Measurements of charmonium production in p+p, p+Au, and Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV with the STAR experiment

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Abstract

We present the first results from the STAR MTD of mid-rapidity charmonium measurements via the di-muon decay channel in p+p, p+Au, and Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV at RHIC. The inclusive $J/\psi$ production cross section in p+p collisions can be described by the Non-Relativistic QCD (NRQCD) formalism coupled with the color glass condensate effective theory (CGC) at low transverse momentum ($p_T$) and next-to-leading order NRQCD at high $p_T$. The nuclear modification factor in p+Au collisions for inclusive $J/\psi$ is below unity at low $p_T$ and consistent with unity at high $p_T$, which can be described by calculations including both nuclear PDF and nuclear absorption effects. The double ratio of inclusive $J/\psi$ and $\psi(2S)$ production rates for $0 < p_T < 10$ GeV/c at mid-rapidity between p+p and p+Au collisions is measured to be $1.37 \pm 0.42 \pm 0.19$. The nuclear modification factor in Au+Au collisions for inclusive $J/\psi$ shows significant $J/\psi$ suppression at high $p_T$ in central collisions and can be qualitatively described by transport models including dissociation and regeneration contributions.

Keywords: heavy-ion collisions, quarkonium, $J/\psi$ suppression, color screening, cold nuclear matter effect

1. Introduction

The $J/\psi$ dissociation by the color-screening effect in the hot and dense medium was initially proposed as direct evidence of the quark-gluon plasma formation. However, the interpretation of $J/\psi$ suppression observed in heavy-ion collisions has remained a challenge due to the contribution of regenerated $J/\psi$ from the coalescence of deconfined $c\bar{c}$ pairs in the medium as well as cold nuclear matter effects. Quantifying the cold and hot nuclear matter effects at the RHIC requires precise measurements of charmonium production in p+p, p+Au, and Au+Au collisions. The Muon Telescope Detector (MTD), which provides both the muon triggering and identification capabilities at mid-rapidity, opens the door to measuring quarkonia via the di-muon decay channel at STAR. Using the MTD di-muon trigger, the STAR experiment recorded data corresponding to an integrated luminosity of 14.2 nb$^{-1}$ in Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV in the RHIC 2014 run, and integrated luminosities of 122 pb$^{-1}$ in p+p collisions and 409 nb$^{-1}$ in p+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV in the RHIC 2015 run. In these proceedings, we present (i) measurements of nuclear
modification factors for inclusive $J/\psi$ production over a broad kinematic range in both p+Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV; and (ii) the first measurement of the double ratio of inclusive $\psi(2S)$ and $J/\psi$ production rates at mid-rapidity between p+p and p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

2. Inclusive $J/\psi$ measurements in p+p and p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

Figure 1 shows the production cross section of inclusive $J/\psi$ in p+p collisions at $\sqrt{s} = 200$ GeV via the di-muon decay channel for the transverse momentum ($p_T$) range of $1 < p_T < 10$ GeV/c (red circles), along with a similar measurement via the di-electron decay channel (blue squares) in $0 < p_T < 14$ GeV/c. These results are consistent in the overlapping $p_T$ range. The experimental results can be well described by CGC+NRQCD [2] and NLO NRQCD [3] calculations for prompt $J/\psi$ at low and high $p_T$ ranges, respectively. While an improved color evaporation model (ICEM) calculation for direct $J/\psi$ [4] can describe the data for $p_T < 3$ GeV/c, it generally underestimates the yield at higher $p_T$. 

Figure 2 shows the nuclear modification factor, $R_{pAu}$, of inclusive $J/\psi$ in 0-100% central p+Au collisions. The measured $R_{pAu}$ is generally consistent with the previous $R_{dAu}$ result reported by the PHENIX experiment [5] within statistical and systematic uncertainties. The largest deviation between these results is 1.4$f_T$ in the range of $3 < p_T < 5$ GeV/c. This overall consistency suggests similar cold nuclear matter effects in p+Au and d+Au collisions. Calculations, taking into account the nuclear PDF effect using the nCTEQ15 [6, 7, 8] or EPS09NLO [6, 7, 8, 9] nuclear PDF sets, can touch the upper limit of the data within uncertainties. However, the model calculation including an additional nuclear absorption effect [10] is favored by the data.

Fig. 1. Inclusive $J/\psi$ production cross section scaled by the branching ratio ($B$) as a function of $p_T$ in the di-muon (red circle) and the di-electron decay channels (blue square).

Fig. 2. Nuclear modification factor $R_{pAu}$ as a function of $p_T$ for inclusive $J/\psi$ in the di-muon decay channel.

3. Double ratio of inclusive $J/\psi$ and $\psi(2S)$ yields between p+p and p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

Figure 3 shows the ratio of inclusive $J/\psi$ and $\psi(2S)$ production cross sections as a function of $p_T$ in p+p collisions at $\sqrt{s} = 200$ GeV. The new STAR result for $0 < p_T < 10$ GeV/c follows the global trend of results by HERA [11], PHENIX [12, 13], and CDF [14] experiments. The ICEM calculation at $\sqrt{s} = 200$ GeV [4] can describe the increasing trend of the ratio with $p_T$. 

Figure 4 shows the double ratio of $\psi(2S)$ and $J/\psi$ production rates between p+p and p+Au collisions as a function of rapidity. The new STAR results at $|y| < 0.5$ is $1.37 \pm 0.42(\text{stat}) \pm 0.19(\text{sys})$, which is consistent with the published PHENIX results at $|y| < 0.35$ in d+Au collisions [15]. The co-mover model calculation [16, 17] can qualitatively describe the double ratio at forward and backward rapidities in p+Au collisions reported by the PHENIX experiment [15], and is consistent with the new STAR result at mid-rapidity within uncertainties.
4. Inclusive $J/\psi$ measurements in Au+Au collisions at $\sqrt{s_{_{NN}}}=200$ GeV

Shown in Fig. 5 is the nuclear modification factor $R_{AA}$ of inclusive $J/\psi$ in 0-40% central Au+Au collisions compared with LHC results \[18,19\]. The strong suppression at RHIC at high $p_T$ indicates significant $J/\psi$ dissociation. The hint of the increasing $R_{AA}$ with increasing $p_T$ can be explained by the formation-time effect and the feed-down contribution from $B$ hadron decays \[20\]. The stronger suppression of $J/\psi$ at RHIC at low $p_T$ can be explained by less regeneration contribution due to smaller charm production cross section, while the smaller suppression of $J/\psi$ at RHIC at high $p_T$ could arise from a smaller dissociation rate due to the lower temperature of the medium. The $R_{AA}$ as a function of the number of participant nucleons ($N_{\text{part}}$) for $p_T > 0$ GeV/$c$ and $p_T > 5$ GeV/$c$ are compared with the $R_{pAu}$ in Fig. 6. The nuclear modification factors in the most peripheral Au+Au collisions are consistent with those measured in p+Au collisions.

Transport models from Tsinghua \[21,22\] and Texas A&M University (TAMU) \[20,23\] groups, including dissociation and regeneration contributions, can qualitatively describe the $p_T$ dependence of the RHIC and the LHC data as shown in Fig. 5. Centrality dependences of the $J/\psi$ $R_{AA}$ at the RHIC \[24\] and the LHC are shown in Fig. 7 for $p_T > 0$ GeV/$c$ and in Fig. 8 for $p_T > 5$ GeV/$c$. For $p_T > 0$ GeV/$c$, both models can describe the centrality dependence at the RHIC, but tend to overestimate the suppression at the LHC. For $p_T > 5$ GeV/$c$, there is tension among models and data. The discontinuities seen in the $R_{AA}$ as a function of $N_{\text{part}}$ from the Tsinghua model calculation can be attributed to the complete dissociation of $J/\psi$ when the medium temperature exceeds the dissociation temperature.
STAR preliminary

STAR: Au+Au, √s = 200 GeV, J/ψ → e⁺e⁻, |y| < 0.5

CMS: Pb+Pb, √s = 2.76 TeV, J/ψ → e⁺e⁻, |y| < 2.4, pT > 6.5 GeV/c

ALICE: Pb+Pb, √s = 2.76 TeV, J/ψ → e⁺e⁻, |y| < 0.8

LHC

Fig. 7. Nuclear modification factor R_AA for pT > 0 GeV/c as a function of N_{part}.

Fig. 8. Nuclear modification factor R_AA for pT > 5 GeV/c as a function of N_{part}.

5. Summary

In summary, we presented the first charmonium measurements in the di-muon decay channel at mid-rapidity at the RHIC. In p+p collisions at √s = 200 GeV, inclusive J/ψ production cross section can be described by CGC+NQCD and NLO NRQCD model calculations for prompt J/ψ at low and high pT ranges, respectively. While the ICEM calculation for direct J/ψ can describe the data for pT < 3 GeV/c, it generally underestimates the yield at higher pT. In p+Au collisions at √s_{NN} = 200 GeV, we observe (i) inclusive J/ψ R_{pAu} is consistent with R_{dAu} suggesting similar cold nuclear matter effects in p+Au and d+Au collisions; (ii) calculations incorporating the nuclear PDF and nuclear absorption effects can well describe R_{pAu}; and (iii) the double ratio of inclusive J/ψ and ψ(2S) production rates between p+p and p+Au collisions is 1.37 ± 0.42 ± 0.19. In Au+Au collisions at √s_{NN} = 200 GeV, we observe (i) significant J/ψ suppression in central collisions at high pT indicating dissociation; (ii) the J/ψ R_AA can be qualitatively described by transport models including dissociation and regeneration; and (iii) the R_AA in the most peripheral collisions is consistent with the R_{pAu}. These measurements in Au+Au collisions will gain additional statistical precision by combining with the similar amount of data recorded in the RHIC 2016 run.

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