Abstract

We present the analysis of $\Upsilon \rightarrow e^+e^-$ production in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the STAR experiment. Using higher level dedicated $\Upsilon$ triggers, STAR has sampled 32 nb$^{-1}$ of integrated luminosity in year 2008 d+Au run. The cross section is found as $BR \times \left( \frac{d\sigma}{dy} \right)_{\Upsilon(1S+2S+3S)} = 35 \pm 4$(stat.) $\pm 5$(sys.) nb and it is consistent with NLO CEM prediction with anti-shadowing effects. In addition we calculated the nuclear modification factor $R_{dAu} = 0.98 \pm 0.32$(stat.) $\pm 0.28$(sys.), which suggests the $\Upsilon(1S+2S+3S)$ production follows $N_{bin}$ scaling.

1. Introduction

Calculations based on lattice QCD predict that strongly interacting systems at very high temperature lead to the suppression of heavy quarkonium states due to Debye screening of the color charges, providing a potential signature of Quark-Gluon Plasma (QGP) formation in heavy ion collisions [1]. However, this simple picture is complicated by competing effects that either reduce the yield, such as co-mover absorption [2, 3], or enhance it, such as recombination models [4, 5, 6]. With the low cross section of the $\Upsilon$ family, the roles of absorption and recombination are negligible. Lattice QCD studies of quarkonia spectral functions suggest that while the $\Upsilon(3S)$ melts at RHIC and the $\Upsilon(2S)$ is likely to melt, the $\Upsilon(1S)$ is expected to survive [7, 8]. Therefore, the production of $\Upsilon$ family in pp, pA, and AA collisions is an important tool to study the QGP properties [9]. STAR has successfully measured the $\Upsilon$ production in p+p [10] and Au+Au collisions [11]. It is important to study the $\Upsilon$ production in d+Au collisions to further understand the initial and final state cold nuclear matter effects. In this article, we report the preliminary results of the $\Upsilon$ cross section measurement at midrapidity obtained with the STAR detector in d+Au collision at $\sqrt{s_{NN}} = 200$ GeV.

2. Main Detectors

The main detectors used in the STAR $\Upsilon$ measurements are the TPC (Time Projection Chamber) [12] and the BEMC (Barrel Electro-Magnetic Calorimeter) [13]. They cover a pseudorapidity range of $|\eta| < 1$ with full azimuthal acceptance. The TPC is the tracking detector which measures the particles momenta and energy loss ($dE/dx$) which provides particle identification. The BEMC includes a total of 4800 towers. Each tower covers approximately 0.05 $\times$ 0.05 in $\eta \times \phi$ space. The BEMC can be used to trigger on high energy electron pairs thus allowing us to maximize the sampled luminosity provided by RHIC. Due to the removal of the Silicon Vertex Tracker (SVT) and Silicon Strip Detector (SSD), a significant improvement of the signal to background ratio for non-photonic electrons is achieved.
3. \( \Upsilon \) Trigger at STAR

The STAR \( \Upsilon \) trigger is based on a two-stage decision comprising a level-0 (L0) hardware component and a level-2 (L2) software component. The L0 trigger will be issued once a high energy BEMC tower is measured. The L0 threshold is set to \( E_T \sim 4.3 \) GeV in Run8 d+Au collisions. The advantage of triggering at such high energy is the added hadron rejection power \( e/h \sim 100 \) of the BEMC towers. The L2 trigger performs tower clustering to reclaim energy leaked into neighboring towers. The invariant mass is calculated as \( M_{\text{ee}} = \sqrt{2E_1E_2(1 - \cos \theta)} \).

Where \( \theta \) is the opening angle between clusters and \( E_1 \) and \( E_2 \) are the energy of the clusters. Cuts are applied on \( E_1 > 4.5 \) GeV and \( E_2 > 3.0 \) GeV, \( \cos \theta < 0 \) and \( 6.5 < M_{\text{ee}} < 25 \) GeV/c\(^2\).

4. Data Analysis and Results

For d+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV in 2008, the STAR \( \Upsilon \) trigger sampled 32 nb\(^{-1}\) of integrated luminosity. The p+p equivalent integrated luminosity is \( \sim 12.5 \) pb\(^{-1}\), which is more than a factor of 2 larger than the sample analyzed in the preliminary data reported in Ref \[10\] of the 2006 pp run. Electrons are identified \[14\] by selecting charged particle tracks, where more than 22 out of 45 points are fitted and whose specific ionization energy loss in the TPC is \( -2 < n\sigma_e < 3 \) (\( n\sigma_e \) is the normalized dE/dx and it is defined by \( n\sigma_e = \log(dE/dx_{\text{measure}}/B_e)/\sigma_e \), where \( B_e \) is the expected mean dE/dx of electrons and \( \sigma_e \) is the dE/dx resolution of the TPC). The selected particle tracks have to match to BEMC clusters that contain energy consistent with the L0 and L2 trigger conditions. A cut on \( 0.7 < E/p < 1.3 \) is applied to further reject hadrons from the electron candidates, where \( E \) and \( p \) are the particle’s energy deposited in BEMC and the momentum measured by the TPC, respectively. The \( e^+e^- \) pairs are then combined to produce the invariant mass spectrum. The combinatorial background is estimated using like-sign pairs. The like-sign electron pairs are combined to form the invariant mass spectrum and the geometric mean \( 2 \sqrt{N^{++}N^{-+}} \) is used to calculate the combinatorial background, where \( N^{++} \) (\( N^{-+} \)) is the number of the positive (negative) like-sign electron pairs. The left panel of Fig. 1 shows the unlike-sign and the like-sign invariant mass spectra. The right panel of Fig. 1 shows the transverse momentum reach for the unlike-sign and like-sign electron pairs indicating that STAR has the capability to measure the transverse momentum spectra of the \( \Upsilon \) family up to \( p_T \sim 7 \) GeV/c. The total yield is extracted by integrating the invariant mass spectrum from 7 to 11 GeV/c\(^2\). The invariant mass range used for integration is the same as that for the STAR measurement of p+p \[10\]. The integrated yield is \( 172 \pm 20 \) (stat.) and the signal significance is \( \sim 8\sigma \). This is to-date, the strongest signal of \( \Upsilon(1S + 2S + 3S) \) states at RHIC energies. The cross section is then calculated with the formula:

\[
\sum_{nS=1}^{3} BR(nS) \times \frac{d\sigma}{dy}^{\Upsilon(nS)} = \frac{N}{dy \times \epsilon \times \int Ldt} \tag{1}
\]

where \( BR(nS) \) is the branching ratio fraction for \( \Upsilon(nS) \rightarrow e^+e^- \), \( N = 172 \pm 20 \) (stat.) is the raw yield, \( dy = 1.0 \) is the rapidity interval, \( \int Ldt = 32 \) nb\(^{-1}\) is the integrated luminosity and \( \epsilon = \epsilon_{\text{acc}} \times \epsilon_{\text{L0+L2}} \times \epsilon_{\text{TPCreco}} \times \epsilon_{\text{IDcuts}} \times \epsilon_{\text{mass}} \) is the efficiency for reconstructing \( \Upsilon \) family. \( \epsilon_{\text{acc}} \) is the geometrical acceptance, \( \epsilon_{\text{L0+L2}} \) is the L0 and L2 trigger efficiency, \( \epsilon_{\text{mass}} \) is the efficiency of the invariant mass cut, \( \epsilon_{\text{TPCreco}} \) and \( \epsilon_{\text{IDcuts}} \) is the efficiency for single electron reconstruction and the electron identification cuts, respectively. Each term and its uncertainty is estimated through simulations and the total efficiency is found to be \( \epsilon = 0.15 \pm 0.02 \). The cross-section
at midrapidity in $\sqrt{s_{NN}} = 200$ GeV d+Au collisions is found to be $BR \times (d\sigma/dy)_{\Upsilon(1S+2S+3S)} = 35 \pm 4(\text{stat.}) \pm 5(\text{sys.})$ nb. The contribution to the di-electron yield in the $\Upsilon$ mass region coming from Drell-Yan and $b\bar{b}$ is estimated to be $\sim 10\%$ based on [15] and PYTHIA. The detailed systematic uncertainty is under study.

We compare our midrapidity measurement with NLO (next-to-leading-order) calculations the Color Evaporation Model (CEM) [15] in Fig. 2. The calculation includes the anti-shadowing effect which is obtained from the EKS’98 parameterization [16]. It doesn’t include absorption effect. We also calculate the nuclear modification factor $R_{dAu} = 0.98 \pm 0.32(\text{stat.}) \pm 0.28(\text{sys.})$. The cross section in p+p collisions is taken from STAR measurement [10].

5. Conclusion

The STAR experiment made the first measurement of the $\Upsilon(1S+2S+3S) \rightarrow e^+e^-$ cross section at midrapidity in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. An 8$\sigma$ significant signal is observed and $BR \times (d\sigma/dy)_{\Upsilon(1S+2S+3S)} = 35 \pm 4(\text{stat.}) \pm 5(\text{sys.})$ nb. The large acceptance of the detectors and the L0+L2 trigger are essential for the success of the measurement. The cross section is consistent with CEM predictions including anti-shadowing. It is found that $R_{dAu} = 0.98 \pm 0.32(\text{stat.}) \pm 0.28(\text{sys.})$, which suggests the $\Upsilon(1S+2S+3S)$ production follows the number of binary collisions scaling in d+Au collision. With the current uncertainty of $R_{dAu}$ we can not quantify the cold nuclear matter effect. The uncertainties are dominated by the statistical error of the $\Upsilon$ cross section measurement in p+p collision. In the RHIC 2009 p+p run, STAR has sampled 21 pb$^{-1}$ of integrated luminosity and that will provide us a precise baseline for $\Upsilon$ measurements.
Figure 2: The red star shows the measured \( BR \times (d\sigma/dy)_{\Lambda(1S+2S+3S)} \) at midrapidity. The bar indicates the statistical error and the band shows the systematic uncertainty. The cross section is compared with the NLO CEM model prediction (blue solid circles), see text for details. The raw yields vs. rapidity is shown by the red histogram at the bottom with the statistical errors.

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