Quarkonium production via recombination

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Abstract

The contrast between model predictions for the transverse momentum spectra of $J/\psi$ observed in Au-Au collisions at RHIC is extended to include effects of nuclear absorption. We find that the difference between initial production and recombination is enhanced in the most central collisions. Models utilizing a combination of these sources may eventually be able to place constraints on their relative magnitudes.

1 Introduction

The original motivation [1] to consider heavy quarkonium production in a region of color deconfinement was the realization that the number of charm pairs initially produced in a central heavy collision will be at least of order $10^{2,3}$ at RHIC 200 energy. Preliminary model estimates indicated that interactions of a quark and antiquark which were not produced in the same nucleon-nucleon collision (the so-called off-diagonal pairs) will result in formation of additional $J/\psi$ (now called recombination) which would mask the expected suppression [4] due to medium effects. However, these model estimates proved to be very sensitive to details of various parameters which control the recombination process [5]. PHENIX results have now provided a first look at the total $J/\psi$ population in terms of the ratio $R_{AA}$ over a large range of collision centrality [6]. Surprisingly, one sees a suppression factor which is very close to that observed at SPS energy. A number of models predicted that there would be substantially more suppression at RHIC, and all were thus incompatible with these initial results. However, models in which some sort of in-medium recombination process is included find a total $J/\psi$ population which is not incompatible with the PHENIX results. This can be taken as evidence that the recombination process is indeed significant at RHIC energy. However, one must have confidence that the suppression parameters used are indeed appropriate at RHIC, which at this time has no independent confirmation. In fact, there is a proposed alternate scenario [7,8] in which the observed suppression at both SPS and RHIC energies is entirely due to dissociation of the
ψ and χc which would otherwise have provided additional J/ψ from decay feed-down. We show in Figure 1 some model predictions with and without recombination compared with the initial PHENIX measurements. The set of model parameters was motivated in [5] which uses an initial temperature $T_0 = 500$ MeV and $N_{ce} = 10$ initially-produced $c\bar{c}$ pairs for central collisions, where the charm quark momentum distribution is calculated in pQCD. The prediction for no recombination (stars) leads to almost complete suppression of initially-produced $J/\psi$. Inclusion of in-medium charm quark recombination (blue circles) dominates over almost the complete centrality range, and the sum (green diamonds) is seen to follow the trend of the measured points fairly well. We note that since the normalization of $R_{AA}$ was not contained in the model predictions, we choose to normalize $R_{AA}$ to unity at the most peripheral points.

To illustrate the fragility of such an interpretation, we also show model predictions in which no recombination process occurs and the initial temperature is decreased to 350 MeV. The resulting $R_{AA}$ (black squares) is also seen to be roughly compatible with the data. Thus in the absence of independent information on the initial temperature parameter in this model, we cannot use the
measurements to make a definitive statement.

Fortunately, the transverse momentum spectra of the surviving $J/\psi$ are also measured, and we can use this additional information to test the various scenarios. In the next section we review the use of spectra as a signal of the production mechanism. The following section summarizes the crucial role of centrality dependence and presents a comparison with the PHENIX measurements. Finally, we include for the first time the effects of nuclear absorption on these signals, and illustrate the experimental precision necessary for a definitive result.

2 Spectra as signals of recombination

The number of $J/\psi$ formed in a medium via recombination of pairs of $c$ and $\bar{c}$ quarks is determined by the competition between the recombination and dissociation cross sections. In the case where the total number $N_{J/\psi}$ is much less than the initial number of quark pairs $N_{c\bar{c}}$, the solution is of the form

$$N_{J/\psi}(t_f) = \epsilon(t_f)[N_{J/\psi}(t_0) + N_{c\bar{c}}^2 \int_{t_0}^{t_f} \lambda_F [V(t) \epsilon(t)]^{-1} dt],$$

where $t_0$ and $t_f$ define the lifetime of the deconfined region, and $\lambda_{F,D}$ are the formation and dissociation cross section reactivities, respectively, and $V(t)$ is the (expanding) volume of the deconfinement region. Note that the function $\epsilon(t_f) = e^{-\int_{t_0}^{t_f} \lambda_D \rho_g dt}$ would be the suppression factor in this scenario if the formation mechanism were neglected.

One sees that the second term, quadratic in $N_{c\bar{c}}$, is precisely the total number of possible recombinations which could occur in the deconfinement volume, modified by the factor $\epsilon(t_f)/\epsilon(t)$, which is just the suppression factor for $J/\psi$ formed between times $t$ and $t_f$. To calculate the transverse momentum or rapidity spectra of the $J/\psi$ formed via recombination, one must use a version of this solution which is differential in the $J/\psi$ momentum. Since the cross section used here is simple gluo-ionization of the $J/\psi$ bound state by the interaction of its color dipole with free gluons in the medium, the differential cross section expression is trivial. To solve the equation, we first generate a set of $c\bar{c}$ pairs according to pQCD amplitudes [9] to fix the kinematic distributions of the recombining quarks. The resulting spectra of the $J/\psi$ is then

$$\frac{dN_{J/\psi}}{d^3P_{J/\psi}} = \int \frac{dt}{V(t)} \sum_{i=1}^{N_c} \sum_{j=1}^{N_{\bar{c}}} v_{rel} \frac{d\sigma}{d^3P_{J/\psi}}(P_c + P_{\bar{c}} \rightarrow P_{J/\psi} + X),$$

(2)
where the sum over all $c\bar{c}$ pairs incorporates the total formation reactivity.

The charm quark spectra we calculate from pQCD have used collinear parton interactions only. To simulate the effects of confinement in nucleons, and more importantly the initial state $p_T$ broadening due to multiple scattering of nucleons, we have supplemented the quark pair $p_T$ distributions by adding a transverse momentum kick to each quark in a diagonal pair, chosen from a Gaussian distribution with width characterized by $\langle k_T^2 \rangle$. This effect is magnified in the difference between diagonal and off-diagonal pairs. Since the azimuthal direction of the $\vec{k}_T$ is uncorrelated from pair-to-pair, an off-diagonal pair with initial $\langle p_T^2 \rangle$ will inherit an increase of $2 \langle k_T^2 \rangle$. However, the azimuthal correlation inherent in the diagonal pair will result in an increase $4 \langle k_T^2 \rangle$. This effect is evident when we investigate the $\langle k_T^2 \rangle$ dependence of charm quark pairs and $J/\psi$ formed from recombination. We find that:

\[
\begin{align*}
\langle p_T^2 \rangle_{\text{diagonal } c\bar{c}} &= 0.8 + 4 \langle k_T^2 \rangle \text{ GeV}^2 \\
\langle p_T^2 \rangle_{\text{off-diagonal } c\bar{c}} &= 4.9 + 2 \langle k_T^2 \rangle \text{ GeV}^2 \\
\langle p_T^2 \rangle_{\text{in-medium } J/\psi \text{ formation}} &= 2.4 + \langle k_T^2 \rangle \text{ GeV}^2
\end{align*}
\]

We use reference data on $J/\psi$ production in pp interactions [10], which of course involves diagonal pairs, to fix $\langle k_T^2 \rangle_{pp} = 0.5 \pm 0.1 \text{ GeV}^2$. The corresponding value in nuclear interactions depends on the centrality, which we determine in the next section.

### 3 Centrality Dependence of $\langle p_T^2 \rangle$

We use the standard random walk picture of initial state NN interactions to model the transverse momentum broadening in pA and AA interactions [11]. This uses a parameter $\lambda^2$, which is proportional to the average $\langle k_T^2 \rangle$ per initial state collision (a factor of 0.5 times the probability for initial state parton elastic scattering in a given inelastic NN collision is conventionally absorbed in the definition). The net broadening in a pA collision can be parameterized in terms of the product of this $\lambda^2$ and $N_n$, the average number of inelastic collisions each nucleon incurs before the interaction in which the charm quark pair is produced. In terms of the total number of collisions per initial state nucleon ($n$), this number is

\[
N_n = \frac{1}{n} \sum_{m=1}^{n} (m - 1) = \frac{(n - 1)}{2}.
\]  

We extract $\lambda^2 = 0.56 \pm 0.08 \text{ GeV}^2$ from the nuclear broadening measurements of $J/\psi$ produced in minimum bias d-Au interactions [10]. The corresponding
\( \langle k_T^2 \rangle_{AA} \) is then calculated as a function of centrality, parameterized by the total number \( N_{\text{coll}} \) of binary collisions. The final results for \( \langle p_T^2 \rangle \) of initially-produced \( J/\psi \) from diagonal \( c\bar{c} \) pairs and \( \langle p_T^2 \rangle \) of \( J/\psi \) formed in-medium are shown in Figure 2. One sees that they differ by increasing amounts as centrality increases, which is a direct consequence of their different \( c\bar{c} \) pair precursors (diagonal or off-diagonal). We note that the initial production curve (higher \( \langle p_T^2 \rangle \)) should describe the sequential production scenario, in which all observed \( J/\psi \) originate from unsuppressed direct production [8]. The in-medium production curve (lower \( \langle p_T^2 \rangle \)) would describe a situation in which all of the initially-produced \( J/\psi \) have been screened away, and thus all observed \( J/\psi \) are due to in-medium formation processes. We should stress that these calculations of \( \langle p_T^2 \rangle \) use the charm quark momentum distributions which follow from initial production via pQCD amplitudes. One might expect that the actual physical situation would be some weighted sum of these two extreme cases. (For a discussion of comparison with preliminary data, see [12].) We should stress that these calculations of \( \langle p_T^2 \rangle \) use the charm quark momentum distributions which follow from initial production via pQCD amplitudes.

Fig. 2. Centrality dependence of \( \langle p_T^2 \rangle \) comparing model predictions for initial (direct) production and in-medium formation, both assuming charm quarks with momentum spectra as predicted by pQCD.
4 Effects of Nuclear Absorption

There is an additional effect on the $p_T$ spectrum of directly-produced $J/\psi$ due to their interaction in cold nuclear matter which they encounter on their path out of the interaction region. We note that this effect cannot modify the $J/\psi$ formed via recombination in the medium, since the formation process takes place at a later stage. One could include the nuclear absorption effect in a full Glauber calculation of the initial production of $J/\psi$, but for simplicity we here extract a correction factor for the $p_T$ spectra using an effective absorption cross section in a path length geometry. This will involve an extension of the random-walk picture of individual NN collisions which occur both before and after the point at which a hard interaction produces the $c\bar{c}$ pair which eventually emerges as a $J/\psi$. What we wish to calculate in this picture is the average number of such NN collisions which occur before the collision in which the $J/\psi$ production is initiated. In the absence of nuclear absorption, the relative probability of observing a $J/\psi$ will be independent of the spatial position of its production point. This leads to the expression in Eq. 3. With nuclear absorption, however, one must weight each of the possible production points by the probability that the $J/\psi$ produced at a given position will survive to be observed in the final state.

Let $P_{mn}$ be the relative probability that the $J/\psi$ survives its path through the remaining nuclear matter, where $n$ is the total number of NN interactions and $m$ specifies the number in this sequence at which the $J/\psi$ production point occurs. We parameterize this in a simple straight-line trajectory model, to obtain

$$P_{mn} = \epsilon_n^{n-m},$$

where $\epsilon_n = \exp(-\rho \sigma L_{\text{max}}/n)$ is the average absorption factor encountered by the $J/\psi$ in each path length between NN collisions. Here $\rho$ is the density of nuclear matter and $\sigma$ is the absorption cross section.

Then the average effective number of NN collisions which an observed $J/\psi$ will have experienced is

$$N_n = \frac{1}{P_{\text{tot}}} \sum_{m=1}^{n} (m-1)P_{mn},$$

where

$$P_{\text{tot}} \equiv \sum_{m=1}^{n} P_{mn} = \frac{\epsilon_n^n - 1}{\epsilon_n - 1}.$$  \hspace{1cm} (5)

In the limiting case of zero nuclear absorption, $P_{mn} = 1$, $P_{\text{tot}} = n$, and one recovers $N_n = \frac{n-1}{2}$. In the opposite limit of infinite absorption, $P_{mn}$ vanishes.
unless m=n, resulting in $N_n = n-1$. This correctly describes the effective number of initial state collisions for a $J/\psi$ which is produced in the final collision point at the back of the nucleus, the only possibility which avoids complete absorption. We show in Figure 3 the corresponding (maximum) increase in $\langle p_T^2 \rangle$.

![Graph showing the increase in $\langle p_T^2 \rangle$ for initial (direct) production in the limit of infinite nuclear absorption.](image)

**Fig. 3.** Maximum increase of $\langle p_T^2 \rangle$ for initial (direct) production in the limit of infinite nuclear absorption.

For finite nuclear absorption in terms of $\beta \equiv \rho \sigma L_{\text{max}}$, a numerical evaluation yields $N_n \approx (1 + 0.2 \beta)^{n-1}$, for $0 \leq \beta \leq 1.5$. We show in Figure 4 the predicted $\langle p_T^2 \rangle$ spectra of initially produced diagonal $c\bar{c}$ pairs, as appropriate for initial production of $J/\psi$ in Au-Au interactions. One sees that the effect of nuclear absorption always results in increased $\langle p_T^2 \rangle$, which enhances the difference with respect to in-medium $J/\psi$ production. Even the smallest absorption cross section considered (3 mb) shifts the prediction upward to an extent which may prove difficult to reconcile with preliminary PHENIX data at both forward and mid rapidity [12].

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