Cold Nuclear Matter Effects on J/ψ 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/ψ yields in $d + \mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV recorded by the PHENIX experiment and compare them with yields in $p + p$ collisions at the same energy per nucleon-nucleon collision. The measurements cover a large kinematic range in J/ψ 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. The forward rapidity data are inconsistent with nuclear modifications that are linear or exponential in the density weighted longitudinal thickness, such as those from the final state breakup of the bound state.

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The measured yields of quarkonium 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 proton (or deuteron) in the rest frame of the nucleus and by the relative longitudinal momentum of the $c\bar{c}$ pair. Fixed target $p + A$ experiments at Fermilab [1] showed that the J/ψ and ψ' mesons suffer a similar (and substantial) suppression at forward rapidity, suggesting that the suppression must occur at the prehadronic stage. An analysis [2] of results for $\sqrt{s_{NN}} = 17$–42 GeV highlighted the importance of (initial-state) nuclear modifications to the parton distribution functions (nPDFs) and of the (final state) breakup of the $c\bar{c}$ precursor with a breakup cross section (σ_{br}) that decreases as the relative center-of-mass energy between the $c\bar{c}$ and the nucleon increases. It is essential to extend this kind of study to the higher energies provided by the Relativistic Heavy Ion Collider (RHIC).

At RHIC, quarkonium states are predominantly produced via gluon-gluon interactions, and thus the yields in $d + \mathrm{Au}$ collisions at forward rapidity, the deuteron-going direction, are sensitive to the low-x region of the gluon densities in the gold nucleus (x being the fractional momentum carried by the gluon), where shadowing [3,4] and saturation effects [5] are expected. Additionally, the observation of quarkonium suppression in relativistic heavy ion collisions [6,7] is expected to provide a measure of the color screening length in the quark gluon plasma [8]. However, this suppression of quarkonia must be separated from the aforementioned cold nuclear matter effects. Thus, precise measurements of quarkonia suppression in $d + \mathrm{Au}$ are needed.

The PHENIX experiment at RHIC has previously published J/ψ results in $d + \mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV [9] from data taken in 2003. In this paper we present results from $d + \mathrm{Au}$ 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 2. Additionally, the $p + p$ reference data sets are updated to include larger data samples from 2006 and 2008.

The PHENIX apparatus is described in detail in [10]. It comprises two sets of spectrometers referred to as the central arms, which measure single-particles emitted in the pseudorapidity region $|\eta| < 0.35$, and the muon arms, measuring single muons in the pseudorapidity range $1.2 < |\eta| < 2.4$. J/ψ particles are measured via their dielectron (dimuon) decays at mid (backward and forward) rapidities, as described in detail in [9,11]. The $d+\mathrm{Au}$ data used for this analysis were recorded using selective level-1 triggers in coincidence with a minimum bias interaction requirement of one hit in each of two beam-beam counters (BBCs) located on each side of the interaction point ($3 < |\eta| < 3.9$). This minimum bias selection covers $88 \pm 4\%$ of the total $d+\mathrm{Au}$ inelastic cross section of 2260 mb [12]. Additional Level-1 triggers independently require (1) one hit above threshold (600 or 800 MeV) in the electromagnetic calorimeter with a matching hit in the ring imaging Čerenkov detector identified as an electron or (2) two tracks identified as muon candidates [9]. The data sets sampled via the Level-1 triggers represent analyzed integrated luminosities of 62.7 nb^{-1} (electrons) and 55.2 nb^{-1} (muons). For the midrapidity dielectrons we use $p+p$ reference data from [13]. For the forward and backward rapidity dimuons, we report here new $p+p$ data from 2006 and 2008 with a total integrated luminosity of 5.1 pb^{-1}.

The p_T-integrated J/ψ invariant yield as a function of rapidity is calculated for both $p+p$ and $d+\mathrm{Au}$ collisions via

$$B_{ll}\frac{dN}{dy} = \frac{CN_{J/\psi}}{N_{\mathrm{MB}}\epsilon A \Delta y}, \tag{1}$$

where B_{ll} is the branching fraction for $J/\psi \to e^+e^-$ or $\mu^+\mu^-$, $N_{J/\psi}$ is the number of J/ψ counts, N_{MB} is the number of sampled minimum bias (MB) events, Δy is the width of the rapidity bin and ϵA represents the product of the efficiency and acceptance, including the Level-1 trigger efficiency. We also include a correction factor (C) to account for trigger and (in $d+\mathrm{Au}$) centrality bias in J/ψ events. For $p+p$ ($d+\mathrm{Au}$) collisions, the correction factor is $C = 0.69$ (0.89—1.03). The corrected J/ψ invariant yield integrated over all centralities (0%–100%) corresponds to the $d+\mathrm{Au}$ inelastic event class.

The number of J/ψ particles is determined using the invariant mass distribution of unlike-sign lepton pairs. Approximately 38 000, 8900, and 42 000 J/ψ counts are measured at backward, mid, and forward rapidity, respectively. Figure 1(a) shows the J/ψ invariant yields in $p+p$ and $d+\mathrm{Au}$ collisions, integrating over centrality (0%–100%). The error bars (boxes) represent point-to-point uncorrelated (correlated) uncertainties. The global scale uncertainties are indicated. The dominant systematic uncertainty is from the efficiency and acceptance corrections and is determined from detailed simulation and real detector performance comparisons.

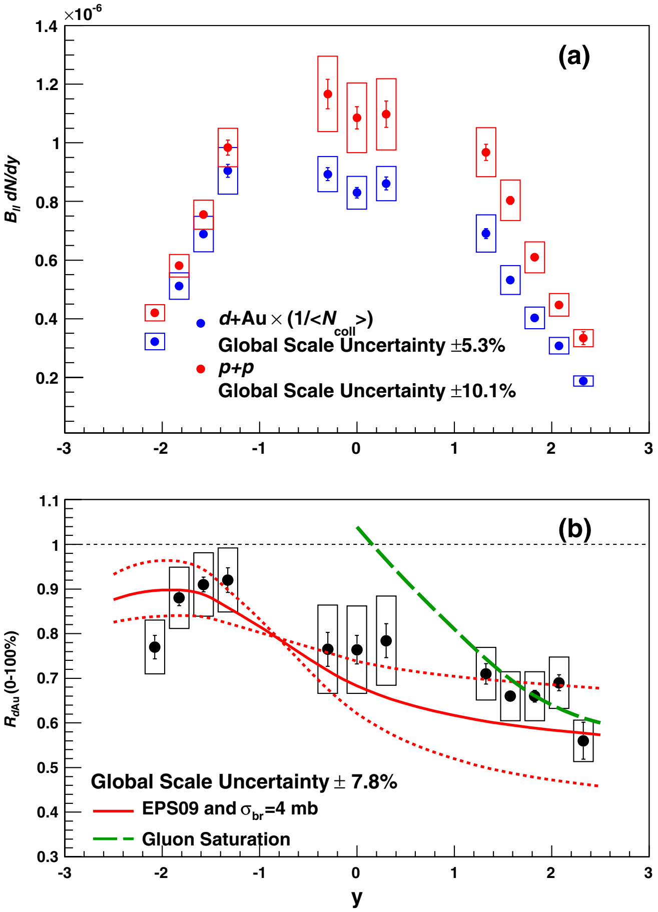

FIG. 1 (color online). (a) J/ψ invariant yields as a function of rapidity in $p+p$ and $d+\mathrm{Au}$ (integrated over all centralities 0%–100%) collisions. In $d+\mathrm{Au}$ the yields are divided by the average number of nucleon-nucleon collisions (as calculated with the Glauber model [9]). (b) J/ψ nuclear modification factors for 0%–100% collisions. Lines are model calculations detailed in the text.

We quantify the cold nuclear matter effects by calculating the nuclear modification factor R_{dAu},

$$R_{d\mathrm{Au}}(i) = \frac{dN^{d+\mathrm{Au}}(i)/dy}{\langle N_{\mathrm{coll}}(i)\rangle (dN^{p+p}/dy)}, \tag{2}$$

where i refers to the centrality bin (e.g. 0%–20%) and $\langle N_{\mathrm{coll}}(i)\rangle$ is the corresponding number of nucleon-nucleon collisions, determined from the total energy deposited in the BBC located at negative rapidity. For a given centrality bin $\langle N_{\mathrm{coll}}(i)\rangle$ is derived using a Glauber calculation coupled to a simulation of the BBC response, with Woods-Saxon density distributions and a $p+p$ inelastic cross section of 42 mb (see [9] for details).

The centrality bins used in this analysis are characterized as follows: central $\langle N_{\mathrm{coll}}(0\%\text{–}20\%)\rangle = 15.1 \pm 1.0$, $\langle N_{\mathrm{coll}}(20\%\text{–}40\%)\rangle = 10.2 \pm 0.7$, $\langle N_{\mathrm{coll}}(40\%\text{–}60\%)\rangle = 6.6 \pm 0.4$, $\langle N_{\mathrm{coll}}(60\%\text{–}88\%)\rangle = 3.2 \pm 0.2$, and $\langle N_{\mathrm{coll}} \times (0\%\text{–}100\%)\rangle = 7.6 \pm 0.4$. Figure 1(b) shows R_{dAu} corresponding to $d+\mathrm{Au}$ collisions integrated over all centralities. Figure 2 shows R_{dAu} for $d+\mathrm{Au}$ centralities of 60%–88% (a) and 0%–20% (b).

For peripheral collisions, the $R_{d\mathrm{Au}}$ ratio shows a mild suppression, roughly independent of rapidity, within the systematic uncertainties of approximately $\pm 15\%$. For central collisions $R_{d\mathrm{Au}}$ indicates a much larger suppression for J/ψ at forward rapidity.

We also calculate the ratio R_{CP}, which gives the nuclear modification between central and peripheral $d+\mathrm{Au}$ collisions:

$$R_{\mathrm{CP}} = \frac{[dN^{d+\mathrm{Au}}(0\%\text{–}20\%)/dy]/\langle N_{\mathrm{coll}}(0\%\text{–}20\%)\rangle}{[dN^{d+\mathrm{Au}}(60\%\text{–}88\%)/dy]/\langle N_{\mathrm{coll}}(60\%\text{–}88\%)\rangle}. \qquad (3)$$

This variable, shown in Fig. 2(c) as a function of rapidity, has a much better accuracy because many of the systematic uncertainties cancel in the ratio. One observes a significant suppression of forward rapidity J/ψ yields in central $d+\mathrm{Au}$ events, while at backward rapidity there is almost no modification.

Following the prescription in [14], we utilize the EPS09 nPDF set [15] and an example $\sigma_{\mathrm{br}} = 4$ mb is chosen to match the backward rapidity $R_{d\mathrm{Au}}$ data. We also show (as red dashed lines) the differences within the EPS09 nPDFs for the single parameter change that gives the largest variation [15]. While the calculation reproduces reasonably well the 0%–100% integrated $R_{d\mathrm{Au}}$ data, as shown in Fig. 1(b), it fails to describe the R_{CP} measurement at forward rapidity [Fig. 2(c)]. No parameter choice of the EPS09 nPDF set and of σ_{br} is able to describe the rapidity and centrality dependence of the data (see [16] for more details). Thus, there is no single σ_{br} value to be quoted (as also seen at lower energies [2]).

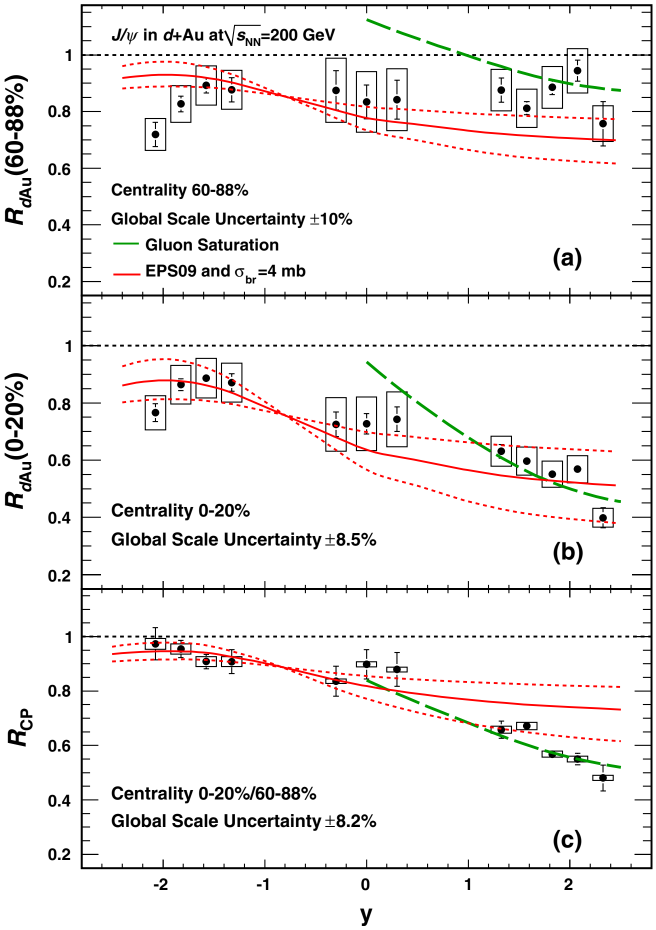

FIG. 2 (color online). Nuclear suppression factors $R_{d\mathrm{Au}}$ peripheral (a), $R_{d\mathrm{Au}}$ central (b), and R_{CP} (c) as a function of rapidity.

A second class of calculations incorporates gluon saturation effects at small-x [5,17], and is compared with experimental data in Figs. 1 and 2. A modest J/ψ enhancement is predicted at midrapidity due to double-gluon exchange processes (not seen in the data) and a substantial J/ψ suppression at forward rapidity and in more central $d+\mathrm{Au}$ events due to saturation effects (in agreement with the data). However, a similar suppression of forward rapidity J/ψ observed at lower $\sqrt{s_{NN}}$ [1,18] presents a challenge to this saturation interpretation.

In order to further explore the centrality dependence of the nuclear effects we categorize each $d+\mathrm{Au}$ 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. 3(a). 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 ρ_0 is the density in the center of the nucleus. This quantity is also shown in Fig. 3(a) as a function of r_T.

Following the work in [16], we posit three different functional dependencies of the nuclear modification on $\Lambda(r_T)$:

$$\text{Exponential}: M(r_T) = e^{-a\Lambda(r_T)}, \qquad (4)$$

$$\text{Linear}: M(r_T) = 1.0 - a\Lambda(r_T), \qquad (5)$$

$$\text{Quadratic}: M(r_T) = 1.0 - a\Lambda(r_T)^2, \qquad (6)$$

where a is a parameter depending on the average modification level. The EPS09 nPDF based calculation, shown in Figs. 1 and 2, assumes the linear relation [14,19] in Eq. (5) in order to make centrality-dependent predictions. In contrast, contributions from a breakup of the $c\bar{c}$ via a σ_{br} follow the exponential relation in Eq. (4).

Using the $\Lambda(r_T)$ dependence and the r_T distributions for each centrality bin shown in Fig. 3(a), one can calculate the nuclear modification $R_{d\mathrm{Au}}$ in each centrality bin that results from Eqs. (4)–(6) for any given value of a. This allows one to plot the R_{CP} in the most central bin versus the average modification $R_{d\mathrm{Au}}$ (0%–100%) for each of the three geometric dependencies, as shown in Fig. 3(b). Varying the parameter a results in a unique locus of points

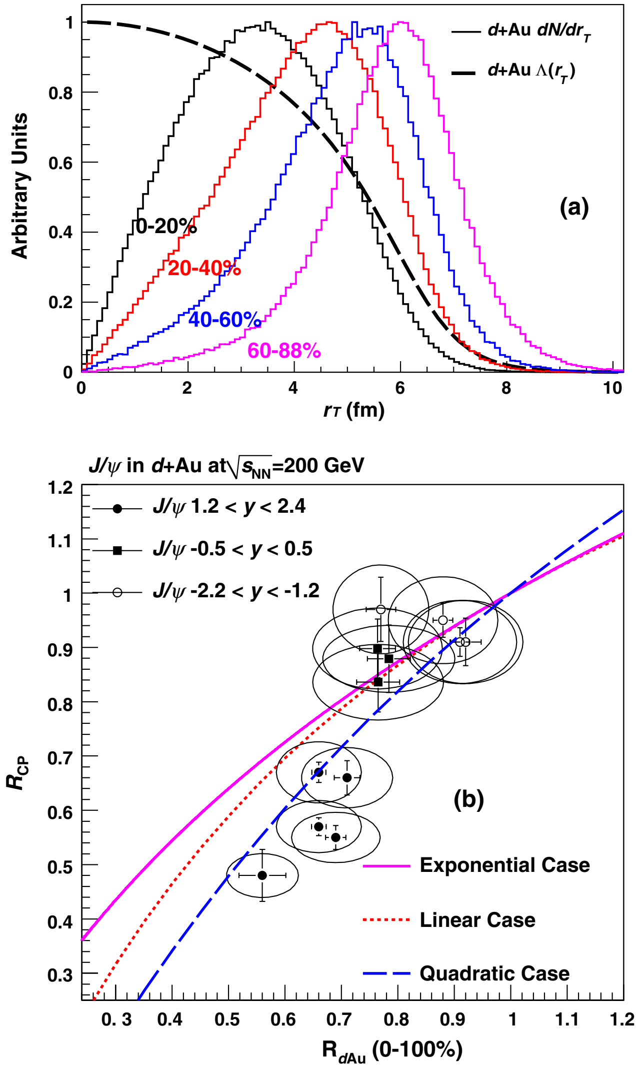

FIG. 3 (color online). (a) Normalized to unity at the maximum bin are (solid curves) transverse radial r_T distributions in the gold nucleus for four d + Au centrality selections and (dashed curve) density weighted longitudinal thickness as a function of r_T [$\Lambda(r_T)$]. (b) $R_{\rm CP}$ versus $R_{d\rm Au}$ for the experimental data (points) and constraint lines for three geometric dependencies of the nuclear modification (curves).

on which any suppression with a given geometric dependence must lie.

The experimental data are also plotted in Fig. 3(b) for the same quantities. The ellipses represent a 1 standard deviation contour for the systematic uncertainties, which are largely uncorrelated between the $R_{d\rm Au}$ and $R_{\rm CP}$. 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. The forward rapidity data suggest that the dependence on $\Lambda(r_T)$ is nonlinear and closer to quadratic. If the dominant mechanism 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 is not. This is reinforced by the EPS09 plus $\sigma_{\rm br}$ calculation, where regardless of the variation of the nPDF or $\sigma_{\rm br}$ one cannot simultaneously describe the full centrality dependence of the data, as seen in Fig. 2.

Other nonlinear density effects (e.g., quadratic) for the geometric dependence [20] and for the breakup of the $c\bar{c}$ after production [21,22] have been proposed. An alternative explanation is that initial-state parton energy loss results in a backward shift of the J/ψ rapidity distribution [23]. It has been observed [24] 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.

In summary, we have presented precision data on J/ψ 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 $\sigma_{\rm br}$) 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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