From production to suppression, 
a critical review of charmonium measurements at RHIC.

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Abstract
Charmonium suppression in hot and dense nuclear matter has been argued to be a signature for the production of the quark gluon plasma (QGP). In order to search for this effect in heavy ion collisions one must have a clear understanding of all the factors that can contribute to such a suppression. These may include shadowing of the partons in a nuclear environment, breakup of a correlated $c \bar{c}$ pair as it traverses the nuclear fragment, suppression of feed-down from higher mass states as well as other initial state interactions. In order to disentangle these effects one must measure charmonium production rates in both proton+proton ($p+p$) and proton+nucleus ($p+A$) collisions. The $p+p$ collisions serve as a baseline for searching for suppression compared to binary scaling predictions, allow one to quantify the amount of feed-down from higher states as well as serve as a tool to distinguish between different theoretical calculations for charmonium production mechanisms. In order to quantify nuclear effects it is also necessary to study charmonium production in $p+A$ collisions where the temperature and density of the system are low compared to a heavy ion collision. These measurements allow one to determine the influence of nuclear shadowing and breakup in “cold” nuclear matter which can be extrapolated to heavy ion collisions in order to determine the amount anomalous suppression. Of course, extrapolations that rely on a model based technique depend heavily on the assumption of a production mechanism, a fact that reinforces the importance of the $p+p$ measurements. The PHENIX and STAR experiments at Brookhaven National Laboratory have measured charmonium production in $p+p$, $d+Au$, $Au+Au$ and $Cu+Cu$ collisions at $\sqrt{s_{NN}} = 200$ GeV for both forward and mid rapidities. I will present a review of the latest measurements from both experiments with an emphasis on what we have and can still learned from them about charmonium production and suppression with these experimental apparatuses.

1. Why the $J/\psi$

The heavy nature of charmonium ($c\bar{c}$) allows one to apply potential models in non-relativistic quantum mechanics to calculate the mesons binding radius. Originally it was predicted that the modification of the heavy quark pairs potential in the hot dense matter created in heavy ion collisions would cause the pair to become uncorrelated due to color charge screening. This modification of the pair potential via a Debye mass term leads to charmonium suppression when compared to a binary collision scaled $p+p$ reference. Due to the different binding energies for the different charmonium states one could gain access to the temperature of the medium. At RHIC the suppression of the lowest energy charmonium state, the $J/\psi$ meson, has been measured in $Au+Au$ and $Cu+Cu$ collisions in $\sqrt{s_{NN}} = 200$GeV collisions.
These measurements are then compared to the invariant yield measured in a baseline p+p collision at the same center of mass energy. It is assumed that any modification due to the medium will show up as a deviation from the prediction of the binary collision scaled reference data. This is of course true when no modifications due to normal nuclear matter are present. However in the case of the J/ψ we know this is not the case from lower energy measurements made in p+Au collisions at SPS [2] and FNAL [3]. Therefore, to interpret these data one must remove any effects that occur in normal density cold nuclear matter (CNM). One such effect is the modification of parton distribution functions in a nuclear environment [4, 5]. Another is Cronin enhancement that leads to a hardening of the transverse momentum spectrum of collision products due to multiple scattering. To this end the PHENIX experiment has also measured the nuclear modification present in d+Au collisions in √s =200GeV collision. The d+Au data is used to extrapolate within a Glauber [6] based data driven model to the Au+Au collision case to predict the suppression that would result from CNM effects and search for an anomalous suppression of J/ψ mesons in the sQGP.

2. J/ψ Production

The production mechanism for charmonium has not been well understood theoretically for nearly 20 years. The magnitude of the pT spectrum measured at the Tevatron [7, 8] was underpredicted by an order of magnitude by the color singlet (CS) model [9]. This led to the proposal of the color octet (CO) model [10, 11] wherein the pre-charmonium charm quark pair become correlated in a color charged state and must color neutralize via soft gluon emission. While the CO model had some success in describing the kinematic spectra it also predicted a large transverse polarization at intermediate to large pT [10, 11]. Another undesirable aspect of the CO is its reliance on overlap matrices between the color charged pre-hadron and final state J/ψ, which are nearly free parameters in the model [12].

Measuring the p+p spectra and polarization at RHIC is a tool for distinguishing between charmonium production mechanisms. PHENIX has measured the invariant yield of J/ψs, in p+p collisions at √s = 200 GeV, over a wide range in transverse momentum at forward (1.2 < |y| < 2.2) and mid rapidity (|y| < 0.35) (Figure 1) as well as the J/ψ polarization at mid rapidity (Figure 1). The quality of these data make them natural metrics for testing new models of charmonium production such as the four-point modified CS model proposed by Lansberg and Haberzettl [13]. The mid-rapidity data agrees well with the polarization predictions. At forward rapidity there is a two sigma difference between the measurement and prediction.

Another, quite recently measured, observable that may help establish the production mechanism for the J/ψ is azimuthal correlations with hadrons. One could imagine that the spatial correlation between the J/ψ and the remainder of the hadrons forming the jet that results from the hard initial collision may be very different depending on the production mechanism. STAR has recently released [16] azimuthal correlations between J/ψs and hadrons(Figure 2) measured in √sNN = 200 GeV p+p collisions. The J/ψ trigger particle is required to have pT > 5 GeV/c and the associated hadrons to have pT > 0.5 GeV/c (see Section 3). This new observable may prove very fruitful in distinguishing between different production models in the future. One can imagine handing a MC generator (i.e. PYTHIA) the QCD calculation for different models and extracting the resulting correlation of prompt J/ψ mesons and hadrons within experimental cuts and then comparing these to data.

Understanding the production mechanism establishes the map between the measured kinematics of the J/ψ (y, pT) and the kinematics of the partons (x1, x2) at the interaction vertex. Dif-
different production models provide these mappings and can result in different conclusions about the magnitude of the cold nuclear matter effects \[17\] discussed in Section 4. The J/ψ polarization and azimuthal correlation measurements provide us with another lever arm to distinguish between these models.

3. Feed Down

One of the contributors to the J/ψ spectrum is expected to come from the feed down of higher charmonium states as well as B-meson decays. The ψ′(ψ(2S)), χc and B mesons all have a decay mode to J/ψ+X. Considering the predictions from the lattice for the dis-association temperatures of these states at \(T_C \lesssim 170\) MeV \[19\] and the most recent interpretations of the temperatures reached in heavy ion collisions at RHIC \(\approx 1.5T_C \[20\] one would expect the depletion of at least the \(\chi_c\) and the \(\psi'\) which would in turn lead to a J/ψ suppression beyond that in cold nuclear matter collisions. Of course this depletion must also be accounted for when one attempts full accounting of J/ψ suppression in heavy ion collisions.

To this end, the PHENIX collaboration has measured the feed down fraction (R) of the \(\psi'\) and set a 90% confidence level upper limit for the \(\chi_c\) to J/ψ in p+p collisions at 200 GeV via

![Graph showing the invariant yield of J/ψ measured with the PHENIX spectrometer versus \(p_T\) (top left) and y (top right). The theoretical curves are the four point modified CS model \[14\] and NRCD \[15\]. J/ψ polarization versus \(p_T\) (bottom left) measured at mid and forward rapidity with the PHENIX spectrometer. The dashed lines are the predictions from the four point modified CS model \[14\].]
the di-electron channel at central rapidity \cite{21}. The results are in agreement with theoretical predictions \cite{22} as well as the world average \cite{23} (see table in \cite{24}).

As mentioned above the STAR experiment has also measured the azimuthal correlation of J/\(\psi\) and hadrons (Fig. 2). Using this correlation one can extract the feed-down fraction of J/\(\psi\) arising from B meson decays if one knows the azimuthal shape of the B-decay and prompt J/\(\psi\) correlations. In order to extract this quantity STAR parameterizes the shape as \(C(\Delta \phi) = x \ast C_p(\Delta \phi) + (1 - x) \ast C_B(\Delta \phi)\), where \(C_p\) is the correlation function from prompt J/\(\psi\) mesons and \(C_B\) comes from the B decay. The prompt correlation function is then taken from a PYTHIA simulation that has been tuned (i.e. both color octet and singlet mechanisms mixed) to match real data transverse momentum distributions. While this may be a rather drastic assumption, it is necessary to extract the B feed down fraction in this manner. One would naturally argue that an assumption of this nature would inherently introduce a large systematic uncertainty. This is especially true if one considers that the production mechanism (as discussed above) is still not known and that PYTHIA simulations do not reproduce either the cross section or polarizations measured in data. However, this extraction yields a feed-down fraction of 13 ± 5 % \cite{16}.

4. Cold Nuclear Matter Effects

In order to interpret suppression in heavy ion data one must remove any effects that occur in normal density cold nuclear matter (CNM). One such effect is the modification of parton distribution functions in a nuclear environment \cite{4,5}. Another is Cronin enhancement that leads to a hardening of the transverse momentum spectrum of collision products due to multiple scattering. The PHENIX experiment has also measured the nuclear modification present in deuteron+gold (d+Au) collisions in \(\sqrt{s} = 200\) GeV collision.

During the 2008 RHIC deuteron-gold (d+Au) run PHENIX recorded a factor of 30 greater integrated luminosity than the previous run in 2003. The PHENIX collaboration has not yet released nuclear suppression factors for d+Au collisions compared to the Run-3 p+p baseline. However, the data were analyzed to measure the central to peripheral ratio \(R_{CP}\) in these collisions (Eq. 1). In order to calculate the central to peripheral ratio \(R_{CP}\) the invariant yield of J/\(\psi\) mesons from d+Au central and peripheral collisions must be measured. Figure 3 shows the nuclear modification as a function of rapidity (\(y\)) in a given centrality bin (\(i\)) which defines the average number of binary collisions (\(N_{coll}\)).

These data have sparked much interest in the community (for details see the 2009 ECT and INT quarkonia workshops) as it is clear that a rapidity independent breakup cross section combined with nuclear shadowing cannot match the shape of the data. This has lead to the conclusion that there may be some physics missing in the models. PHENIX is currently working to understand a normalization effect, between different RHIC runs, for the nuclear suppression factor (\(R_{dAu}\)) and these results are expected to be made available later this year.
Figure 3: (color online) Central to peripheral ratio ($R_{CP}$) measured by the PHENIX collaboration using the RHIC 2008 $d+Au$ data set (left). The theoretical curves represent the prediction for $R_{CP}$ using the EKS [25] nPDF parameterization and different constant-with-rapidity breakup cross sections. Published PHENIX $Au+Au$ nuclear modification factor [26] showing a larger suppression at forward rapidity than central (top right). Comparison of the PHENIX and STAR results for nuclear modification in $Cu+Cu$ at $\sqrt{s} = 200$ GeV (bottom right).

$$R_{CP}(y; i) = \frac{dN^d_{i+Au}/dy}{N^i_{coll}dN^{d+Au}_{periph}/dy}$$ (1)

5. What’s Hot in Hot nuclear matter

In Figure 3(top right) we show the nuclear suppression factor for $Au+Au$ collisions at $\sqrt{s} = 200$ GeV, as a function of centrality, measured at forward and mid rapidity by the PHENIX collaboration at RHIC [26]. One striking feature of this comparison is the similarity between the suppression patterns at mid rapidity between the RHIC ($|y| < 0.35$) and SPS ($0 < y < 1$) data [27], despite the difference in center of mass energies of the two measurements ($\sqrt{s} = 200$ GeV and $\sqrt{s} \sim 20$ GeV respectively). This engenders the question “Why are the results so similar?” for measurements probing different rapidity regions, shadowing regimes and energy densities. It is clear from the PHENIX data that the suppression at forward rapidity is greater than at mid rapidity. This is a challenge to local density based suppression models and is one piece of evidence that supports the idea of regeneration discussed below, where the $J/\psi$ yield is enhanced due to close proximity in phase space of uncorrelated pairs.
We also show (Figure 3 (bottom right)) the high \( p_T \) measurements of \( R_{AA} \) made by the PHENIX and STAR experiments in Cu-Cu at \( \sqrt{s_{NN}} = 200 \) GeV. One should note that the PHENIX measurement is for minimum bias collisions while the STAR measurement is for centrality 0-60%. Given this small difference one can still compare the measurements. It is clear that the STAR data favors a reduction of the suppression at high \( p_T \) (with large systematic and statistical uncertainty), while the PHENIX data favors a nearly constant suppression from mid to high \( p_T \).

6. A glimpse of the future.

Regeneration (also called coalescence) \[28,29\] is a process whereby un-correlated \( c\bar{c} \) pairs coalesce to form charmonium states, an effect that could be enhanced due to the close phase space proximity of partons in a heavy ion collision. This process would increase the yield of \( J/\psi \) in heavy ion collisions and must be accounted for when interpreting the overall magnitude of suppression.

It has been suggested that one metric for determining the magnitude and/or existence of this effect would be to measure the elliptic flow \( (v_2) \) of the \( J/\psi \) in heavy ion collisions. The elliptic flow of the recombined \( J/\psi \) would be related to the flow of uncorrelated charm \[30\] in the medium and could be very different from that of \( J/\psi \) formed early on in the fireball’s evolution. This experimental signature can be compared to the \( v_2 \) from open charm and models that contain the regeneration mechanism. The PHENIX experiment has made the first measurement of \( J/\psi \) elliptic flow at forward and mid rapidity \[31\] for RHIC energies. The result does not have the statistical precision to distinguish between models and the comparison to the open charm elliptic flow \[32\] is not very enlightening (Figure 4). A long, high-luminosity Au+Au run at RHIC will be necessary for this metric to be improved.

In addition STAR has measured a clear \( \Upsilon \) peak in the d+Au data taken in 2008 Figure 5 (right). This coupled with the previous p+p measurement \[38\] can be used to calculate \( R_{dAu} \) for the \( \Upsilon \). The value is \( 0.98 \pm 0.32 \) (stat.) \( \pm 0.28 \) (syst.). This measurement suffers from very large uncertainties which engenders the question of whether or not the RHIC program for higher mass charmonium states would benefit from a long d+Au run in the future. The current measurement would allow for suppression in cold nuclear matter of up to 30% within one standard deviation of
the statistical error alone. A long d+Au run will be required if one wants to precisely characterize any cold nuclear matter effects that would be present for the \( \Upsilon \) state.

PHENIX has also released a new measurement of \( \Upsilon \) suppression in Au+Au collisions. Due to a lack of statistics the value is presented as an upper limit on the amount of suppression seen in a HI collision. An upper limit of 0.64, at a 90% confidence level, is calculated by coupling the Poisson probability distributions for the numerator (Au+Au) and denominator (p+p) to arrive at a probability distribution for \( R_{AuAu} \) Figure 5 (left). Interpreting this result is difficult due to the lack of information regarding cold nuclear matter effects for the \( \Upsilon \). However, note that if the \( \Upsilon(2s) \) and \( \Upsilon(3s) \) states are melted in the medium a suppression of 30% would be expected in HI collisions.

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