J/$\psi$ Production in Cu+Cu Collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC-PHENIX

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1. Introduction

The quarkonium yields are predicted to be suppressed in the quark gluon plasma (QGP) by the Debye color screening [1]. J/$\psi$ is especially promising because of its large production cross section and di-lepton decay channels, which make it easily detected. The PHENIX experiment at RHIC measures J/$\psi$ at midrapidity ($|y| < 0.35$) via its $e^+e^-$ decay and at forward rapidity ($1.2 < |y| < 2.2$) via its $\mu^+\mu^-$ decay.

Models of J/$\psi$ production in heavy ion collisions contain a number of competing effects, including destruction of J/$\psi$ by thermal gluons in the QGP, modification of the J/$\psi$ yield by the cold nuclear matter (CNM) effects, reduced feed-down from excited charmonium states that melt just above the QGP transition temperature, the bottom quark decay and enhancement of the J/$\psi$ yield due to recombination of uncorrelated charm quark pairs [2].

The PHENIX Au+Au data at $\sqrt{s_{NN}} = 200$ GeV showed that J/$\psi$ suppression at forward rapidity is larger than that at midrapidity and degree of the suppression at midrapidity is similar to that observed by the NA50 experiment at the SPS in Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV [3,4]. Since these results are not well understood theoretically, systematic study of J/$\psi$ production in heavy ion collisions across the entire range of the number of participants ($N_{\text{part}}$) is required to disentangle the competing effects.

In 2005, PHENIX recorded Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV to obtain precise data in the range of $N_{\text{part}} \leq 126$, where Au+Au data is limited by statistics and systematic uncertainty and the CNM effects might be dominant. Accomplishments of the J/$\psi$ measurement in the $e^+e^-$ decay mode in Cu+Cu collisions by 2006 is described in Ref. [5]. In this report, the final analysis and results are described.

2. Analysis in 2007

The invariant yield of J/$\psi$ is defined as follows,

$$
\frac{BR}{2\pi p_T d^2 N} \frac{d^2 N}{d p_T dy} = \frac{1}{2\pi p_T} \frac{n(p_T, \text{cent})}{N_{MB}(\text{cent}) \Delta p_T \Delta y \epsilon(p_T, \text{cent})},
$$

where, $BR(= 5.94\%)$ is the branching ratio of J/$\psi$ into an $e^+e^-$ pair, $n$ is the number of reconstructed J/$\psi$, $\epsilon$ is the overall efficiency, $\Delta y(= 1)$ is the rapidity bin width, $\Delta p_T$ is the transverse momentum bin width and $N_{MB}$ is the number of minimum bias triggered events. The impact parameter decreases with the increase of the collision centrality, $\text{cent}$.

The analysis in 2007 was mainly concentrated on the evaluation of the overall efficiency. The overall efficiency is decomposed into three parts,

$$
\epsilon(p_T, \text{cent}) = \epsilon_{\text{acc}}(p_T) \times \epsilon_{\text{embed}}(\text{cent}) \times \epsilon_{\text{L1}}(p_T, \text{cent}),
$$

where $\epsilon_{\text{acc}}$ is the J/$\psi$ reconstruction efficiency including acceptance in the $e^+e^-$ decay mode, $\epsilon_{\text{embed}}$ is the embedding efficiency which represents the inefficiency by high particle multiplicity and $\epsilon_{\text{L1}}$ is the electron trigger efficiency for J/$\psi$.

The reconstruction efficiency $\epsilon_{\text{acc}}$ was evaluated with GEANT3 simulation. In Fig. 1, $\epsilon_{\text{acc}}$ is shown as a function of $p_T$ of and is about 1%. Distributions of variables which were used to select electron candidates were compared between the real data and simulation. From the difference between the real data and simulation, the systematic error of $\epsilon_{\text{acc}}$ was assigned to be 6% (relative).

Figure 1. The J/$\psi$ reconstruction efficiency including acceptance as a function of the transverse momentum of J/$\psi$. Only the statistical errors are shown.

The embedding efficiency $\epsilon_{\text{embed}}$ was estimated by embedding simulated single J/$\psi$ events into the real data and reconstructing them. In the most central Cu+Cu collisions, $\epsilon_{\text{embed}}$ is $97 \pm 2(syst)\%$ and this means the inefficiency is only $3 \pm 2(syst)\%$.

The electron trigger efficiency for J/$\psi$ ($\epsilon_{\text{L1}}$) was determined for each centrality bin as a function of $p_T$ of J/$\psi$ from the measured single electron trigger efficiency with simulation samples of single J/$\psi$ events. The determined
\( \varepsilon_{L1} \) is larger than 70% for all \( p_T \) range and its systematic error was determined to be 4% (relative) by various parameterizations of the single electron trigger efficiency.

3. Results and discussion

To quantify the difference between a nucleus-nucleus collision and the superposition of nucleon-nucleon collisions, the nuclear modification factor, \( R_{AA} \), is defined as follows,

\[
R_{AA} = \frac{dN}{dy}_{AA} \left/ \left( N_{\text{coll}} \cdot \frac{dN}{dy}_{pp} \right) \right.,
\]

where \( \frac{dN}{dy}_{AA} \) and \( \frac{dN}{dy}_{pp} \) are the \( J/\psi \) yields in a nucleus-nucleus collision and in a \( p + p \) collision, respectively, and \( N_{\text{coll}} \) is the number of collisions, estimated by the Glauber model. The \( p + p \) collision data at the same energy taken in 2005 [6] is used as a reference. A calculation of the CNM effects estimated breakup cross sections, \( \sigma_{\text{breakup}} \), with the \( d + Au \) collision data and EKS98 nuclear shadowing model [7]. Figure 2 shows \( R_{AA} \) in Cu+Cu and Au+Au collisions with predictions of the calculation \( (R_{NN}^{CNM}) \). Not only results of \( e^+e^- \) decay mode at midrapidity (a), but ones of \( \mu^+\mu^- \) decay mode at forward rapidity (b) are shown.

**Figure 2.** a) The nuclear modification factor \( R_{AA} \) of \( J/\psi \) as a function of the number of participants in Cu+Cu and Au+Au collisions at midrapidity with the prediction curves with the EKS98 nuclear shadowing model [7]. b) The same figure at forward rapidity. c) Forward/mid rapidity \( R_{AA} \) ratio.

Survival probability of \( J/\psi \), \( S^{J/\psi} \), can be defined as

\[
S^{J/\psi} = R_{AA} / R_{AA}^{CNM}.
\]

Bjorken energy density \( \varepsilon_{Bj} \) is an estimation of initial energy density using the transverse energy \( E_T \) in a collision,

\[
\varepsilon_{Bj} = \frac{1}{A \tau_0} \left. \frac{dE_T}{dy} \right|_{y=0},
\]

where \( A \) is the transverse area of a collision and \( \tau_0 \) is the thermalization time [8]. Figure 3 shows \( S^{J/\psi} \) at RHIC and SPS as a function of \( \varepsilon_{Bj} \) with the assumption of \( \tau_0 = 1 \text{ fm/c} \) [4, 9, 10]. The \( J/\psi \) suppression seems to start at \( \varepsilon_{Bj} \sim 2.5 \text{ GeV/fm}^3 \) regardless of rapidity and collision energy. This energy density corresponds to those in the most central S+U collisions at \( \sqrt{s_{NN}} = 19.4 \text{ GeV} \) and the most central collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). If the QGP consists of gluons, up, down and strange quarks, \( \varepsilon_{Bj} \sim 2.5 \text{ GeV/fm}^3 \) corresponds to the temperature \( T \sim 180 \text{ MeV} \).

**Figure 3.** Survival probability of \( J/\psi \) \( (S_{J/\psi}) \) is shown as a function of the Bjorken energy density \( \varepsilon_{Bj} \). Results from SPS and RHIC are shown. For the SPS results, all errors are added in quadrature. For the RHIC results, the quadrature sum of statistical, uncorrelated and correlated systematic errors is represented by a bar, the global systematic error is represented by an open box, and the error of the breakup cross section is represented by a shaded box.

4. Summary

The analysis of \( J/\psi \) production in Cu+Cu collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) has been completed. \( J/\psi \) suppression seems to be started in the most central Cu+Cu collisions. If the QGP which consists of gluons, up, down and strange quarks is assumed, the temperature in the most central Cu+Cu collisions is about 180 MeV.

References