\textbf{Y Production in Heavy-Ion Collisions from the STAR Experiment}

Zaochen Ye for the STAR Collaboration$^1$

$^1$University of Illinois at Chicago, Chicago, Illinois, 60607, USA

In these proceedings, we present recent results of \( Y \) measurements in heavy-ion collisions from the STAR experiment at RHIC. Nuclear modification factors \( (R_{AA}) \) for \( Y(1S) \) and \( Y(1S+2S+3S) \) in U+U collisions at \( \sqrt{s_{NN}} = 193 \text{ GeV} \) are measured through the di-electron channel and compared to those in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) and Pb+Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \). The ratio between the \( Y(2S+3S) \) and \( Y(1S) \) yields in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) is measured in the di-muon channel and compared to those in p+p collisions and in Pb+Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \). Prospects for future \( Y \) measurements with the STAR experiment are also discussed.

Keywords: Quark-Gluon Plasma (QGP), Color screening, Dissociation, Suppression, Upsilon, STAR

I. INTRODUCTION

Quark-Gluon Plasma (QGP), a new state of matter where quarks and gluons are de-confined, is believed to have existed up to a few milliseconds after the Big Bang. Quarkonia could dissociate in the QGP due to color screening of quark-antiquark potential by the surrounding partons in the medium \cite{1}, which was suggested as a signature of QGP formation in heavy-ion collisions. Moreover, different quarkonium states may dissociate at different temperatures depending on their binding energies \cite{2,4}. This so-called “sequential melting” phenomenon could be used to deduce the temperature of the QGP. However, other effects, such as regeneration from deconfined heavy quark-antiquark pairs, shadowing and antishadowing of nuclear parton distribution functions and co-mover absorption, need to be taken into account when interpreting experimental results. Compared to charmonium production at RHIC energies, bottomonium production has several advantages: 1) the regeneration contribution is negligible due to the much smaller \( b \bar{b} \) production cross section \( (\sigma_{bb} \approx 1.87^{+0.99}_{-0.67} \mu b) \) compared to \( \sigma_{c\bar{c}} \approx 550 - 1400 \mu b \) \cite{5}; 2) the cross section for inelastic collisions of \( Y \) with hadrons is very small, hence the co-mover absorption is predicted to be minimal \cite{7}; 3) the suppression of \( Y \) production due to cold-nuclear-matter (CNM) effects has been measured to be smaller than that for \( J/\psi \) reported by NA50 \cite{8}. Thus, the \( Y \) family is expected to be a cleaner and more direct probe of the QGP, and the corresponding color deconfinement effects.

\( Y \) production has been studied via the di-electron decay channel at STAR in different collision systems, including p+p, d+Au and Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) \cite{9}. The latest \( Y \) measurement via the di-electron channel in U+U collisions at \( \sqrt{s_{NN}} = 193 \text{ GeV} \) allows a study of \( Y \) suppression in a new heavy-ion collision system \cite{10}. Since 2014, a new detector, the Muon Telescope Detector (MTD), has been fully installed and taking data, allowing measurements of \( Y \) production via the di-muon channel. Compared to the di-electron channel, the di-muon channel has better sensitivity to different Upsilon states due to the reduced bremsstrahlung radiation.

II. \( Y_{R_AA} \) VIA THE DI-ELECTRON CHANNEL IN U+U AND AU+AU COLLISIONS

\( Y \rightarrow e^+e^- \) decays were reconstructed using the Time Projection Chamber (TPC) and Barrel Electromagnetic Calorimeter (BEMC) with full azimuthal coverage over the pseudorapidity range \( |\eta| < 1 \). Electron identification (eID) was achieved by measuring the ionization energy loss \( (dE/dx) \) and track momentum by the TPC, as well as the energy deposition in the BEMC. In addition, shower profiles measured by the Barrel Shower Maximum Detector (BSMD) were used in Au+Au collisions to further suppress hadron contamination. The identified electron and positron candidates are paired to reconstruct the invariant mass of the \( Y \) candidates.

\begin{figure}[h]
    \centering
    \includegraphics[width=\textwidth]{fig1.png}
    \caption{(Color online) Reconstructed invariant mass distribution of \( Y \) candidates \cite{10}. Fits to the combinatorial background, \( bb \) and Drell-Yan contributions and to the \( Y \) peaks are plotted as dash-dotted, dashed and solid lines respectively. The fitted contributions of the individual \( Y(1S), Y(2S) \) and \( Y(3S) \) states are shown as dotted lines.}
\end{figure}

The \( Y(1S+2S+3S) \) and \( Y(1S) \) \( R_{AA} \) in U+U collisions at \( \sqrt{s_{NN}} = 193 \text{ GeV} \) were calculated by dividing the invariant \( Y \) yields in U+U collisions by those in p+p collisions scaled by the number of binary nucleon-nucleon collisions \( (N_{\text{coll}}) \) \cite{10}. They are shown as a function of the number of participating nucleons \( (N_{\text{part}}) \) in Fig. 2 and compared to those in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) within \( |y| < 1 \).
from STAR [9], within \(|y| < 0.35\) from PHENIX [11], and 

in Pb + Pb collisions at \(\sqrt{s_{NN}} = 2.76\) TeV within \(|y| < 2.4\) 

from CMS [12]. \(\Upsilon(1S + 2S + 3S)\) suppression becomes signif-

icant only in the most central collisions at RHIC energies. After combining U+U and Au+Au results, we find that 

\[ R_{AA}^{\Upsilon(1S)} = 0.63 \pm 0.16 \pm 0.09, \]

which suggests that \(\Upsilon(1S)\) is significantly but not completely suppressed in central heavy-ion collisions at top RHIC energies. While both the RHIC and LHC data show suppression in the most central bins, \(R_{AA}^{\Upsilon(1S)}\) is slightly, although not significantly, higher in semi-central collisions at RHIC than that at the LHC.

In Fig. 3 we compare STAR measurements to different the-

oretical models [13-15]. An important source of uncertainty in model calculations for quarkonium dissociation stems from 

the unknown nature of the in-medium potential between the 

quark-antiquark pairs. Two limiting cases that are often used 

are the internal-energy-based heavy quark potential corre-

sponding to a strongly bound scenario (SBS), and the free-

energy-based potential corresponding to a more weakly bound 

scenario (WBS) [16]. The model of Emerick, Zhao and 

Rapp [13] includes CNM effects, dissociation of bottom-

onia in the hot medium (assuming a temperature \(T = 330\) 

MeV) and regeneration for both the SBS and WBS scenarios. 

The Strickland-Bazow model [14] calculates dissociation in 

the medium in both a free-energy-based “model A” and an 

internal-energy-based “model B”, with an initial central tem-

perature \(428 < T < 442\) MeV. The model of Liu et al. [15] 

uses an internal-energy-based potential and an input temperature \(T = 340\) MeV. In Fig. 3 we show all three internal-energy-

based models together with the “model A” of Ref. [14] as 

an example for the free-energy-based models. The compar-

ison between data and theoretical predictions suggests that 

internal-energy-based models generally describe RHIC data 

better than the free-energy-based models for the \(\Upsilon(1S)\).

Figure 3 shows the \(R_{AA}\) versus \(N_{\text{part}}\) in \(\sqrt{s_{NN}} = 193\) GeV U+U collisions (solid circles) [10] and 

200 GeV Au+Au collisions (solid squares), compared to different 

models [13-15] described in the text. Each point is plotted at the 

center of its bin. Centrality integrated (0-60\%) U+U and Au+Au 

data are also shown as open circles and squares, respectively.

FIG. 3. (Color online) \(\Upsilon(1S + 2S + 3S)\) (a) and \(\Upsilon(1S)\) (b) \(R_{AA}\) vs. \(N_{\text{part}}\) in \(\sqrt{s_{NN}} = 193\) GeV U+U collisions (solid circles) [10] and 

200 GeV Au+Au collisions (solid squares), compared to different 

models [13-15] described in the text. Each point is plotted at the 

center of its bin. Centrality integrated (0-60\%) U+U and Au+Au 

data are also shown as open circles and squares, respectively.
 Binding energy (GeV)

0 0.2 0.4 0.6 0.8 1 1.2 1.4

AA

0 0.2 0.4 0.6 0.8 1 1.2 1.4

=200 GeV

NN

s

Au+Au =193 GeV

NN

s

U+U

0-10%

ϒ

0-10%

ϒ

0-60%

ϒ

0-60%

ϒ

>5 GeV/c 0-10%

T

pψ   J/

<6 GeV/c 0-60%

T

5<pψ   J/

common norm. syst.

(1S)ϒ(2S+3S)ϒ

ψ

J/

STAR Quarkonia |y|<1

III. Υ(2S+3S)/Υ(1S) VIA THE DI-MUON CHANNEL IN Au+Au COLLISIONS

The new STAR detector MTD was fully installed in 2014, allowing the Υ reconstruction via the di-muon channel for the first time at STAR. Muon candidates are identified using the TPC and MTD. Charged tracks are required to have $p_T$ above 1.5 GeV/c, and the differences between the measured and expected energy losses for muons are within $[-1\sigma, +3\sigma]$ where $\sigma$ is the $dE/dx$ resolution of the TPC. Tracks also need to geometrically match to the hits measured by the MTD, which covers about 45% in azimuth within $|\eta|<0.5$. Cuts are applied to the residuals between projected track positions and MTD hit positions along both $z$ and $\phi$ directions. In addition, the differences between the measured and expected time-of-flight for tracks from primary vertices to the MTD do not exceed 0.46 ns for accepted muon candidates. The identified muon candidates are then paired to reconstruct the invariant mass of the $\Upsilon$ candidates.

U+U collisions are consistent with the Au+Au measurements as well as with the expectations from the sequential melting hypothesis. In the Au+Au data, the $\Upsilon(1S)$ measurement is denoted by a blue square, while for the $\Upsilon(2S+3S)$ states, a blue horizontal line indicates a 95% upper confidence boundary. The black diamonds mark the high-$p_T$ $J/\psi$ measurement. The data points are slightly shifted to the left and right from the nominal binding energy values to improve their visibility.

Figure 5 shows the di-muon mass spectrum in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV. The raw yields of $\Upsilon$ states are...
obtained by a simultaneous fit to the like-sign and unlike-sign distributions. The \( \Upsilon \) state masses are fixed to the PDG values and their widths are determined by simulation. The ratio of \( \Upsilon(2S)/\Upsilon(3S) \) is fixed to the value from world-wide measurements in p+p collisions, and the shape of \( b \bar{b} \) and Drell-Yan background is determined from PYTHIA.

Figure 6 shows the fitted \( \Upsilon(2S+3S)/\Upsilon(1S) \) ratio compared with the world-wide p+p data[20] and CMS data [12, 21]. There is a hint of less melting of excited \( \Upsilon \) states relative to the ground \( \Upsilon(1S) \) state at RHIC than that at LHC.

### IV. SUMMARY AND OUTLOOK

\( \Upsilon \) production has been studied in different collision systems at the STAR experiment. A significant suppression of \( \Upsilon \) production at RHIC energies was observed in Au+Au and confirmed in U+U collisions at \( \sqrt{s_{NN}} = 200 \) GeV and 193 GeV, respectively. Measurement of \( \Upsilon \) production via the di-muon channel indicates that the excited \( \Upsilon(2S+3S) \) states are not completely suppressed in Au+Au collisions, and hints that the dissociation of \( \Upsilon(2S+3S) \) relative to \( \Upsilon(1S) \) at RHIC energies is less than that in Pb+Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV at the LHC. The new data taken in 2016 will double the data size for \( \Upsilon \) analysis in the di-muon channel, which may improve the precision of \( \Upsilon \) measurement. The on-going analysis of \( \Upsilon \) measurements via the di-electron channel with further optimized track quality cuts and the large data sets taken in 2011 and 2014 Au+Au runs may also allow the extraction of excited \( \Upsilon \) states. There are also on-going analyses with large-statistics data samples of p+p and p+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV taken in 2015 which will greatly improve the \( \Upsilon \) reference measurements and provide more precise measurements of the CNM effects on the \( \Upsilon \) production at RHIC.

[1] T. Matsui and H. Satz, Phys. Lett. B 178, 416 (1986).
[2] S. Digal, P. Petreczky and H. Satz, Phys. Lett. B 514, 57 (2001).
[3] C. Y. Wong, Phys. Rev. C 72, 034906 (2005).
[4] D. Cabrera and R. Rapp, Eur. Phys. J. A 31, 858 (2007).
[5] M. Cacciari, P. Nason and R. Vogt, Phys. Rev. Lett. 95, 122001 (2005) doi:10.1103/PhysRevLett.95.122001 [hep-ph/0502203].
[6] J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 94, 062301 (2005) doi:10.1103/PhysRevLett.94.062301 [nucl-ex/0407006].
[7] Z. w. Lin and C. M. Ko, Phys. Lett. B 503, 104 (2001) doi:10.1016/S0370-2693(01)00092-2 [nucl-th/0007027].
[8] B. Alessandro et al. [NA50 Collaboration], Eur. Phys. J. C 48, 329 (2006) doi:10.1140/epjc/s10052-006-0079-4 [nucl-ex/0612012].
[9] L. Adamczyk et al. [STAR Collaboration], Phys. Lett. B 735, 127 (2014); L. Adamczyk et al. [STAR Collaboration], Phys. Lett. B 743, 537 (2015).
[10] L. Adamczyk et al. [STAR Collaboration], [arXiv:1608.06487 [nucl-ex]]
[11] A. Adare et al. [PHENIX Collaboration], Phys. Rev. C 91, 024913 (2015).
[12] S. Chatrchyan et al. [CMS Collaboration], Phys. Rev. Lett. 109, 222301 (2012).
[13] A. Emerick, X. Zhao and R. Rapp, Eur. Phys. J. A 48, 72 (2012).
[14] M. Strickland and D. Bazow, Nucl. Phys. A 879, 25 (2012).
[15] Y. Liu, B. Chen, N. Xu and P. Zhuang, Phys. Lett. B 697, 32 (2011).
[16] L. Grandchamp, S. Lumpkins, D. Sun, H. van Hees and R. Rapp, Phys. Rev. C 73, 064906 (2006).
[17] H. Satz, Nucl. Phys. A 783, 249 (2007).
[18] L. Adamczyk et al. [STAR Collaboration], Phys. Lett. B 722, 55 (2013).
[19] Y. Liu, Z. Qu, N. Xu and P. Zhuang, Phys. Lett. B 678, 72 (2009).
[20] W. Zha, C. Yang, B. Huang, L. Ruan, S. Yang, Z. Tang and Z. Xu, Phys. Rev. C 88, no. 6, 067901 (2013) doi:10.1103/PhysRevC.88.067901 [arXiv:1308.4720 [hep-ex]].
[21] S. Chatrchyan et al. [CMS Collaboration], JHEP 1404, 103 (2014) doi:10.1007/JHEP04(2014)103 [arXiv:1312.6300 [nucl-ex]].
[22] F. Arleo and S. Peigne, JHEP 1303, 122 (2013) doi:10.1007/JHEP03(2013)122 [arXiv:1212.0434 [hep-ph]].