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J/ψ production at high transverse momenta in $p+p$ and Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV

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The STAR Collaboration at the Relativistic Heavy Ion Collider presents measurements of $J/\psi \to e^+e^-$ at midrapidity and high transverse momentum ($p_T > 5\,\mathrm{GeV}/c$) in $p + p$ and central Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV. The inclusive J/ψ production cross section for Cu + Cu collisions is found to be consistent at high p_T with the binary collision-scaled cross section for $p + p$ collisions. At a confidence level of 97%, this is in contrast to a suppression of J/ψ production observed at lower p_T. Azimuthal correlations of J/ψ with charged hadrons in $p + p$ collisions provide an estimate of the contribution of B-hadron decays to J/ψ production of 13% ± 5%.

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Suppression of the $c\bar{c}$ bound state J/ψ meson production in relativistic heavy-ion collisions arising from J/ψ dissociation due to screening of the $c\bar{c}$ binding potential in the deconfined medium has been proposed as a signature of quark-gluon plasma (QGP) formation [1]. Measurements at $\sqrt{s_{NN}} = 17.3$ GeV at the CERN-SPS observed a strong suppression of J/ψ production in heavy-ion collisions [2], although the magnitude of the suppression decreases with increasing J/ψ p_T. This systematic dependence may be explained by initial state scattering (Cronin effect [3,4]), as well as the combined effects of finite J/ψ formation time and the finite space-time extent of the hot, dense volume where the dissociation can occur [5].

At higher beam energy ($\sqrt{s_{NN}} = 200$ GeV), the PHENIX Collaboration at the Relativistic Heavy Ion Collider (RHIC) has measured J/ψ suppression for $p_T < 5$ GeV/c in central (small impact parameter) Au + Au and Cu + Cu collisions [6] that is similar in magnitude to that observed at the CERN-SPS. This similarity is surprising in light of the expectation that the energy density is significantly higher at larger collision energy. It may be due to the cold nuclear absorption and the counterbalancing of larger dissociation with recombination of unassociated c and $\bar{c}$ in the medium, which are more abundant at higher energy [7–10] (i.e., for a recent review see Ref. [11]).

Measurements of open heavy-flavor production may also shed light on J/ψ suppression mechanisms. Nonphotonic electrons from the semileptonic decay of heavy flavor mesons are found to be strongly suppressed in heavy-ion relative to $p + p$ collisions at RHIC [12,13], an effect that has been attributed to partonic energy loss in dense matter [14–16]. This process may also contribute to high-p_T J/ψ suppression, if J/ψ formation proceeds through a channel carrying color.

The medium generated in RHIC heavy-ion collisions is thought to be strongly coupled [17], making accurate QCD calculations of quarkonium propagation difficult. The anti-de-Sitter space/conformal field theory (AdS/CFT) duality for QCD-like theories may provide insight into heavy fermion pair propagation in a strongly coupled liquid. One such calculation predicts that the dissociation temperature decreases with increasing J/ψ p_T (or velocity) [18]. The temperature achieved at RHIC ($\sim 1.5\, T_c$) [17] is below this dissociation temperature at low J/ψ p_T and above it at $p_T \gtrsim 5$ GeV/c. Consequently, J/ψ production is predicted to be more suppressed at high p_T, in contrast to the standard suppression mechanism. This prediction can be tested with measurements of J/ψ over a broad kinematic range, in both $p + p$ and nuclear collisions.

The interpretation of J/ψ suppression observed at the CERN Super Proton Synchrotron (SPS) and by the PHENIX Collaboration requires understanding of the quarkonium production mechanism in hadronic collisions, which include direct production via gluon fusion and color-octet (CO) and color-singlet (CS) transitions, as described by nonrelativistic quantum chromodynamics (NRQCD) [19], parton fragmentation, and feed-down from higher charmonium states [χ_c, $\psi(2S)$] and B-hadron decays. No model at present fully explains the J/ψ systematics observed in elementary collisions [20]. J/ψ measurements at high p_T both in $p + p$ and nuclear collisions may provide additional insights into the basic processes underlying quarkonium production.

This letter reports new measurements by the STAR Collaboration at RHIC of J/ψ production at high transverse momentum in $p + p$ and Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV [21]. The inclusive cross section and semi-inclusive J/ψ-hadron correlations are presented.

TABLE I. Trigger conditions, off-line cuts, and J/ψ signal statistics. E_T is the BEMC trigger threshold. p_{T1} and p_{T2} are the lower bounds for the two electron candidates. BBC (ZDC) means the coincidence of beam-beam counters (zero degree calorimeters). S/B is the ratio of signal to background.

	$p + p$ (2005)	$p + p$ (2006)	Cu + Cu
MB trigger	BBC	BBC	ZDC
E_T (GeV)	>3.5	>5.4	>3.75
Sampled int. lum.	2.8 pb^{-1}	11.3 pb^{-1}	860 μb^{-1}
p_{T1} (GeV/c)	>2.5	>4.0	>3.5
p_{T2} (GeV/c)	>1.2	>1.2	>1.5
J/ψ p_T (GeV/c)	5–8	5–14	5–8
J/ψ counts	32 ± 6	51 ± 10	23 ± 8
S/B	8.0:1	1.9:1	0.7:1

The Cu + Cu data are from the RHIC 2005 run, while the $p + p$ data are from 2005 and 2006. The online trigger, utilizing the STAR Barrel Electromagnetic Calorimeter (BEMC) [22] as well as other trigger detectors, required one BEMC tower with an energy deposition above a given threshold in coincidence with a minimum bias (MB) collision trigger [23]. The online trigger threshold, MB trigger condition, and sampled integrated luminosity for each data set are listed in Table I. In Cu + Cu data, the most central 0–20% and 0–60% of the total hadronic cross section were selected based on the distribution of charged-particle multiplicity within $|\eta| < 0.5$ [23,24].

In this analysis, $J/\psi \rightarrow e^+e^-$ (branching ratio $(B) =$ 5.9%) was reconstructed using the STAR Time Projection Chamber (TPC) [25] and BEMC, with acceptance $|\eta| < 1$ and full azimuthal coverage. Hadron rejection was achieved through the combination of BEMC shower energy, shower shape measured in the embedded Shower-Maximum Detector (SMD), and ionization loss (dE/dx) in the TPC [12,26]. Electron purity is >70% with high efficiency. At moderate p_T, the TPC alone can measure electrons with efficiency >90% and sufficient hadron rejection ($\sim 10^3$) [12,27].

Figure 1 shows dielectron invariant mass distributions for (a) $p + p$ and (b) Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV. The like-sign distribution measures random pair background from Dalitz decays and photon conversions. The J/ψ signal was obtained from a mass window of $2.7 < M_{\mathrm{inv}}^{\mathrm{ee}} < 3.2$ GeV/c^2. Other correlated e^+e^- background is estimated to be less than 5%. Table I lists the offline cuts and J/ψ signal statistics. Different thresholds were used for the two electron candidates, corresponding to different online trigger thresholds.

The J/ψ detection efficiency was calculated by two complementary methods. The first method was to determine the electron trigger efficiency by comparing triggered electron yield to the measured inclusive electron spectrum [12]. The nontriggered electron efficiency depends only on the TPC tracking efficiency, which was determined by embedding simulated electron tracks into real events [23], and dE/dx efficiencies, determined from the distributions in real data [26]. The second method was to simulate J/ψ events in PYTHIA [28], embed them into real events, and reconstruct

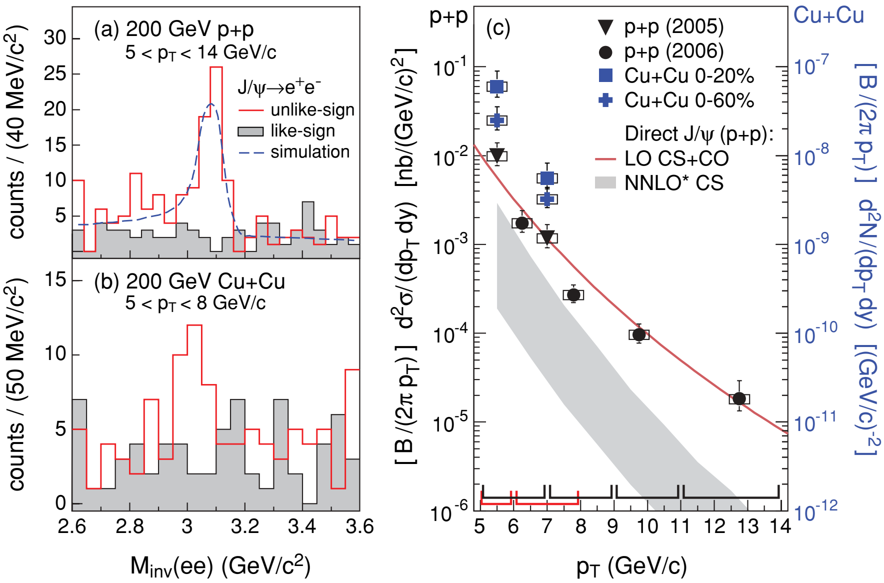

FIG. 1. (Color online) (Left) Dielectron invariant mass distribution in (a) $p+p$ and (b) Cu + Cu collisions, for opposite sign (solid red) and same sign pairs (grey band) from data, and simulated J/ψ peak for $p+p$ (dashed). (Right) J/ψ p_T distributions in $p+p$ and Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV. Horizontal brackets show bin limits. Also shown are perturbative calculations for LO CS + CO (solid line) and NNLO* CS (band) direct yields, without feed-down contributions.

the hybrid event to determine the J/ψ trigger and detection efficiencies. The difference in estimated efficiency between the two methods is $<$10% for all data sets and is included into the systematic uncertainties of the inclusive spectra. This systematic uncertainty is correlated in $p+p$ and Cu + Cu. A log-likelihood method is used to correct the J/ψ efficiency and calculate the yields [29].

Figure 1(c) shows the measured $J/\psi \to e^+e^-$ p_T spectra. The systematic uncertainties are dominated by kinematic cuts, trigger efficiency (9%), and reconstruction efficiency (8%), and are similar and correlated in $p+p$ and Cu + Cu. The normalization uncertainty for the inclusive nonsingly diffractive $p+p$ cross section is 14% [30]. Theoretical calculations shown in the figure are NRQCD from CO and CS transitions for direct J/ψ's in $p+p$ collisions [31] (solid line) and NNLO* CS result [32] (gray band). Neither calculation includes feed-down contributions. The band for NNLO* gives the uncertainty due to scale parameters and the charm quark mass. The CS+CO calculation describes the data well and leaves little room for feed-down from ψ', χ_c, and B. At Tevatron energies, the feed-down contribution from ψ' and χ_c was found to be p_T independent between $5 < p_T < 18$ GeV/c and increases the yield of the directly produced J/ψ's by a factor of ~1.55 [33]. NNLO* CS predicts a steeper p_T dependence.

Proton and pion inclusive production cross sections in high-energy $p+p$ collisions have been found to follow x_T scaling [34–36]: $E\frac{d^3\sigma}{dp^3} = g(x_T)/s^{n/2}$, where $x_T = 2p_T/\sqrt{s}$. In the parton model, n reflects the number of constituents taking an active role in hadron production. Figure 2 shows the x_T distributions of this data and previous J/ψ, pion, and proton data from $p+p$ collisions. The J/ψ data [37–41] cover the range $\sqrt{s} = 30$ GeV to $\sqrt{s} = 1.96$ TeV. The J/ψ exhibits x_T scaling ($n = 5.6 \pm 0.2$) at high p_T, similar to the trend for pions and protons ($n = 6.6 \pm 0.1$) [42,43]. While low p_T J/ψ production originates in a hard process due to the mass scale, subsequent soft processes could cause violation of x_T scaling. At high p_T, the power parameter $n = 5.6 \pm 0.2$ is closer to the predictions from CO and color-evaporation production ($n \simeq 6$) [31,44] and much smaller than that from next-to-next-to leading order (NNLO*) CS production ($n \simeq 8$) [32]. This is also evident from Fig. 1(c).

The nuclear modification factor $R_{AA}(p_T)$ [45], defined as the ratio of the inclusive hadron yield in nuclear collisions to that in $p+p$ collisions scaled by the underlying number of binary nucleon-nucleon collisions, measures medium-induced effects on inclusive particle production. In the absence of such effects, R_{AA} is unity for hard processes.

Figure 3 shows R_{AA} for J/ψ vs. p_T, in 0–20% Cu + Cu collisions from PHENIX [46] and STAR, and 0–60% Cu + Cu from STAR. Cu + Cu and $p+p$ data with $p_T > 5$ GeV/c are from STAR. The R_{AA} systematic uncertainty takes into account the correlated efficiencies of the Cu + Cu and $p+p$ data sets. R_{AA} for J/ψ is seen to increase with increasing p_T. The average of the two STAR 0–20% data points at high-p_T is $R_{AA} = 1.4 \pm 0.4(\text{stat.}) \pm 0.2(\text{syst.})$. Utilizing the

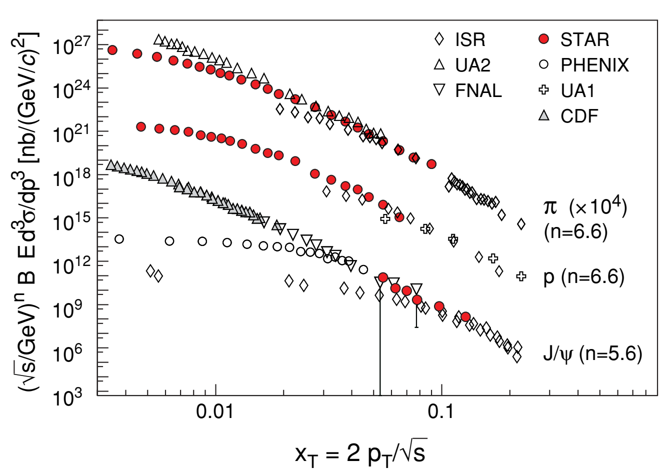

FIG. 2. (Color online) x_T distributions of pions and protons [42, 43,47–49] and J/ψ (CDF [37,38], UA1 [39], PHENIX [40], and ISR [41]).

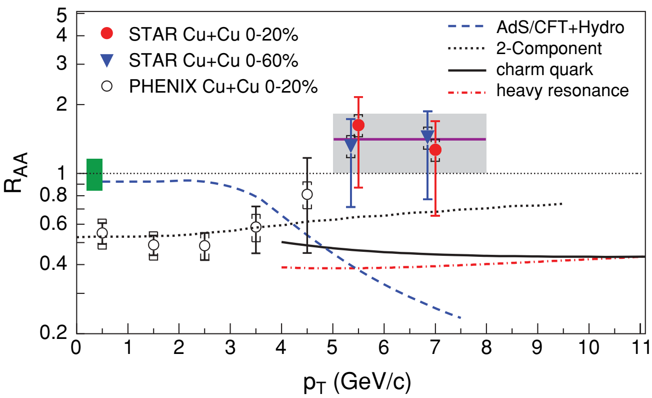

FIG. 3. (Color online) J/ψ R_{AA} vs. p_T. STAR data points have statistical (bars) and systematic (caps) uncertainties. The box about unity on the left shows R_{AA} normalization uncertainty, which is the quadrature sum of $p + p$ normalization and binary collision scaling uncertainties. The solid line and band show the average and uncertainty of the two 0–20% data points. The curves are model calculations described in the text. The uncertainty band of 10% for the dotted curve is not shown.

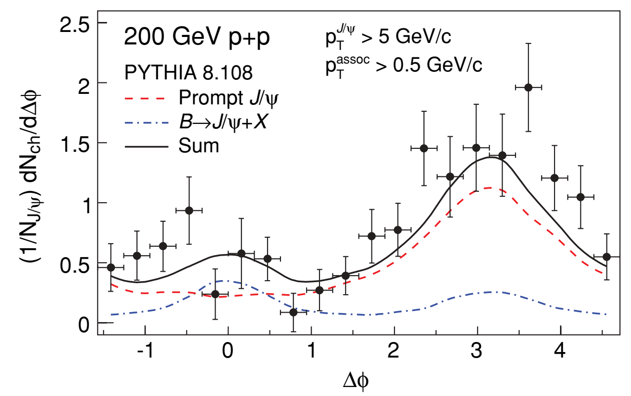

FIG. 4. (Color online) J/ψ-hadron azimuthal correlations. Lines show PYTHIA calculation of prompt (dashed) and B-hadron (dot-dashed) feed-down contributions and their sum (solid).

STAR Cu + Cu and $p + p$ data reported here and PHENIX Cu + Cu data at high p_T [46] gives $R_{AA} = 1.1 \pm 0.3(\text{stat.}) \pm 0.2(\text{syst.})$ for $p_T > 5$ GeV/c. Both results are consistent with unity and differ by two standard deviations from a PHENIX measurement at lower p_T ($R_{AA} = 0.52 \pm 0.05$ [46]).

The $p + p$ data presented here enable the measurement of R_{AA} at substantially higher p_T than that accessible from previous data [40]. A value of R_{AA} <0.6 for $p_T > 5$ GeV/c is excluded at the 97% confidence level. The enhanced p_T range from our data allows comparison to a calculation based on AdS/CFT+hydrodynamics [50], whose prediction is excluded at the 99% confidence level. A notable conclusion from these data is that J/ψ is the only hadron measured in RHIC heavy-ion collisions that does not exhibit significant high-p_T suppression. However, for the J/ψ population reported here, the initial scattered partons have average momentum fraction $x \sim 0.1$ (see also Fig. 2), where initial-state effects such as antishadowing may lead to increasing R_{AA} with increasing p_T.

The dashed curve in Fig. 3 shows the prediction of an AdS/CFT-based calculation, in which the J/ψ is embedded in a hydrodynamic model [50] and the J/ψ dissociation temperature decreases with increasing velocity according to Ref. [18]. Its p_T dependence is at variance with that of the data. The dotted line shows the prediction of a two-component model, including color screening, hadronic phase dissociation, statistical $c\bar{c}$ coalescence at the hadronization transition, J/ψ formation time effects, and B-hadron feed-down [3]. This calculation describes the overall trend of the data.

The other calculations in Fig. 3 provide a comparison to open charm R_{AA}. The solid line is based on the Wicks-Horowitz-Djordjevic-Gyulassy model for charm quark energy loss, with assumed medium gluon density $dN_g/dy = 254$ for 0–20% Cu + Cu [51]. The dash-dotted line shows a generalized Lotka-Volterra model calculation for D-meson energy loss, with $dN_g/dy = 275$ [16]. Both models, which correctly describe heavy-flavor suppression in Au + Au collisions, predict charm meson suppression of a factor ∼2 at $p_T > 5$ GeV/c. This is in contrast to the J/ψ R_{AA}. This comparison suggests that high-p_T J/ψ production does not proceed dominantly via a channel carrying color. However, other effects [3,52] may compensate for the predicted loss in this p_T range.

Figure 4 shows the azimuthal correlation between high-p_T J/ψ ($p_T > 5$ GeV/c) and charged hadrons with $p_T > 0.5$ GeV/c in 200 GeV $p + p$ collisions. The J/ψ mass window is narrowed to 2.9–3.2 GeV/c^2 to increase the S/B ratio. There is no significant correlated yield in the near-side ($\Delta\phi \sim 0$), in contrast to dihadron correlation measurements [53]. The lines show the result of a PYTHIA calculation [28], which exhibits a near-side correlation due dominantly to $B \to J/\psi + X$. A χ^2 fit to the data of the summed distribution (directly produced J/ψ, feed-down from χ_c, $\psi(2S)$, and B hadron) gives a contribution from B-hadron feed-down to inclusive J/ψ production of 13% ± 5% at $p_T > 5$ GeV/c.

In summary, we report new measurements of J/ψ production in $\sqrt{s} = 200$ GeV $p + p$ and Cu + Cu collisions at high p_T ($p_T > 5$ GeV/c) at RHIC. The J/ψ inclusive cross section was found to obey x_T scaling for $p_T \gtrsim 5$ GeV/c, in contrast to lower p_T J/ψ production. The J/ψ nuclear modification factor R_{AA} in Cu + Cu increases from low to high p_T and is consistent with no J/ψ suppression for $p_T > 5$ GeV/c, in contrast to the prediction from a theoretical model of quarkonium dissociation in a strongly coupled liquid using an AdS/CFT approach. The two-component model with finite J/ψ formation time describe the increasing trend of the J/ψ R_{AA}. Based on the measurement of azimuthal correlations and the comparison to model calculations, we estimate the fraction of J/ψ from B-hadron decay to be 13 ± 5% at $p_T > 5$ GeV/c in $p + p$ collisions.

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