairs is the dominant mechanism for charmonium production in heavy ion collisions at RHIC. The strong sensitivity of coalescence yields to the elementary production of free charm is evident. A reasonable picture emerges for rapidity and transverse momentum distributions of $J/\psi$ as well as for the variation of the yield with centrality. Throughout, we emphasized PHENIX data in our comparisons; underpinning our calculation of the magnitudes of the $J/\psi$ yield by the PHENIX open charm production cross-section $\sigma_{pp}$ at 200A GeV though, of course, charm production cross-sections at lower energy were also require, and used. The coalescence calculation clearly could be relatively easily extended to the treatment of bottomonia.

Coalescence must be taken seriously as a mechanism for production of heavy quarkonia in higher energy heavy ion collisions; direct production of charmonium, though successful at the SPS, was not found to be a viable explanation for $J/\psi$ yields at RHIC. The nature of the bound state wave functions for the coalesced particles plays an important role, as does the explicit inclusion of all of the charmonium bound states. These factors greatly enhance the likelihood of $J/\psi$ formation. Knowledge of the actual structure of bound $c\bar{c}$ states as presented by Eichten et al. [31,32] and supported by the plethora of data on charmonium decays, provides a solid foundation for the conclusions drawn, for both the absolute coalescence yields and the momentum distributions. An improved determination of elementary open charm production could perhaps turn the heavy ion $J/\psi$ measurements into a spectroscopic tool.

Further, as stated above, the $p_\perp$ dependence of the $J/\psi$ yield from coalescence is unambiguously tied to the magnitude of early charm quark production and to the strength of the charm quark interaction in the dense medium: and thus charmonium date provide, perhaps, the lone hadronic signal of the initial collision environment. More generally, heavy quarkonia may provide alternative signals of interaction within the dense medium present at early stages of ion-ion collisions. The approach pursued here is consonant with our overall model of the 'pre-hadron' dynamics [1,2] employed in LUCIFER to extract single particle spectra in general, that is to say: we could equally well consider charmonia as heavy pre-mesons. By explicitly including charm quarks as participants in the cascade we obviously recognize that at some level pQCD, which surely underlies all hadronic dynamics, must be considered. Our previous work [12,26,27] gave credence to the notion of pre-mesons: these being simply correlated $q\bar{q}$ pairs arising very likely by coalescence of their quark and anti-quark components [24,25]. In any case
coalescence for $c\bar{c}$ constitutes one estimate of a soft QCD process, i.e. the fragmentation of charmed quarks.

At RHIC energies and above, and for more central ion-ion collisions, coalescence of $c\bar{c}$ dominates the production of charmonia. Heavy quarkonia may well be key to understanding the early collision history when ions are collided at the LHC. But the large number of free quarks and gluons expected to be produced at such energies, on the basis of jet statistics in $p\bar{p}$ collisions, means that partons are more likely to be directly involved. For example the large gluon numbers created in ion collisions may well enhance the likelihood of thermalisation.

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Figure 1. Comparison of Au+Au $J/\psi$ central production (0 − 20%) and open charm rapidity distributions from LUCIFER and PHENIX. The large theoretical variation in overall coalescence yield that results from the stated PHENIX errors in open charm production $pp \rightarrow c\bar{c}$ at 200 GeV, is shown. We chose the most recent PHENIX value ($\sigma_{pp}^{c\bar{c}} = 0.57$ mb) for open charm production [11] in estimating the yield of charmonium from coalescence. The factor $s$ modulates the charmed quark-medium interaction, shown here for the range (0.5, 1.0) with $s = 1$ corresponding to quark counting (see later text discussion).
Figure 2. Comparison of $J/\psi$ production in 20% central Au + Au collisions: LUCIFER versus PHENIX. The marked variation in overall coalescence normalisation with stated PHENIX errors in the $\sigma_{pp}^{pp}$ seen in Figure (1) is also present here, though it’s not depicted. The coalescence model gives an adequate description of the magnitude and behaviour of the $J/\psi$ transverse momentum distribution [11].
Figure 3. Comparison of the centrality dependence of $J/\psi$ and open charm production: LUCIFER vs PHENIX. A good agreement between the simulation and experiment is evident, mostly resulting from the geometry of the ion-ion collisions.
Figure 4. Open charm invariant cross-section. LUCIFER vs STAR: Analysis of $D^0$ production enabled STAR to obtain transverse momentum distributions for $c\bar{c}$ production in Au+Au collisions. Comparison of LUCIFER yields are made to this data for various values of $\sigma_{c\bar{c}}^{NN}$ including the estimates from STAR D+Au (1.4mb) and PHENIX(0.57mb), and the value extracted by STAR from Au+Au collisions (1.1mb). Clearly, the calculated differences for open charm production in Au+Au are not as strong as the theoretical variation seen in coalesced $J/\psi$. Interestingly the STAR comparison to theory is self-consistent, given their determination of the $NN \rightarrow c\bar{c}$ and Au+Au cross-sections.
Figure 5. Momentum distribution of coalesced $c\bar{c}$ pairs vs the same for all $c\bar{c}$ pairs in 200A GeV Au+Au collisions: a sharp cutoff in $c\bar{c}$ relative momentum is evident for the coalesced pairs, reflecting the structure of the charmonium wave functions taken from the Cornell model.
Figure 6. Rapidity distribution for direct production of $J/\psi$. Direct production involves the input of elementary hadron-hadron $J/\psi$ cross-sections at a variety of energies. As discussed in the text, the direct process is expected to be of less importance at sufficiently high collision energy. This is evidently already the case at the maximum RHIC energy of 200A GeV.
Figure 7. Dependence of the $J/\psi$ transverse momentum distribution on the strength of the in-medium charm quark interactions. The quark-counting estimate ($s=1$) for the quark/pre-hadron interaction is clearly necessary to explain the relatively slow decrease with $p_\perp$ seen in the PHENIX data. For the purposes of this comparison, the $s=0$ curve has been normalized to agree with $s=1$ at low $p_\perp$, in order to highlight the differences in transverse momentum behaviour. Charm quark interactions with the medium occur early on in our simulation, and this suggests that heavy quarkonia at the LHC may again provide a hadronic signal of the initial state in ion-ion collisions at such elevated energies.