In-medium formation of quarkonium

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Abstract. We confront preliminary RHIC data on \(J/\psi\) production in nuclear interactions with expectations which follow in scenarios involving charm quark recombination in a region of color deconfinement. The focus is on transverse momentum and rapidity spectra of the \(J/\psi\), which carry a memory of the spectra of the charm quarks. In such a scenario, one predicts that both spectra will be narrower than those expected without recombination. Preliminary results for the transverse momentum spectra point toward a preference for the recombination picture, while the rapidity spectra do not exhibit any narrowing within present large uncertainties. We present new calculations in the recombination model for the centrality behavior of these signals, which map out the necessary experimental precision required for a definitive test.

1. Introduction

Recent PHENIX results on \(J/\psi\) production in pp, dA, and AA collisions at RHIC provide a first opportunity to test for the presence of in-medium formation, which is expected to become significant when multiple pairs of heavy quarks are present in a single AA collision [1]. Preliminary results [2] for \(R_{AA}\) as a function of centrality show less suppression than expected in several model calculations, but can be reproduced by revised models in which the initially-produced \(J/\psi\) are almost completely suppressed, and are then augmented by an additional component which can be attributed to in-medium formation. However the precise magnitude of in-medium formation is in general sensitive to several model parameters which are not at present well-constrained from independent measurements. An alternative scenario asserts that there is no dissociation of primary \(J/\psi\) even at RHIC energy [3]. Thus one must await results at LHC energy to test the sequential suppression scenario using only the magnitude of \(J/\psi\) production.

Our recent work in this area concentrated on finding a signature for in-medium \(J/\psi\) formation which is independent of the detailed dynamics and magnitude of the formation. We found that the normalized \(p_T\) spectrum of the formed \(J/\psi\) may provide such a signature [4], because the spectrum of \(J/\psi\) formed in-medium is closely correlated with the spectrum of \(c\bar{c}\) pairs from which they are formed. The difference between \(J/\psi\) formed in-medium and those which are produced in the initial stages is due to the combined effect of (a) different properties of the “off-diagonal” pairs compared with the “diagonal pairs”, and (b) inclusion of a formation probability which characterizes the
in-medium process. The virtue of this approach is that we do not require a knowledge of the absolute magnitude of in-medium formation in order to isolate the signatures.

In the next section, we review the properties of a generic kinetic model for in-medium recombination and the resulting formalism to calculate normalized spectra. We calculate the initial charm quark spectra using NLO pQCD amplitudes, adjusted for initial state broadening in AA collisions. This is appropriate in the case where the interaction between charm quarks and the medium is negligible. We find that the resulting $J/\psi$ $p_T$ spectra are quite distinct from that of the initial state diagonal pair sample. The following section exhibits the model calculations of normalized spectra. More recent work on the centrality behavior of these spectra is presented in the next section, along with a comparison with preliminary PHENIX measurements. A brief summary completes this presentation.

2. Kinetic model of recombination

We calculate the net number of $J/\psi$ produced in a color-deconfined medium due to the competing reactions of (a) in-medium formation involving recombination of $c$ and $\bar{c}$ and (b) dissociation of $J/\psi$ induced by interactions with the medium. The simplest dissociation reaction utilizes absorption of single deconfined gluons in the medium to ionize the color singlet $J/\psi$, $g + J/\psi \rightarrow c + \bar{c}$, resulting in a $c\bar{c}$ pair in a color octet state. The inverse of this process then serves as the corresponding formation reaction, in which a $c\bar{c}$ pair in a color octet state emits a color octet gluon and falls into the color singlet $J/\psi$ bound state. Of course, any dissociation mechanism will have a corresponding in-medium formation mechanism involving the time-reversed reaction, but the relative magnitudes will depend on the momentum distribution of the initial state participants.

One can then follow the time evolution of charm quark and charmonium numbers according to a Boltzmann equation in which the formation and dissociation reactions compete.

$$\frac{dN_{J/\psi}}{dt} = \lambda_{F} N_{c} N_{\bar{c}} [V(t)]^{-1} - \lambda_{D} N_{J/\psi} \rho_{g},$$  

with $\rho_{g}$ the number density of gluons in the medium. The reactivity $\lambda$ is the product of the reaction cross section and initial relative velocity $\langle \sigma v_{rel} \rangle$ averaged over the momentum distribution of the initial participants, i.e. $c$ and $\bar{c}$ for $\lambda_{F}$ and $J/\psi$ and $g$ for $\lambda_{D}$. The gluon density is determined by the equilibrium value in the medium at each temperature, and the volume must be modeled according to the expansion and cooling profiles of the heavy ion interaction region.

Eq. 1 has an analytic solution in the case where the total number of formed $J/\psi$ is much smaller than the initial number of $N_{c\bar{c}}$.

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

(2)
where $t_0$ and $t_f$ define the lifetime of the deconfined region. Note that the function $\epsilon(t_f) = e^{-\int_{t_0}^{t_f} \lambda_d \rho_d \, dt}$ 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 recombinations which 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 $t_f$.

It is obvious that a prediction of total initial plus in-medium formation population depends on many parameters, not all of which are constrained by independent information. Certainly the number of $c\bar{c}$ pairs in the region of color deconfinement sets an important overall scale and centrality dependence. There are measurements by STAR [5] and PHENIX [6] of these quantities, which at present have uncertainties in the factor of 2 range. At least as significant is the variation of $\lambda_F$ for different charm quark momentum distributions. We find that this quantity decreases by a factor of approximately five when the distribution changes between thermal equilibrium and that predicted by initial production as calculated in pQCD. In addition, one needs to model the geometric properties of the region of color deconfinement, including the centrality dependence and accounting for the expansion profile. An initial temperature $T_0$ controls the dissociation rate, and also the time evolution of the geometry. Another parameter ($x$) specifies the initial number of $J/\psi$ produced in normal nucleon-nucleon interactions as a fraction of $N_{c\bar{c}}$.

We show in Fig. 1 the initial PHENIX data [7], which consisted of measurements of $dN_{J/\psi}/dy$ at central rapidity in three centrality intervals. Within limited statistics, it is evident that there is suppression below even binary scaling. However, the flexibility of this model is quite substantial, as shown in Fig. 2. The most recent PHENIX data for $J/\psi$ production in Au-Au interactions at 200 GeV is presented in terms of $R_{AA}$, in which the normalizing factor is the equivalent binary-scaled $J/\psi$ yield from a superposition of pp collisions. We show in Fig. 3 predictions of the kinetic model using

![Figure 1: Centrality dependence of initial data.](image1)

![Figure 2: Exploration of formation model parameter space allowed by initial data.](image2)
the parameter set as shown in Fig 1. Our model calculations are limited to normalized spectra, so that predictions for $R_{AA}$ are uncertain up to an overall magnitude. For purposes of comparison with data, we normalize to unity at the most peripheral $N_{\text{part}}$. One sees that the suppression of initially-produced $J/\psi$ is almost complete, which is controlled by the initial temperature parameter $T_0 = 0.5$ GeV in this case. Inclusion of the in-medium contribution is seen to be generally consistent with the data within present uncertainties. For contrast, we insert in Fig. 4 the model predictions without in-medium formation, using a much lower $T_0 = 0.35$ GeV. One sees that this scenario is also roughly consistent with the data. Thus we are in a situation where one needs additional input on an “expected” baseline which contains no in-medium formation, in order to make a clear case for its presence or absence.

Fortunately, the $J/\psi$ momentum spectra are also measured, and they contain independent signatures with which to compare.

3. Normalized $J/\psi$ y and $p_T$ spectra

We present here a brief overview of the method used to extract these spectra. The details are contained in Ref. [4]. The starting point is a version of Eq. 1 which is differential in $J/\psi$ momentum. For the in-medium formation contribution, one obtains

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

(3)

where the sum over all $c\bar{c}$ pairs incorporates the total formation reactivity. Since we are only interested in the normalized spectra, the overall magnitude factors which proved to be extremely sensitive to model parameters can be disregarded. We just calculate the relative formation probability using a model cross section and evaluate the relative formation rates from each pair. The quark momentum distributions were obtained by generating a sample of $c\bar{c}$ pairs directly from NLO pQCD amplitudes. Fortunately,
we find that the resulting normalized spectra are quite insensitive to the details of the formation cross section. In addition, we have shown [4] that final state dissociation effects have a negligible effect on the normalized formation spectra.

The key signature is generated by utilizing appropriate subsets of the $c\bar{c}$ pairs. For no in-medium formation, we include only the “diagonal” pairs, i.e. those which were generated in the same parton-parton interaction from pQCD amplitudes. In this case we employ a color-evaporation type of scenario, in which the relative probability of hadronization into a $J/\psi$ is independent of the quark pair momentum. For the in-medium formation, we include also the “off-diagonal” pairs, in which a charm quark from one interaction forms the $J/\psi$ by combining with an anticharm quark which was produced in a different pQCD interaction. Thus the difference between $J/\psi$ spectra with and without in-medium formation arises from a combination of two effects: the different pair momentum distributions of the diagonal vs. off-diagonal pair sample, and the inclusion of a formation probability for the formation reaction in the medium. This behavior is shown in Fig. 5 and Fig. 6. The effect of in-medium formation on the

![Figure 5: Charm quark and pairs $p_T$ distributions from pQCD amplitudes.](image)

![Figure 6: Charm quark and pairs rapidity distributions from pQCD amplitudes.](image)

rapidity spectra is quite simple. The dominant factor comes from the weighting of the $c\bar{c}$ pairs by the formation probability, which has previously been shown to predict a narrowing of the rapidity distribution. Initial PHENIX data [2] is now available, and does not show any evidence for narrowing of the spectra. However, the uncertainties are still quite large, so that a definitive statement cannot be made at this time. For now, we proceed with a detailed analysis of the transverse momentum spectra.

4. Initial state effects and centrality dependence of $\langle p_T^2 \rangle$

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
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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 increase to \( \langle p_T^2 \rangle + 2\langle k_T^2 \rangle \). However, the azimuthal correlation inherent in the diagonal pair will result in an increase to \( \langle p_T^2 \rangle + 4\langle k_T^2 \rangle \). This effect will be evident when we consider the centrality dependence of \( p_T \) spectra.

We next use reference data [8] on \( J/\psi \) production in pp and d-Au interactions to determine some of these parameters. A fit to the dimuon data \( p_T \) spectra fixes \( \langle k_T^2 \rangle_{pp} = 0.5 \pm 0.1 \) GeV\(^2\). We determine the initial state nuclear \( p_T \) broadening with a standard random walk picture.

\[
\langle p_T^2 \rangle_{pA} - \langle p_T^2 \rangle_{pp} = \lambda^2 [\bar{n}_A - 1],
\]

where \( \bar{n}_A \) is the average number of inelastic interactions of the projectile proton as it traverses the nucleus A, and \( \lambda^2 \) is proportional to the square of the transverse momentum transfer per collision. For a nucleus-nucleus collision, the corresponding relation is

\[
\langle p_T^2 \rangle_{AB} - \langle p_T^2 \rangle_{pp} = \lambda^2 [\bar{n}_A + \bar{n}_B - 2].
\]

We now update the determination of the parameter \( \lambda^2 \) from that in Ref. [4]. This update uses a Woods-Saxon nuclear density parameterization, rather than the sharp sphere model used previously. We should note that \( \bar{n} \) and \( \lambda^2 \) are correlated within a given nuclear geometry. We use the published [8] \( \langle p_T^2 \rangle_{pp} = 2.51 \pm 0.21 \) and the average of \( \langle p_T^2 \rangle_{d-Au} = 4.28 \pm 0.31(y = -1.7) \) and \( 3.63 \pm 0.25(y = +1.8) \) and calculate \( \bar{n}_A = 3.56 \) for minimum bias d-Au interactions at RHIC energy (using \( \sigma_{pp} = 42 \) mb), to extract \( \lambda^2 = 0.56 \pm 0.08 \) GeV\(^2\). Given this parameter, one can use calculated values of \( \bar{n}_{Au-Au} \) as a function of centrality to predict \( \langle p_T^2 \rangle \) for the \( J/\psi \) which originate from initially-produced diagonal \( c\bar{c} \) pairs.

An extension of this procedure is then used to predict \( \langle p_T^2 \rangle \) as a function of centrality for the \( J/\psi \) which originate from in-medium formation. Here there are two effects which contribute. One involves the same (centrality-dependent) intrinsic \( \langle k_T^2 \rangle \) due to initial state effects in AA interactions, but which now enters with a different numerical coefficient for off-diagonal pairs. The other follows the \( \langle p_T^2 \rangle \) of the in-medium formation process, which has its own characteristic dependence on this same \( \langle k_T^2 \rangle \).

Results of this calculation are shown in Fig. 7. The centrality measure is parameterized by the number of binary collisions, also calculated in the Glauber formalism using the Woods-Saxon density parameterization. The stars and dashed bars indicate the central value of the model predictions for the two scenarios. One sees clearly that the centrality dependence of \( \langle p_T^2 \rangle \) is significantly different for the \( J/\psi \) produced initially as compared with those which were formed in-medium. Thus measurements in very central collisions will have an enhanced ability to differentiate between these two mechanisms of \( J/\psi \) production. The dashed lines indicate the uncertainty in the model calculations, primarily due to the value of the parameter \( \lambda^2 \) determined from the broadening in dAu interactions, but also including the uncertainty in the measured \( \langle p_T^2 \rangle \) in pp interactions.
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Figure 7: Centrality dependence of $\langle p_T^2 \rangle$ comparing initial (direct) production and in-medium formation with preliminary PHENIX data.

The preliminary PHENIX data [2] for $\langle p_T^2 \rangle$ is also shown in Fig. 7 for three centrality intervals, spanning 0-20%, 20-40%, and 40-90%. Although the experimental uncertainties make a definitive conclusion difficult, it appears that the in-medium formation predictions may be somewhat more consistent with the data. Unfortunately the most central point for the forward rapidity region is not available, but a corresponding measurement for backward rapidity may be forthcoming. Measurements in the central rapidity interval and the forward rapidity interval appear to differ in the 20-40% centrality interval, which would be difficult to interpret in terms of the initial production vs. in-medium formation scenario we have presented. However, the model calculations have been performed over the entire rapidity region, and thus one can look for differences within the experimental rapidity intervals. Fig. 8 shows that this variation for the diagonal $c\bar{c}$ pairs is much smaller than that for the measurements, and Fig. 9 exhibits the same situation for the in-medium formation scenario. Thus for a definitive conclusion to be reached in this model comparison, one will require not only a decreased experimental uncertainty in the measured $\langle p_T^2 \rangle$, but will require that either the dependence on rapidity interval must essentially disappear, or that some rapidity-dependent final state effect dominates the spectra.
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5. Summary

We have shown that the width of $J/\psi$ $p_T$ spectra in AA interactions can differentiate between initial production and in-medium formation via pQCD charm quarks. At large centrality, one requires only a measurement of $\langle p_T^2 \rangle$ with less than approximately 20% uncertainty. The present differences between spectra using measurements at central and forward rapidity are puzzling within this framework. The corresponding spectra for in-medium formation using thermal charm quark distributions, as well as direct hadronization of $J/\psi$ with a thermal distribution [4] result in $\langle p_T^2 \rangle$ substantially smaller than either the preliminary data or the two model results presented here. It remains to be seen if a combination of such production processes can be made consistent with the data.

Acknowledgments

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