Cold Nuclear Matter Effects on $J/\psi$ Yields as a Function of Rapidity and Nuclear Geometry in $d+A$ Collisions at $\sqrt{s_{NN}}=200$ GeV

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We present measurements of $J/\psi$ yields in $d+Au$ collisions at $\sqrt{s_{NN}}=200$ GeV recorded by the PHENIX experiment and compare with yields in $p+p$ collisions at the same energy per nucleon-nucleon collision. The measurements cover a large kinematic range in $J/\psi$ rapidity ($-2.2 < y < 2.4$) with high statistical precision and are compared with two theoretical models: one with nuclear shadowing combined with final state breakup and one with coherent gluon saturation effects. In order to remove model dependent systematic uncertainties we also compare the data to a simple geometric model. We find that calculations where the nuclear modification is linear or exponential in the density weighted longitudinal thickness are difficult to reconcile with the forward rapidity data.

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The measured yields of quarkonia states in $p+A$ (or $d+A$) collisions provide information about the time scale and dynamics for the creation of a $c\bar{c}$ pair and its evolution to a color-singlet quarkonium state. The propagation time of the $c\bar{c}$ pair through the nucleus is set by the incident energy of the projectile and target and by the relative longitudinal momentum of the $c\bar{c}$ pair. Fixed target $p+A$ experiments at Fermilab [1] reveal a substantial suppression for forward rapidity $J/\psi$ and $\psi'$ at a similar level, leading to the conclusion that the suppression must occur at the prehadronic stage. An analysis [2] of results for $\sqrt{s_{NN}} = 17-42$ GeV indicates that in addition to modified initial production due to nuclear-modified parton distribution functions (nPDFs), a break up cross section ($\sigma_{BP}$) for the $c\bar{c}$ precursor state to the $J/\psi$ is important, and that $\sigma_{BP}$ decreases as the relative center-of-mass energy between the $c\bar{c}$ and the nucleon increases. Extending these results to collider energies at RHIC is important. The dominant production mechanism for charm (at RHIC) is via gluon-gluon interactions, and thus the yields at forward rapidity, the deuteron-going direction, are sensitive to low-$x$ in the gold nucleus where gluon shadowing [3,4] and/or gluon saturation effects [5] become important, providing a crucial test of these effects.

There is also significant interest in determining the color screening length in the quark-gluon plasma for temperatures $T > 170$ MeV, as achieved in relativistic heavy ion collisions [6]. One proposal for determining this is the measurement of several quarkonia states where the different binding energies (and thus radii) can bracket the screening length of interest [7,8]. However, this suppression of quarkonia must be separated from the aforementioned cold nuclear matter effects. Thus precise measurement of quarkonia suppression in $d+Au$ is needed.

The PHENIX experiment has previously published $J/\psi$ results in $d+Au$ collisions at $\sqrt{s_{NN}}=200$ GeV [9] from data taken in 2003. In this paper we present results from $d+Au$ collision data taken in 2008, representing an increase in yield by a factor of 30-50 over the previous results and a reduction in the systematic uncertainties by up to a factor of two. Additionally, the $p+p$ reference data sets are updated to include higher statistics data from 2006 and 2008.

The PHENIX apparatus is described in detail in [10]. It consists of two sets of spectrometers referred to as the central arms, which measure single-particles emitted over pseudorapidity ($|\eta| < 0.35$), and the muon arms, measuring single muons over pseudorapidities ($1.2 < |\eta| < 2.4$). $J/\psi$ particles are measured via their dielectron (dimuon)
decays at mid (backward and forward) rapidities, and detailed analysis methods are given in [4, 11]. The d+Au data used for this analysis were recorded using selective Level-1 triggers in coincidence with a minimum bias interaction requirement, which requires one hit in each of two beam-beam counters (BBCs) located at positive and negative pseudorapidity ($3 < |\eta| < 3.9$). This minimum bias selection covers 88 ± 4% of the total d+Au inelastic cross section of 2260 mb [12]. This can be corrected to an unbiased sample, 100% of the total cross section, to a simulation of the BBC response (as described in [9]). The centrality bins used in this analysis are characterized as follows: central $\langle N_{\text{coll}}(0-20\%) \rangle = 15.1 \pm 1.0$, $\langle N_{\text{coll}}(20-40\%) \rangle = 10.3 \pm 0.7$, $\langle N_{\text{coll}}(40-60\%) \rangle = 6.6 \pm 0.6$, $\langle N_{\text{coll}}(60-88\%) \rangle = 3.2 \pm 0.2$ and unbiased $\langle N_{\text{coll}}(0-100\%) \rangle = 7.6 \pm 0.3$. Figure 1 shows the $R_{\text{dAu}}$ nuclear modification factors for unbiased collisions.

The $p_T$-integrated $J/\psi$ yield as a function of rapidity is calculated via:

$$B_{\text{dAu}} \frac{dN}{dy} = \frac{c N_{J/\psi}}{N_{\text{MB}} A \Delta y}$$

(1)

where $B_{\text{dAu}}$ is the branching fraction for $J/\psi \rightarrow e^+ e^-$ or $\mu^+ \mu^-$, $N_{J/\psi}$ is the number of $J/\psi$ counts, $c$ is the bias correction factor, $N_{\text{MB}}$ is the number of sampled minimum bias events, $\Delta y$ is the width of the rapidity bin, and $cA$ represents the product of the efficiency and acceptance corrections, including the Level-1 trigger efficiency. The number of $J/\psi$ particles is determined using the invariant mass distribution of unlike-sign lepton pairs. Approximately 38000, 8900, and 42000 $J/\psi$ counts are measured at backward, mid, and forward rapidity, respectively. Figure 1a shows the $J/\psi$ yields in $p+p$ and $d+Au$ unbiased collisions.

We quantify the cold nuclear matter effects by calculating the nuclear modification factor $R_{\text{dAu}}$ as given by:

$$R_{\text{dAu}}(i) = \frac{\frac{dN^{d+Au}(i)}{dy}}{\langle N_{\text{coll}}(i) \rangle \frac{dN^{p+p}}{dy}}$$

(2)

where $i$ is the index of the centrality bin and $\langle N_{\text{coll}}(i) \rangle$ is the average number of nucleon-nucleon collisions and is determined from the total energy deposited in the BBC located at negative rapidity. For a given centrality bin $\langle N_{\text{coll}}(i) \rangle$ is derived using a Glauber calculation coupled to a simulation of the BBC response (as described in [4]). The centrality bins used in this analysis are characterized as follows: central $\langle N_{\text{coll}}(0-20\%) \rangle = 15.1 \pm 1.0$, $\langle N_{\text{coll}}(20-40\%) \rangle = 10.3 \pm 0.7$, $\langle N_{\text{coll}}(40-60\%) \rangle = 6.6 \pm 0.6$, $\langle N_{\text{coll}}(60-88\%) \rangle = 3.2 \pm 0.2$ and unbiased $\langle N_{\text{coll}}(0-100\%) \rangle = 7.6 \pm 0.3$. Figure 1 shows the $R_{\text{dAu}}$ corresponding to unbiased collisions. Figure 2a (b) shows $R_{\text{dAu}}$ corresponding to d+Au centralities of 60–88% (0–20%). Note that more central collisions correspond to cases where the nucleons in the deuteron strike closer to the middle of the gold nucleus, and thus nuclear effects are expected to be enhanced (which is seen in the data).

The peripheral $R_{\text{dAu}}$ favors some suppression at all rapidities, though this result is tempered by the current systematics of approximately ±15%. The central $R_{\text{dAu}}$ indicates a much larger suppression for $J/\psi$ at forward rapidity.

We also calculate the ratio $R_{\text{CP}}$ as the nuclear modification between central and peripheral $d+Au$ collision classes of events:

$$R_{\text{CP}} = \frac{\frac{dN^{d+Au}(0-20\%)}{dy}}{\langle N_{\text{coll}}(0-20\%) \rangle} / \frac{dN^{d+Au}(60-88\%)}{dy} / \langle N_{\text{coll}}(60-88\%) \rangle$$

(3)

Figure 2a shows the $R_{\text{CP}}$ ratio for the most central category relative to the peripheral 60–88% category as a function of rapidity. The quantity $R_{\text{CP}}$ has the advantage that many of the systematic uncertainties cancel in
the ratio. One observes a dramatic suppression of forward rapidity yields for central \(d+Au\) events compared to peripheral events. At backward rapidity, there is little to no modification seen.

In order to further explore the centrality dependence of the nuclear effects we categorize each \(d+Au\) centrality class in terms of the distribution of transverse radial positions \((r_T)\) of the nucleon-nucleon collisions relative to the center of the gold nucleus. The \(r_T\) distributions for the four centrality categories are shown in Fig. 3a. We expect that the nuclear effects are dependent on the density weighted longitudinal thickness through the gold nucleus \((\Lambda(r_T) \equiv \frac{1}{\rho_0} \int dz \rho(z, r_T))\), where \(\rho_0\) is the density in the middle of the nucleus. This quantity is also shown in Fig. 3a as a function of \(r_T\).

We now posit three different functional dependencies of the nuclear modification on \(\Lambda(r_T)\).

\[
\text{Exponential : } M(r_T) = e^{-a \Lambda(r_T)} \tag{4}
\]

\[
\text{Linear : } M(r_T) = 1.0 - a \Lambda(r_T) \tag{5}
\]

\[
\text{Quadratic : } M(r_T) = 1.0 - a \Lambda(r_T)^2, \tag{6}
\]

where \(a\) is a parameter depending on the average level of modification. The EPS09 nPDF based calculation, shown in Figs. 12 assumes the linear relation \([15, 17]\) in Eq. \(\ref{eq:lin}\) in order to make centrality-dependent predictions. In contrast, contributions from a break up of the \(c\bar{c}\) via a \(\sigma_{br}\) follow the exponential relation in Eq. \(\ref{eq:exp}\).

Figure 3b shows the nuclear modification \(R_{CP}\) in the most central bin versus the (unbiased) average modification \(R_{dA}\). This particular set of quantities is chosen because for each of the three geometric dependencies (Eqs. \(\ref{eq:lin}, \ref{eq:quad}\)), a given value of the parameter \(a\) results in a unique point on the plot and varying the parameter \(a\) results in a unique locus of points on which any suppression with that geometric dependence must lie.

The experimental data is also plotted in Fig. 3b for the same quantities. The ellipses represent a one standard deviation contour for the systematic uncertainties, which are largely uncorrelated between the unbiased \(R_{dA}\) and \(R_{CP}\). There is a substantial deviation between the exponential and linear cases and the experimental data at forward rapidity, while at mid and backward rapidities the data cannot discriminate between the cases. Thus, the forward rapidity data suggest that the dependence on \(\Lambda(r_T)\) is non-linear and closer to quadratic. If the dominant physics leading to the modification is different at different rapidities, it is possible for example that the modification at backward rapidities is linear while at forward rapidities it is not. This is reinforced by the EPS09 plus \(\sigma_{br}\) calculation where regardless of the variation of the nPDF or \(\sigma_{br}\) one cannot simultaneously describe the full centrality dependence of the data as seen in Fig. 2.

Other non-linear density effects (e.g., quadratic) for the geometric dependence \([18]\) and for break up of the \(c\bar{c}\) after production \([19, 20]\) have been proposed. An alternative explanation is that initial-state parton energy...
FIG. 3: (color online) (a) Normalized to unity at the maximum bin are (solid curves) transverse radial $r_T$ distributions in the gold nucleus for four $d+Au$ centrality selections and (dashed curve) density weighted longitudinal thickness as a function of $r_T$ ($\Lambda(r_T)$). (b) (points) Unbiased $R_{dA}$ versus $R_{CP}$ for the experimental data and (curves) constraint lines for three geometric dependencies of the nuclear modification.

loss results in a backward shift of the $J/\psi$ rapidity distribution [21]. It has been observed [22] that the nuclear modification as a function of center-of-mass rapidity is similar to that observed at lower energies [1] with a steep increase in suppression at forward rapidities, as predicted for initial-state parton energy loss.

In summary, we have presented precision data on $J/\psi$ yields in $d+Au$ and $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV over a broad range in rapidity and $d+Au$ centrality. Nuclear modification factors at forward rapidity as a function of centrality cannot be reconciled with a picture of cold nuclear matter effects (nPDFs and a $\sigma_{br}$) when an exponential or linear dependence on the nuclear thickness is employed. Effects of gluon saturation may play an important role in understanding the forward rapidity modifications, though other explanations involving initial-state parton energy loss need further investigation.

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