Suppression of Upsilon Production in d+Au and Au+Au Collisions at √s_{NN} = 200 GeV


(START Collaboration)
We report measurements of $\Upsilon$ meson production in $p+p$, $d+Au$, and $Au+Au$ collisions using the STAR detector at RHIC. We compare the $\Upsilon$ yield to the measured cross section in $p+p$ collisions in order to quantify any modifications of the yield in cold nuclear matter using $d+Au$ data and in hot nuclear matter using $Au+Au$ data separated into three centrality classes. Our $p+p$ measurement is based on three times the statistics of our previous results. We obtain a nuclear modification factor...
in $d$+Au collisions of $R_{dAA} = 0.67 \pm 0.12$(stat.) $\pm 0.04$(sys.) $\pm 0.08$(p+p sys.). A comparison with models including shadowing and initial state parton energy loss indicates the presence of additional cold-nuclear matter suppression. In the top 10% most-central Au+Au collisions, we measure a nuclear modification factor of $R_{AA} = 0.36 \pm 0.09$(stat.) $\pm 0.01$(sys.) $\pm 0.04$(p+p sys.), which is a larger suppression factor than that seen in cold nuclear matter. Our results are consistent with complete suppression of excited-state $\Upsilon$ mesons in Au+Au collisions. The additional suppression in Au+Au is consistent with the level expected in model calculations that include the presence of a hot, deconfined Quark-Gluon Plasma. However, understanding the effects seen in $d$+Au is still needed before fully interpreting the Au+Au results.

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INTRODUCTION

In the study of the properties of the Quark-Gluon Plasma (QGP) an extensive effort has been devoted to measuring quarkonium yields since these have been predicted to be sensitive to color deconfinement [1]. Studies have mainly focused on charmonium, but with the high collision energies available at RHIC and LHC we can now study bottomonium in hot nuclear matter with sufficient statistics. For a recent review of quarkonium in-medium, see e.g. Ref. [2], Sec. 5. One prediction is that excited quarkonium states are expected to dissociate at temperatures near that of the crossover to the QGP phase, $T_c \approx 175$ MeV. The more tightly bound ground states are expected to dissociate at even higher temperatures. This leads to a sequential suppression pattern with increasing temperature [3]. The binding energy of the $\Upsilon(2S)$ state (~540 MeV) is about half that of the $\Upsilon(1S)$ state (~1.10 GeV); the $\Upsilon(3S)$ is still more weakly bound at ~200 MeV. Recent studies take into account not only the Debye screening effect on the heavy quark potential but also an imaginary part of the potential which modifies the widths of the various quarkonia states (e.g. [4–7]). In Ref. [5] it is estimated that the $\Upsilon(2S)$ state will melt at a temperature of $T \approx 250$ MeV, whereas the ground state $\Upsilon(1S)$ will melt at temperatures near $T \approx 450$ MeV. We focus here on the measurement of bottomonium mesons in collisions at $\sqrt{s_{NN}}=200$ GeV. An observation of suppression in the bottomonium sector in hot nuclear matter is important for two reasons. First, it would be evidence for color deconfinement in the produced matter since the aforementioned effects are all ultimately based on studies of the high temperature phase of lattice QCD where color is an active degree of freedom. Second, bottomonium suppression provides a way to estimate model-dependent bounds on the temperature with the bounds depending on the particular suppression pattern seen.

The cross section for bottomonium production is smaller than that of charmonium [8–10] making the experimental study of $\Upsilon$ production challenging. However, the theoretical interpretation of bottomonium suppression is less complicated than that of charmonium for several reasons. While charmonium production at RHIC and higher energies can be affected by the statistical re-

EXPERIMENTAL METHODS

The main detectors used are the STAR Time Projection Chamber (TPC) [26] for tracking and the STAR
Barrel Electro-Magnetic Calorimeter (EMC) [27] for triggering and particle identification. The starting point is the STAR Υ trigger whose main components are a fast hardware Level-0 (L0) trigger, which fires when a tower in the EMC has energy $E_{\text{L0-EMC}} \geq 4.2$ GeV, and a software Level-2 (L2) trigger, which requires the presence of two high-energy clusters in the EMC ($>4.5$ GeV and $>3.0$ GeV). The cluster pair must also have an opening angle greater than $90^\circ$ and an invariant mass above 5 GeV/$c^2$ (6.5 GeV/$c^2$) in $p+p$ ($d+Au$). Note that energy measured at the triggering level is partially calibrated leading to small but random biases. Hence, triggering thresholds are not precise in energy. The Υ trigger is required to be in coincidence with the STAR minimum bias trigger. For $p+p$ collisions the minimum bias trigger is based on the STAR Beam-Beam Counters, while for $d+Au$ and Au+Au it is based on the STAR Zero-Degree Calorimeters (ZDC) and the Vertex-Position Detectors (VPD). The L0-L2 combination was used for the $d+Au$ data in 2008 and for $p+p$ data in 2009. In the Au+Au 2010 run an upgrade to the STAR data acquisition system allowed the processing of all the L0 triggers above the $E_{\text{L0-EMC}} = 4.2$ GeV threshold, thus removing the need for a Level-2 trigger.

Some of the key components common to all these analyses are the tracking, matching between TPC tracks and EMC L0 and L2 clusters, and electron identification techniques. The main differences between the three datasets are summarized as follows. For Au+Au collisions we use the charged particle multiplicity measured in the TPC in order to determine the centrality of the collision. Using a Glauber model simulation, the multiplicity classes in the event are used to estimate the average number of participants ($N_{\text{part}}$) and number of binary collisions ($N_{\text{bin}}$). The trigger, tracking, and electron identification efficiencies in the Au+Au case were studied as a function of centrality. The presence of the underlying Au+Au event background increases the energy measured in the calorimeter towers and results in a slight increase in the trigger efficiency with increasing $N_{\text{part}}$ (more central events). Similarly, the increase in the track density in the TPC results in a slight decrease in the tracking efficiency with increasing $N_{\text{part}}$. The combined acceptance times efficiency for detecting an upsilon at mid-rapidity taking into account both effects was found to vary from 21% in peripheral collisions to 16% in central events. We used the specific ionization of the tracks in the TPC gas ($dE/dx$) for electron identification. In addition, the projection of the track onto the location of the EMC shower maximum position was required to match the measured EMC cluster position. Once a track was matched to a calorimeter cluster, the ratio of the energy of the cluster to the TPC momentum ($E/p$) was also used for electron identification.

The cuts used in these analyses were chosen such that the tracking and electron identification efficiencies would be the same across the three datasets, allowing the systematic uncertainties to approximately cancel in the measurement of $R_{AA}$. For further detail, the techniques used in these Υ measurements were described extensively for our previous $p+p$ measurement [10] based on a 7.9 pb$^{-1}$ dataset.

**RESULTS AND DISCUSSION**

Figure 1 shows the invariant mass distributions of electron pairs for $p+p$ (top) and $d+Au$ (bottom) in the kinematic region $|y_\Upsilon| < 0.5$. Unlike-sign pairs are shown as red filled circles and like-sign pairs as hollow blue circles.
The data are fit with a parameterization consisting of the combinatorial background (dashed blue line), the physics background from Drell-Yan and $b\bar{b}$ pairs (dotted-dashed green line), and the $\Upsilon$ contribution (solid red line). The shape of the Drell-Yan continuum is obtained via a perturbative QCD (pQCD) next-to-leading order (NLO) calculation from Vogt[28]. PYTHIA 8 was used to calculate the shape of the $b\bar{b}$ contribution [29]. We model each of the $\Upsilon$ states with a Crystal Ball function [30], which incorporates detector resolution and losses from bremsstrahlung in the detector material.

The fit is done to the unlike and like-sign data simultaneously. The fit to the combinatorial background component extracted from the like-sign data is shared by the functional form used to parameterize the unlike-sign data. In the usual like-sign subtraction procedure some information would be lost. In contrast, by performing a simultaneous fit to both the like-sign and unlike-sign signals we optimize the statistical power of our data. The $L2$ trigger condition has the effect of cutting off the lower invariant masses. This cut-off shape is parameterized in the fits using an error function.

We integrate the unlike-sign invariant mass distribution in the region $8.0 - 11$ GeV/$c^2$ and subtract from the data the fit to the combinatorial, Drell-Yan, and $b\bar{b}$ background components in order to obtain the yield of $\Upsilon(1S+2S+3S)$. After accounting for efficiencies and sampled luminosity, we calculate a production cross section of: $B_{ee} \times \frac{d\sigma}{dy}|_{y<0.5} = 86 \pm 11$ (stat. + fit) $^{+18}_{-16}$ pb. Our result is consistent with our previous measurement of $114 \pm 38^{+23}_{-14}$ pb [10], though with noticeably enhanced statistics.

The gray band in Fig. 1b shows the expected signal from the $p+p$ data scaled by the number of binary collisions. Due to differences in detector occupancy, material budget, and detector calibrations the width of the $\Upsilon$ signal differs between systems and centralities. This can be seen in the line shapes for the $\Upsilon$ states in panels a) and b) of Fig. 1. The comparison of the gray band with the $d+Au$ data in panel b) indicate a suppression of $\Upsilon$ production with respect to binary-collision scaling.

A similar procedure is followed for the region $0.5 < |y_T| < 1$ in $p+p$ collisions. We combine the results to obtain the differential cross section: $B_{ee} \times \frac{d\sigma}{dy}|_{|y|<1} = 85 \pm 9$ (stat. + fit) $^{+18}_{-16}$ pb. In $d+Au$ collisions, we analyze the yield separately in the regions $-1 < y_T < -0.5$ and $0.5 < y_T < 1$ because the $d+Au$ system is not symmetric about $y = 0$. Hence, averaging between forward and reverse rapidities is not warranted as it is in $p+p$.

We extract the $\Upsilon(1S)$ yield directly by integrating over a narrower mass window (8.8-9.8 GeV/$c^2$). This mass window was chosen due to its high acceptance rate for $\Upsilon(1S)$ and its high rejection rate for the excited states. To account for sensitivity to the shape of the $\Upsilon$ signal, we varied the lineshape and recalculated both efficiency and purity. Those variations were taken into account as additional systematics when quoting $\Upsilon(1S)$ results.

Figure 2a shows the extracted $\Upsilon(1S+2S+3S)$ cross-sec-
tion for \( p+p \) and \( d+Au \) as a function of rapidity. The \( p+p \) measurements are shown as blue stars and the \( d+Au \) measurements as red circles. The \( p+p \) result in the region \( 0.5 < |y_T| < 1.0 \) is displayed as a star at \( y = 0.75 \) and also as a hollow star at \( y = -0.75 \) to illustrate that the latter is not an independent measurement. The data from PHENIX at forward rapidity for \( p+p \) (filled blue diamonds) and \( d+Au \) (hollow red diamonds) are also shown [31].

The cross sections in \( p+p \) are compared to a NLO pQCD calculation of \( \Upsilon \) production in the Color Evaporation Model (CEM) [20], which is consistent with our data within the systematic uncertainty. The same calculation is performed for \( d+Au \) including shadowing effects [21]. The EPS09 set of nuclear Parton Distribution Functions (nPDF) [32] were used. The model is in agreement with our data except for the mid-rapidity point which is lower than the prediction.

To focus on expected shadowing effects, we show in Fig. 2b the nuclear modification factor \( R_{dAu} \), as a function of rapidity. The nuclear modification factor is defined in nucleus-nucleus collisions as

\[
R_{AA} = \frac{1}{\sigma_{p+p}} \times \frac{1}{\langle N_{bin} \rangle} \times \frac{B_{ee} \times \left( \frac{d\sigma_{AA}}{dy} \right)^\Upsilon}{B_{ee} \times \left( \frac{d\sigma_{pp}}{dy} \right)^\Upsilon},
\]

where the first factor accounts for the difference in inelastic cross section in \( p+p \) to \( d+Au \) or \( Au+Au \) collisions. The second factor accounts for the average number of nucleon collisions in a \( d+Au \) or \( Au+Au \) event. The third factor accounts for the measured \( \Upsilon \) production in \( p+p \), \( d+Au \) or \( Au+Au \).

The present data (red stars) are compared to CEM calculations with the uncertainty from the EPS09 nPDF shown as the shaded region. Note that this prediction for \( R_{dAu} \), which includes modification of the nuclear PDFs but does not include absorption, implies a modification factor of \( R_{dAu} \approx 1.1 \). A calculation in Ref. [22] explored various nPDFs (EKS98, EPS08, and nDSg) and also gives \( R_{dAu} \) values above 1 with enhancements in the range of 5-20%. The models are in agreement with the data except in the \( y \sim 0 \) region. An additional effect which can suppress the \( \Upsilon \) yield is initial-state parton energy loss. A calculation by Arleo and Peigne [23] incorporating this effect is shown as the dashed line. The calculation for a combination of energy loss and shadowing using EPS09 is shown as the dashed-dotted line. The energy-loss model is also in agreement with the data except for the midrapidity point. The model from [23] does not include absorption from interactions with spectator nucleons. However, those effects only play a role in the midrapidity region \( y \lesssim 1.2 \), where the \( \Upsilon \) mesons would be closer to the frame of the \( Au \) spectators. Therefore, the suppression at mid rapidity is indicative of effects beyond shadowing, initial-state parton energy loss, or absorption by spectator nucleons.

We compare our measurements with results from E772 at \( \sqrt{s_{NN}} = 40 \text{ GeV} \), where suppression of the \( \Upsilon \) states in \( p+A \) was observed. This is illustrated in Fig. 3a, which shows the ratio of the cross section in \( d+Au \) collisions for STAR \((p+A \text{ for E772}) \) to that of \( p+p \) collisions normalized by the mass number \( A \). E772 plotted a ratio...
of extracted cross sections normalized by the data where the proton beam hit a liquid deuterium target \((A = 2)\). Assuming that the cross section scales as \(\sigma_{pp} = A^\alpha \sigma_{pp}\), and using their deuterium result as the baseline, the solid line shows that the ratio should scale as \((A/2)\alpha^{-1}\). Our measurement in \(d+Au\) for the \(\Upsilon(1S)\) state (red star) is consistent with the fit to the E772 data, shown as hollow blue circles for \(\Upsilon(1S)\) and hollow green squares for \(\Upsilon(2S+3S)\). Our results cover the rapidity range \(|y| < 1\) whereas the E772 measurements were in the forward region \(0 < y < 1.05\). To better compare our rapidity coverage, we plot the \(\alpha\) value as a function of \(x_F\) in Fig. 3b.

The larger suppression we observe at mid-rapidity is also consistent with the larger suppression seen in E772 for \(x_F \sim 0\). We next turn to the measurements in \(Au+Au\) collisions. We show the \(Au+Au\) invariant mass spectra in 3 centrality bins: 30-60\% (Fig. 4a), 10-30\% (Fig. 4b), and 0-10\% (Fig. 4c). As in Fig. 1 we show the fits including, in succession, combinatorial background (dashed blue line), the physics background from Drell-Yan and \(b\bar{b}\) pairs (dot-dashed green line), and the \(\Upsilon\) contribution (solid red line). The absence of the L2 trigger in the \(Au+Au\) dataset removes the cut-off effect. One can therefore see the background, dominated by the combinatorial component, rising at lower invariant mass. The gray bands in the \(Au+Au\) figure show the expected signal from the \(p+p\) data scaled by the number of binary collisions. There is a clear suppression of the expected yield in \(Au+Au\) collisions.

This suppression is quantified in Fig. 5, which shows the nuclear modification factor, \(R_{AA}\), plotted as a function of \(N_{\text{part}}\) with the 0-10\% most-central collisions corresponding to \(\langle N_{\text{part}} \rangle = 326 \pm 4\). Figure 5a shows the data for all three states in the rapidity range \(|y| < 1\), while Fig. 5b shows the narrower \(|y| < 0.5\) range. Fig. 5c shows \(R_{AA}\) and \(R_{dAu}\) for the ground state \(\Upsilon(1S)\) in the range \(|y| < 1.0\). The data show that bottomonia are suppressed in \(d+Au\) and in \(Au+Au\) collisions. For \(d+Au\) collisions, we find \(R_{dAu}(1S+2S+3S) = 0.67 \pm 0.12 \pm 0.07 (d+Au \text{ stat.}) \pm 0.04 (d+Au \text{ syst.}) \pm 0.07 (p+p \text{ syst.})\) in the range \(|y| < 1\). We use a total inelastic cross section for \(p+p\) collisions of 42 mb, for \(d+Au\) collisions of 2.2 b, and \(\langle N_{\text{hn}} \rangle = 7.5 \pm 0.4\) for calculating \(R_{dAu}\). In the same rapidity range and for the 0-10\% most-central bin from \(Au+Au\) collisions, we find \(R_{AA}(1S+2S+3S) = 0.36 \pm 0.09 \pm 0.04 (Au+Au \text{ stat.}) \pm 0.01 (Au+Au \text{ syst.}) \pm 0.04 (p+p \text{ syst.})\) which is \(\approx 3\sigma\) lower than the suppression seen in \(d+Au\).

Similar suppression is found by CMS in \(Pb+Pb\) collisions [34, 35]. In the narrower rapidity range (Fig. 5b), we see an indication of a lower \(R_{dAu}\) as discussed earlier. Our data and the E772 data show a larger suppression at \(y \sim 0\) or \(x_F \sim 0\) than that expected from shadowing, the latter staying approximately constant up to central \(Au+Au\) collisions.

FIG. 4: (Color online) Invariant mass distributions of electron pairs in the region \(|y| < 1.0\) for the centrality selections 30-60\% (a), 10-30\% (b), and 0-10\% (c). Unlike-sign pairs are shown as filled red circles and like-sign pairs as hollow blue circles. Fits are described in the text. The gray band shows the expected signal assuming scaling of the \(p+p\) yield with the number of binary collisions.
collisions. This suggests that suppression in $d+Au$ in this kinematic range needs to be understood before interpreting the suppression in Au+Au.

For $d+Au$ collisions we find $R_{dAu}(1S) = 0.77 \pm 0.14$ ($d+Au$ stat.) $\pm 0.08$ ($p+p$ stat.) $\pm 0.04$ ($d+Au$ syst.) $\pm 0.09$ ($p+p$ syst.) in the range $|y| < 1$. For the 0-10% most-central collisions we find $R_{AA}(1S) = 0.44 \pm 0.09$ ($Au+Au$ stat.) $\pm 0.05$ ($p+p$ stat.) $\pm 0.02$ ($Au+Au$ syst.) $\pm 0.05$ ($p+p$ syst.). The ratio of $R_{AA}(1S)$ to $R_{AA}(1S+2S+3S)$ is consistent with an $R_{AA}(2S+3S)$ approximately equal to zero, as can be seen by examining the mass range 10-11 GeV/$c^2$ in Fig. 4. We observe the nuclear modification factor for the $\Upsilon(1S)$ in $d+Au$ to be $\approx 3\sigma$ from unity and consistent with unity in peripheral $Au+Au$ events, whereas we observe a suppression of a factor of $\approx 2$ in the most-central events of $\approx 4.5\sigma$ significance.

Our data are also compared to model calculations incorporating hot-nuclear-matter effects for $Au+Au$ [24, 25]. These aim to incorporate lattice-QCD results pertinent to screening and broadening of bottomonium and to model the dynamical propagation of the $\Upsilon$ meson in the colored medium. Both models are in agreement with the level of suppression seen in $Au+Au$. The model proposed by Emerick, Zhao, and Rapp (EZR), Ref. [25], includes possible CNM effects, modeled as an absorption cross section of up to 3 mb which can account for a value of $R_{AA}$ as low as 0.7. In this model the additional suppression to bring $R_{AA}$ down to $\approx 0.5$ is due to hot-nuclear-matter effects. The initial temperature used in the EZR model is 330 MeV (with a formation time of 0.6 fm/$c$). The temperatures of the QGP needed in Strickland’s model, Ref. [24], are in the range 428 – 442 MeV. However, it should be noted that this model does not include any CNM effects.

With two possible sources of suppression, cold matter and QGP effects, we used a Monte Carlo pseudoexperiment to compare our results to different possible sources of suppression. We investigated four possible scenarios: 1) No suppression compared to $p+p$; 2) Suppression due to cold-nuclear-matter effects only; 3) QGP suppression only; 4) Suppression from both CNM and QGP effects. We simulated $\Upsilon$ production in $p+p$, $d+Au$, and $Au+Au$ collisions via a Poisson generator. CNM effects were included via the suppression parametrization used by E772 [18] and presented in Fig. 3a. We used the predictions from the Strickland model [24] to estimate suppression from QGP effects. For this pseudoexperiment we assumed a flat prior based on the allowed $R_{AA}$ given in Strickland-Bazow [24], depicted as the band for this calculation in Fig. 5, stemming from the choice of $1 < 4\pi\eta/S < 3$.

A summary of the pseudoexperiment results is shown in Fig. 6. Panel (a) shows our result for $R_{dAu}$ in the range $|y| < 1.0$ compared to scenarios 1) and 2), shown as the solid line and dotted histogram, respectively. The 'no-

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**FIG. 5**: (Color online) Nuclear modification factor for $\Upsilon(1S+2S+3S)$ for both $|y| < 1.0$ (a) and $|y| < 0.5$ (b) and $\Upsilon(1S)$ for $|y| < 1.0$ (c) in $d+Au$ (green square) and Au+Au (black circles) collisions as a function of $N_{part}$. The boxes around unity show the statistical (shaded) and systematic (filled) uncertainty from the $p+p$ measurement. The data are compared to model calculations from Refs. [24, 25].
We are able to exclude scenarios 1) and 2) at a $\sim 4.2\sigma$ confidence level. Furthermore, we can exclude scenario 3) where there is no CNM suppression at slightly above a $4.2\sigma$ confidence level by examining the $d+Au$ datapoint. Finally, we see that hypothesis 4) (dot-dashed curve), including both hot and cold nuclear effects, is consistent with our measurements.

We repeated this procedure for the rapidity range $|y| < 0.5$. The results are shown in Figs. 6 (c) and (d). In the midrapidity range we find a larger amount of suppression in $d+Au$ than what we observe in the range $|y| < 1.0$. Furthermore, $R_{dAu}$ is comparable to $R_{AA}$ in 0-10% for this rapidity range. This effect is not predicted by any of the models.

The suppression effects seen in $d+Au$, which are not explained by the models discussed here, still need to be understood before the $Au+Au$ results can be fully interpreted.

**CONCLUSIONS**

In conclusion we studied $\Upsilon(1S+2S+3S)$ production in $p+p$, $d+Au$, and $Au+Au$ collisions at $\sqrt{s} = 200$ GeV. We measured the cross section in $p+p$ collisions to be $d\sigma/dy_{|y|<1} = 85 \pm 9 \text{(stat. + fit)}^{+18}_{-16} \text{(syst.)}$ pb and find it to be consistent within errors with NLO calculations. The cross section in $d+Au$ collisions is found to be $d\sigma/dy_{|y|<1} = 22 \pm 3 \text{(stat. + fit)}^{+3}_{-4} \text{(syst.)}$ nb. We obtain a nuclear modification factor in this rapidity region $(|y| < 1)$ of $R_{dAu} = 0.67 \pm 0.12 \text{(stat.)} \pm 0.04 \text{(syst.)} \pm 0.08 (p+p \text{ syst.})$. Models of $\Upsilon$ production in cold nuclear matter, which include shadowing and initial-state partonic energy loss, over-predict the cross-sections we observe in our $d+Au$ data. To account for the reduction we observe, which is consistent with previous $\Upsilon$ measurements from $p+\bar{p}$ fixed-target experiments [18], additional cold-nuclear suppression is therefore needed. We measured the $\Upsilon(1S+2S+3S)$ nuclear modification factor in $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV as a function of centrality. In the range $|y| < 1$ and in 0-10% most-central collisions we find $R_{AA}(1S + 2S + 3S) = 0.36 \pm 0.09$ (stat.) $\pm 0.01$ (syst.) $\pm 0.04 (p+p \text{ syst.})$, indicating additional $\Upsilon$ suppression in hot nuclear matter compared to cold nuclear matter. Calculations of the centrality dependence of $\Upsilon R_{AA}$ using models based on lattice QCD calculations of bottomonium melting in a hot medium are found to be consistent with our data. Therefore, the suppression seen in central $Au+Au$ collisions is indicative of the presence of deconfined matter in heavy-ion collisions. Nevertheless, we need a better understanding of the suppression seen in $d+Au$ before any definitive statements about deconfinement can be made.
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