Quarkonia production in the STAR experiment

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Abstract
In this proceedings the recent STAR results of $J/\psi$ and $\Upsilon$ production in $p+p$, $d+Au$ and $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV at mid-rapidity are reported. $J/\psi$ $p_T$ spectra in $p+p$ and $Au+Au$ collisions for both low and high $p_T$ are shown. $J/\psi$ nuclear modification factor ($R_{AA}$) in $d+Au$ and $Au+Au$ collisions and $\Upsilon$ $R_{AA}$ in $Au+Au$ collisions are reported. Also, $J/\psi$ polarization in $p+p$ collisions and $J/\psi$ $v_2$ for semi-central $Au+Au$ collisions are presented.

1. Introduction
The suppression of quarkonia (charmonia and bottomonia) production in high energy nuclear collisions relative to $p+p$ collisions, due to the Debye screening of the quark-antiquark potential, was proposed as a signature of the formation of QGP [1]. However, there are other effects that may affect the observed quarkonia production. The cold nuclear matter effects, e.g. nuclear shadowing, Cronin effect, nuclear absorption, can be tested in $p+A$ or $d+A$ collisions. The other hot nuclear effects, such as recombination of quark-antiquark pairs might be also present. The interpretation of the quarkonia modification in QGP requires also understanding of the quarkonia production mechanism in $p+p$ collisions. At RHIC energies the $\Upsilon$ meson is a cleaner probe comparing to $J/\psi$ due to negligible contributions from $b\bar{b}$ recombination and non-thermal suppression from co-mover absorption. Measurements of the quarkonia production in different colliding systems, centralities and collision energies are needed to understand those effects. In this proceedings results on $J/\psi$ production in $p+p$, $d+Au$ and $Au+Au$ collisions and $\Upsilon$ production in $p+p$ and $Au+Au$ collisions via the dielectron decay channel at mid-rapidity at $\sqrt{s_{NN}} = 200$ GeV in the STAR experiment are presented.

2. $J/\psi$ production and polarization in $p+p$ collisions at 200 GeV

Figure [1] shows $J/\psi$ transverse momentum spectrum in $p+p$ collisions from year 2009. The new STAR result covers a broad $p_T$ region ($0 < p_T < 14$ GeV/c). The plot also shows predictions from various $J/\psi$ production models. The Color Evaporation Model (CEM) [3] for prompt $J/\psi$ can describe the $p_T$ spectrum reasonably well. NLO Non-Relativistic QCD (NRQCD) calculations with color-singlet (CS) and color-octet (CO) transitions [4] for prompt $J/\psi$ match the data for $p_T > 4$ GeV/c. NNLO* CS model [5] for direct $J/\psi$ production underpredicts the data, but the prediction does not include contributions from feed-down from higher charmonium states and $B$-hadron decays.

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1 A list of members of the STAR Collaboration and acknowledgements can be found at the end of this issue.

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Different models of $J/\psi$ production are able to describe the measured $J/\psi$ production cross section reasonably well. $J/\psi$ polarization measurement can help to distinguish among the models since they predict different dependence on $p_T$ for the $J/\psi$ polarization. $J/\psi$ polarization in STAR is analyzed in the helicity frame at $|y| < 1$ and $2 < p_T < ~5$ GeV/c [8]. The $J/\psi$ polarization parameter $\lambda_\psi$ is extracted in three $p_T$ bins and the result is shown in Fig. 2. Within current experimental and theoretical uncertainties the obtained transverse momentum dependent $\lambda_\psi$ is consistent with the predictions from NLO+ Color Singlet Model (CSM) [9] and NRQCD calculations with color octet contributions (COM) [10], and with no polarization.

3. $J/\psi$ production in $d+Au$ and $Au+Au$ and $J/\psi$ $v_2$ in Au+Au collisions at 200 GeV

$J/\psi$ $p_T$ spectra in Au+Au collisions for different centralities for both low and high $p_T$ (0 $< p_T < 10$ GeV/c) are shown in Fig. 3. The obtained spectra are softer at low $p_T$ than the Tsallis statistics Blast-wave (TBW) model prediction (dashed curves) which assumes that $J/\psi$ flows like light hadrons [6,7]. The data can be described by TBW fit with radial flow velocity $\beta$ fixed to zero (solid curves) [7]. This could be due to a significant contribution from charm quark recombination at low $p_T$ or small $J/\psi$ radial flow.
$J/\psi$ $v_2$ measurement is a crucial for testing the charm quark recombination effect. Primordial $J/\psi$ which are produced in the initial hard scattering are expected to carry very little flow, while those that are subsequently created from the recombination of thermalized (anti-)charm quarks will exhibit considerable flow. $J/\psi$ $v_2$ as a function of $p_T$ for semi-central (20-60%) Au+Au collisions is shown in Fig. 4 with different model predictions \[15\]-\[20\]. The STAR $v_2$ result is consistent with zero within the errors. It disfavors the case that $J/\psi$ is produced dominantly by coalescence from thermalized charm quarks for $p_T > 2$ GeV/c as predicted by, e.g. model (2). Models that assume only initial production of $J/\psi$ or include both initial production and coalescence process describe the data well.

Figure 5 shows $J/\psi$ $R_{AA}$ in $d+Au$ collisions as a function of $N_{coll}$ for $p_T < 5$ GeV/c. The data are in good agreement with a model prediction using EPS09 parametrization of nuclear parton distribution functions for the shadowing and a $J/\psi$ nuclear absorption of $\sigma_{abs} = 3$ mb \[12\]. The $\sigma_{abs} = 2.8^{+3.5}_{-2.6}\text{(stat.)}^{+4.0}_{-2.8}\text{(syst.)}^{+1.8}_{-1.1}\text{(EPS09)}$ mb was obtained from a fit to the data.

![Graph of $J/\psi$ $R_{AA}$ vs. $N_{coll}$ in $d+Au$ collisions.](image)

Figure 5: $J/\psi$ $R_{AA}$ vs. $N_{coll}$ in $d+Au$ collisions. Filled circles represent the STAR result.

$J/\psi$ $R_{AA}$ in Au+Au collisions as a function of $N_{part}$ at low and high $p_T$ \[2\] is shown in Fig. 6. The observed $J/\psi$ suppression increases with a collision centrality and decreases towards higher $p_T$ across the centrality range. At high $p_T$ we observe suppression only for central collisions. The results are compared to two models that include primordial $J/\psi$ production (with the color screening effect and CNM effects) and the regeneration from charm quarks \[13\]-\[14\]. Low-$p_T$ data agrees with both model predictions. At high $p_T$ Liu et al. model \[13\] describes the data reasonably well while Zhao and Rapp model \[14\] underpredicts the $R_{AA}$ for $N_{part} > 70$.

4. **$\Upsilon$ production in $p+p$ and Au+Au collisions at 200 GeV**

STAR has improved precision of the $p+p\Upsilon(1S+2S+3S)\rightarrow e^+e^-$ cross section measurement using the 2009 data with enhanced statistics. Figure 7 shows the new STAR result as a function of rapidity with two model predictions, CEM \[21\] and CSM \[22\]. The obtained cross section is consistent with the NLO pQCD calculations.

Figure 8 shows $\Upsilon(1S+2S+3S)$ $R_{AA}$ as a function of $N_{part}$ in Au+Au collisions at mid-rapidity. Results are compared with two predictions of dynamic model with fireball expansion and quarkonium feed-down \[23\]. The calculations include variation of initial $\eta/S$ and $T_0$. The observed suppression at central collisions is consistent with the prediction of complete melting of 3S state and very strong suppression of 2S state from the model that uses internal energy as the heavy quark potential.
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STAR √s = 200 GeV p+p → e+e- cross section consistent with pQCD and world data trend

STAR Preliminary
CEM: R. Vogt, Phys. Rep. 462, 125, 2008
CSM: J.P. Lansberg and S. Brodsky, PRD 81, 051502, 2010

5. Summary

In summary, the recent results of STAR J/ψ and Υ measurements in p+p, d+Au and Au+Au collisions at √sNN = 200 GeV are shown. J/ψ RdAu agrees with the model using EPS09 + σJ/ψ-abs (3 mb). J/ψ RAuAu decreases with centrality and increases with pT. At high pT suppression is only seen in central collisions. J/ψ v2 was found to be consistent with zero, it disfavors the case that J/ψ is produced dominantly by coalescence of thermalized charm quarks at pT > 2 GeV/c. Υ(1S+2S+3S) Au+Au results are consistent with the model that predicts complete melting of 3S and a strong 2S suppression.

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