PHENIX Results on $J/\psi$ Production in $p+Al$, $p+Au$ and $^3$He+Au Collisions

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Abstract.

Results are presented of measurements of the $J/\psi$ modification in $p+Au$, $d+Au$ and $^3$He+Au collisions at forward and backward rapidity ($1.2 < |y| < 2.2$) by the PHENIX experiment. The rapidity, transverse momentum and collision centrality dependence of the modifications are presented, and compared between the three light projectile collision systems. The modification for $p+Al$ is found to be small. For $p+Au$ it is depends strongly on collision centrality at forward rapidity. In both cases models describe the data well. The modifications for $d+Au$ and $^3$He+Au are very similar to those for $p+Au$, although there is a hint of slightly increased suppression for $^3$He+Au over $p+Au$ at backward rapidity.

1. Introduction

The effects that modify the $J/\psi$ production probability in nuclear collisions can be broadly separated into two categories, based on the time scale in which they occur. Those that occur during the expansion and hadronization of the energy produced in the collision are generally referred to as hot matter effects. Those that occur on a time scale smaller than the crossing time of the colliding nuclei are frequently referred to as cold nuclear matter (CNM) effects. The latter include modification of the nuclear-parton-distribution functions (nPDFs) in a nucleus [1, 2], initial state parton energy loss [3], coherent gluon saturation [4, 5], breakup of the forming charmonium in collisions with target nucleons [6, 7], and transverse momentum broadening [8].

Prior to the last five years, it was widely assumed that the energy produced in $p(d)+A$ collisions did not cause significant modification of charmonium yields in the final state. This was called into question by two observations. One was the observation of flow-like behavior in $p+Pb$ collisions at LHC (see for example [9]) and later in $d+Au$ collisions at RHIC [10, 11]. This suggested that a quark-gluon plasma of small size is created in high energy collisions of light systems. The second was the observation of strong suppression of the weakly bound $\psi(2S)$ relative to the $J/\psi$ in central $d+Au$ collisions [12], and later in $p+Pb$ collisions [13]. This can not be explained by known CNM effects, but explanations invoking final state effects due to energy produced in the collision have been successful [14, 15, 16]. A transport model [15] that reproduces the differential $\psi(2S)$ suppression also predicts a $J/\psi$ suppression of $\sim 20\%$ in central $d+Au$ collisions.

To further explore the effects of energy production on $J/\psi$ yields in light systems, the PHENIX collaboration has recently measured the modification in three collision systems involving small projectiles, $p+Al$, $p+Au$ and $^3$He+Au [17]. The $p+Au$ and $^3$He+Au data,
combined with the earlier PHENIX d+Au data [18, 19], provide a direct comparison of inclusive charmonium production for projectiles with one, two and three nucleons on a Au target. We will focus here mostly on the p+Au and \(^3\text{He}+\text{Au}\) results.

2. Experiment
The \(J/\psi \rightarrow \mu^+\mu^-\) data for the \(p+\text{Au}\), \(^3\text{He}+\text{Au}\) and reference \(p+p\) collision systems were measured in the PHENIX muon arms [20, 21, 22] during the RHIC runs in 2014 (\(^3\text{He}+\text{Au}\)) and 2015 (\(p+\text{Au}\) and \(p+p\)). All data were recorded at \(\sqrt{s_{NN}} = 200\) GeV. The muon spectrometers cover the range \((-2.2 < \eta < -1.2)\) and \((1.2 < \eta < 2.2)\). Collision centrality was measured using the Beam-Beam Counters (BBC) located at \(3.1 < |\eta| < 3.9\). The corresponding integrated luminosity is 47 pb\(^{-1}\) for \(p+p\), 590 nb\(^{-1}\) for \(p+\text{Al}\), 138 nb\(^{-1}\) for \(p+\text{Au}\), and 18 nb\(^{-1}\) for \(^3\text{He}+\text{Au}\) collisions. The details of the measurement and analysis are described in [17].

3. Results

Figure 1. Nuclear modification factor of inclusive \(J/\psi\) as a function of rapidity for 0–100% \(p+\text{Al}\) (a), \(p+\text{Au}\) (b), and \(^3\text{He}+\text{Au}\) (c) collisions. Bars (boxes) around data points represent point-to-point uncorrelated (correlated) uncertainties. The theory bands are discussed in the text.

There were significant changes to the PHENIX muon arm configuration and to the PHENIX simulation framework between the time that the \(d+\text{Au}\) data set was recorded in 2008 and when the \(p+\text{Al}\), \(p+\text{Au}\), \(^3\text{He}+\text{Au}\) and their reference \(p+p\) data were recorded in 2014 and 2015. In addition, the \(d+\text{Au}\) data set used a different reference \(p+p\) measurement. Therefore the relative systematic uncertainties between the modifications measured for \(p+\text{Al}\), \(p+\text{Au}\) and \(^3\text{He}+\text{Au}\) are smaller, and we focus on those for comparisons.

Figure 1 shows the measured rapidity dependence of the modification for \(p+\text{Al}\), \(p+\text{Au}\) and \(^3\text{He}+\text{Au}\), integrated over \(p_T\) and for 0-100% centrality. The data are compared with model calculations by Shao et al [23, 24, 25, 26] that include only CNM effects. The calculations use the EPPS16 [1] and nCTEQ15 [2] NLO gluon shadowing parameterizations. In the calculations, the gluon shadowing parameterizations for the Au target are modified using a Bayesian reweighting method that imposes \(J/\psi\) constraints from \(p+\text{Pb}\) data at the LHC [23]. This results in considerably reduced uncertainties of the modifications. The theoretical uncertainties (68% CL) are dominated by the uncertainty in the factorization scale.

The forward rapidity data are well described for all three systems, as are the backward rapidity \(p+\text{Al}\) data. However the backward rapidity \(p+\text{Au}\) and \(^3\text{He}+\text{Au}\) data are not reproduced by the shadowing calculation alone. At RHIC energies a significant suppression is expected at backward rapidity due to breakup of the forming charmonium in collisions with nucleons that have not yet passed through the production point (commonly referred to as ”nuclear absorption”). An estimate of this effect has been folded into the shadowing calculation and is included in Figure 1.
The absorption estimate is based on a model [7] that has been fitted to absorption cross sections derived from shadowing corrected data measured at a broad range of beam energies [6]. In the model, the absorption cross section depends on the size of the evolving charmonium, and thus on the proper time before it escapes the target nucleus. Including the absorption estimate brings the backward rapidity calculation into reasonable agreement with the $p+Au$ and $^3He+Au$ data.

**Figure 2.** Nuclear modification factor of inclusive $J/\psi$ as a function of $p_T$ for 0–100% $p+Al$ (a), $p+Au$ (b), and $^3He+Au$ (c) collisions at backward rapidity. Bars (boxes) around data points represent point-to-point uncorrelated (correlated) uncertainties. The theory bands are discussed in the text.

**Figure 3.** Nuclear modification factor of inclusive $J/\psi$ as a function of $p_T$ for 0–100% $p+Al$ (a), $p+Au$ (b), and $^3He+Au$ (c) collisions at forward rapidity. Bars (boxes) around data points represent point-to-point uncorrelated (correlated) uncertainties. The theory bands are discussed in the text.

The $p_T$ dependence of the centrality integrated $J/\psi$ modification is shown for $p+Al$, $p+Au$ and $^3He+Au$ in Figure 2 (backward rapidity) and Figure 3 (forward rapidity). The calculations of Shao et al are compared with the data for the three collision systems. As was the case for the rapidity dependence in Figure 1, the calculations do a reasonable job of describing the data at forward rapidity for all three systems, and at backward rapidity for $p+Al$. The calculations do not include transverse momentum broadening, probably explaining why they fall below the data above about 3 GeV/c. For $p+Au$ and $^3He+Au$ at backward rapidity and low $p_T$, the calculations substantially overpredict the modification. Qualitatively this is expected because the calculation contain only enhancement from anti-shadowing, but do not include suppression from nuclear absorption.

Also shown for $p+Au$ in Figure 2 and Figure 3 are calculations from a transport model by Du and Rapp [15]. This is adapted from a model by Zhao and Rapp [27] that was developed to describe A+A collisions. The calculation includes a fireball generated by a glauber Monte-Carlo
model [28], an NLO gluon shadowing parameterization from EPS09 [29], transverse momentum broadening [30], and an estimate of the $J/\psi$ absorption cross section constrained by PHENIX $d+Au$ data [12]. These calculations do a good job at backward rapidity, but produce too little suppression at low $p_T$ at forward rapidity. The forward rapidity suppression is dominated by the absorption cross section constrained by PHENIX $d+Au$ data [12]. These calculations do a good job at backward rapidity, but produce too little suppression at low $p_T$ at forward rapidity. The forward rapidity suppression is dominated by the gluon shadowing, so this indicates that the EPS09 shadowing used in the model is not strong enough at forward rapidity to describe the data. It is worth noting that at low Bjorken $x$, which is the regime relevant to the forward rapidity $J/\psi$ data, the newer EPPS16 parameterization produces stronger shadowing than EPS09. Also, the Bayesian reweighting used by Shao et al
strengthens the low $x$ shadowing further, resulting in a satisfactory description of the forward rapidity centrality integrated data, as seen in Figure 1(b) and Figure 3(b). On the other hand, in the Bjorken $x$ regime relevant to the backward rapidity $J/\psi$ data, the gluon modifications are similar for EPS09 and EPPS16.

The $p_T$ dependence, in six collision centrality bins, is presented at backward rapidity in Figure 4 and at forward rapidity in Figure 5. The 0-5% bin contains the most central collisions. At backward rapidity there is weak dependence of the modification on centrality. However at forward rapidity the data show very strong centrality dependence, with the most central bin at low $p_T$ having a suppression of a factor of almost three.

In Figure 4 and Figure 5 calculations of the $p_T$ dependence from the transport model by Du and Rapp are compared with the data. At backward rapidity the calculations describe the $p_T$ dependence of the data well at all centralities. At forward rapidity and low $p_T$, the calculations show much less suppression than is seen in the data. As already mentioned, because the modification of $J/\psi$ production in the transport model is small at forward rapidity, the model suppression is dominated by the EPS09 shadowing parameterization. It is important to note here that the EPS09 parameterization is integrated over all centrality, and contains no prediction for the centrality dependence of the shadowing. The centrality dependence was assumed by Du and Rapp to be linear in the nuclear thickness.

![Figure 6](image_url)

**Figure 6.** Comparison of nuclear modification factor of $J/\psi$ as a function of $p_T$ in 0–20% centrality $p+Au$ and $^3He+Au$ collisions. Bars (boxes) around data points represent point-to-point uncorrelated (correlated) uncertainties.

At $\sqrt{s_{NN}} = 200$ GeV the charged particle multiplicity observed by PHENIX in 0-20% central $^3He+Au$ collisions is approximately twice that observed in $p+Au$ collisions [31]. CNM effects are expected to be very similar for the two collision systems. To investigate whether the difference in charged particle multiplicity has an effect on the $J/\psi$ modification, the measured modifications as a function of $p_T$ in the two systems are compared directly in Figure 6. The ratio of the modifications is presented in the lower panel. At forward rapidity the average ratio is found to be
Figure 7. Nuclear modification factor of $J/\psi$ as a function of $\langle N_{\text{coll}} \rangle$ for $p+Au$ collisions compared with the transport model. Bars (boxes) around data points represent point-to-point uncorrelated (correlated) uncertainties.

\[
\frac{R_{3\text{He}Au}}{R_{pAu}} = 0.96 \pm 0.03(\text{stat}) \pm 0.05(\text{syst}),
\]

which is consistent with unity. At backward rapidity it is

\[
\frac{R_{3\text{He}Au}}{R_{pAu}} = 0.89 \pm 0.03(\text{stat}) \pm 0.08(\text{syst}).
\]

which is suggestive of additional suppression in $3\text{He}+Au$, but the systematic uncertainty does not allow a strong statement to be made.

Figure 7 shows the $N_{\text{coll}}$ dependence of the $J/\psi$ modification for $p+Au$, integrated over $p_T$, for each of the muon arms. At backward rapidity the modification is not much smaller than one, and is almost independent of centrality. At forward rapidity the modification decreases strongly with centrality, reaching 0.5 for the most central collisions. Also shown in Figure 7 is the corresponding calculated modification from Du and Rapp [15]. At backward rapidity, the calculated modification involves an almost exact cancelation between the anti-shadowing and nuclear absorption effects, with an additional suppression from transport effects that is of order 10% for the most central collisions. At forward rapidity the calculation substantially underpredicts the suppression in central collisions. As already mentioned, the suppression from EPS09 shadowing is insufficient in the model to explain the data at forward rapidity.

Finally, a comparison of the $p_T$ integrated $p+Au$ modification versus rapidity for the most central collisions and the most peripheral collisions illustrates two points. This is shown in Figure 8. First, at backward rapidity the measured modifications are the same within uncertainties. This can be understood as a cancelation between anti-shadowing and absorption, since those two effects have strong, but opposite, centrality dependence (see also Figure 1). Second, at forward rapidity the 0-5% most central collisions show strong suppression, which increases as the rapidity increases. At the most forward rapidity the $p_T$ integrated modification is about 0.35.

4. Summary and Conclusions
For $p+Al$, $p+Au$ and $3\text{He}+Au$ collisions, the measured $J/\psi$ modifications as a function of rapidity, integrated over $p_T$, was presented. The data are reasonably well described by Bayesian reweighted EPPS16 and nCTEQ15 calculations [23, 24, 25, 26], with estimates of nuclear absorption added by PHENIX at backward rapidity.
Figure 8. Comparison of the nuclear modification factor of $J/\psi$ for $p+Au$ collisions in two centrality classes, as a function of rapidity. Bars (boxes) around data points represent point-to-point uncorrelated (correlated) uncertainties.

The $p_T$ dependence of the $J/\psi$ modification integrated over centrality was presented, and compared with the same Bayesian reweighted EPPS16 and nCTEQ15 calculations. They describe the data well at low $p_T$, but fall below the data above 3 GeV/$c$, likely because they do not contain any transverse momentum broadening.

The $p_T$ dependence of the $J/\psi$ modification in $p+Au$ collisions was presented in six centrality bins at forward and backward rapidity. At backward rapidity the data show little dependence on centrality, and are well described by a model [15] that combines shadowing, nuclear absorption, transverse momentum broadening and (a small) suppression due to transport effects in the fireball created in the collision. At forward rapidity the measured modification shows very strong suppression at low $p_T$ in central collisions, reaching 0.35 at 0-5% centrality. The model substantially underpredicts the suppression at low $p_T$ in more central collisions, indicating that the shadowing component of the model gives insufficient suppression there.

The $J/\psi$ modifications measured for central $p+Au$ and $^3He+Au$ collisions were compared, to look for evidence of final state effects caused by the increased charged particle multiplicity in $^3He+Au$. The ratio of the modifications at forward rapidity is consistent with unity. At backward rapidity the ratio is suggestive of a small additional suppression in $^3He+Au$, however the systematic uncertainty precludes a strong statement.

The centrality dependence of the $p_T$ integrated modification in the two muon arms was presented. At backward rapidity it is close to one and almost independent of centrality. At forward rapidity it has a strong centrality dependence, dropping to 0.5 for 0-5% central collisions. The transport model calculation describes the data reasonably well at backward rapidity. At forward rapidity the model produces too little suppression in central collisions, again indicating that the suppression from shadowing is insufficient.

The rapidity dependence of the modification for peripheral and central $p+Au$ collisions was compared. It shows no change in the modification at backward rapidity, suggesting essentially complete cancelation between the enhancement due to anti-shadowing and the suppression due to nuclear absorption plus transport suppression. At forward rapidity the suppression is strong for central collisions, with the modification dropping to approximately 0.35 at the largest rapidity.
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