Abstract. We report on the most recent measurements of bottomonia and excited states of charmonium made by PHENIX in mid- and forward rapidities at $\sqrt{s} = 200$ GeV. We also discuss the prospects for future measurements and concerns in using the color screening of different quarkonia states in heavy ion collisions as a quantitative observable for the temperature reached at the strong interacting quark gluon plasma.

1. Introduction

For a long time the suppression of quarkonia yields in heavy ion collisions relative to binary scaling and cold nuclear effects has been proposed as a signature for the formation of a quark gluon plasma [1]. Indeed anomalous suppression of $J/\psi$ observed in SPS experiments was the first verification of a quark-gluon-plasma behavior in heavy ion collisions [2]. A similar suppression was observed at RHIC [3] and different levels of suppression were observed in LHC in different kinematic regions [ALICE, ATLAS and CDF in this volume]. All these measurements have concerns on how cold nuclear matter effects can be accounted for in heavy ion collisions [4, 5]. At RHIC and LHC charm coalescence and recombination can also contribute to the nuclear modifications [6].

A series of theoretical studies of the color screening effect on quarkonia states is available in the literature. A nice collection of references on these studies is presented in [7] which includes studies using lattice QCD, QCD sum rules, Ads/QCD, resummed perturbation theory, effective field theories and potential models. Figure 1 shows the range of quark-gluon plasma (QGP) temperatures relative to the critical temperature $T_c$ where each heavy quarkonia state is dissociated. The ranges are from variations from the several estimations and also cover the transition between unmodified and totally dissociated quarkonia peak in the calculations. For comparison, the figure also shows the expected temperature reached at RHIC collisions calculated by hydrodynamics models fitted to PHENIX thermal photon data [8]. The experimental verification of these dissociations would represent a strong constraint to the temperature of the medium created in A+A collisions as well as a test for the color screening models.

One important caveat in using quarkonia dissociation as a thermometer is how the different quarkonia states cross the nucleus. The different states of charmonium and bottomonium are produced with the same initial state but evolve to their final states as color singlet or color octet state with some additional time for its color neutralization. If quarkonia cross the nucleus as a pre-resonant object, different final states will appear with the same suppression. Figure 2 shows...
how $\psi'$, produced as a color octet alike $J/\psi$, and $\chi_c$, produced as a color singlet, would be suppressed in cold nuclear matter relative to $J/\psi$ one. In fact, $J/\psi$ and $\psi'$ data taken in $p+A$ collisions by E866/NuSea [9] reveal a different nuclear absorption between $J/\psi$ and $\psi'$ for small $x_F$ and a pre-resonant like behavior for $x_F > 0.2$, where the magnitude of the absorption of both states are undistinguished. However, the lifetime for the charmonium octet state calculated using FERMILAB and NA50 [10] data was found to be too small demanding the emission of unphysically large energy gluons [11].

Figure 1. Ranges of medium temperatures where quarkonia states are dissociated. Ranges are from variation in the theoretical calculations therein [7] and the transition between unmodified and totally dissociated quarkonia peak.

Figure 2. Rapidity dependence of the $\psi'$ and $\chi_c$ suppression relative to direct $J/\psi$ in the case, or not, of the existence of pre-resonant state for $\psi'$ and $J/\psi$.

PHENIX detector has an extensive program in quarkonia measurements which includes di-lepton decays of $J/\psi$, $\psi'$ and $\Upsilon$ family in the central arms ($|y| < 0.35$) and muon arms ($1.2 < |y| < 2.2$) as well as radiative decays of $\chi_c$ in central arms. The excited state charmonia and the $\Upsilon$ measurements are described in the following sections as well as their implications in understanding the behavior of different quarkonia states in QGP.
2. Excited state charmonia
The ground state charmonium (J/ψ) has been studied in p+p [12], d+Au [4, 5], Cu+Cu [13] and Au + Au collisions at √s_{NN} = 200 GeV [3, 14] as well as a low energy study which has started with √s_{NN} of 39 GeV and 62 GeV [15]. The focus of this section is the measurement of ψ′ and χ_c states.

2.1. ψ′

![Figure 3. Di-electron signal in the J/ψ and ψ′ mass range and the relative ψ′ / (J/ψ) yield obtained by PHENIX compared to lower energy experiments [12].](image)

The first measurements of ψ′ was made in p+p collisions at mid-rapidity [12]. Correlated heavy flavor decays in electrons can contribute with up to 40% of the di-electron signal in the ψ′ mass region. A careful estimation of the heavy flavor contribution was based on PYTHIA [16] using Next-to-Leading-Order (NLO) subprocesses and also randomized opening angle distribution. The yield of di-electron ψ′ decays relative to J/ψ one is of about 2% and follows a rising trend when increasing p_T observed in lower energy experimental results. The feed-down fraction of ψ′ in the J/ψ yields is

\[ F^J/ψ_{ψ′} = B(ψ′ → J/ψ + X) \frac{σ_{ψ′}}{σ_{J/ψ}} = (9.4 ± 2.4)\% \tag{1} \]

which also agrees with previous measurements.

Preliminary result of ψ′ R_dA will be available very soon.

2.2. χ_c
The channel we used to measured χ_c is χ_c → J/ψ + γ → e^+e^- + γ. It is a challenging measurement given that the energy of the γ decayed is in average 600 MeV but can extends to lower energies where calorimetry measurement turns to be difficult. In addition, the correlated background in the J/ψ + γ invariant mass spectrum used to count χ_c decays is significant. Radiative decays of J/ψ, electron bremsstrahlung, jets, ψ′ decays in neutral particles, NNLO c ¯c contributions and bottom decays all can contribute to the correlated background. After consider all these sources and side band e^+e^- mass ranges the χ_c feed-down fraction to J/ψ can be directly determined. Figure 4 shows the e^+e^- mass distributions measured in p+p collisions [12] and in d+Au collisions after the subtraction of the combinatorial and correlated background. The feed-down fraction seems to hold in the presence of cold nuclear matter but large statistical uncertainties still forbids a firm conclusion.
2.3. Outcome of ψ' and χ_c feed-down to J/ψ in Au + Au collisions.

There is no ψ' and χ_c measurements in Au + Au collisions at RHIC up to date. However, their nuclear modifications should influence 42±9 % of the J/ψ yield, this is the fraction of J/ψ which come from ψ' and χ_c decays. In the view of the estimated temperature ranges where ψ' and χ_c are totally melted in QGP and the medium temperature produced at RHIC as obtained in hydro calculations (Figure 1), we should expect these charmonium states are not present in central Au + Au collisions making $R_{AA}$ of the J/ψ decrease. Even this scenario cannot describe all suppression observed for J/ψ, which indicates the presence of cold nuclear matter effects and perhaps some dissociation of the J/ψ as well.
3. $\Upsilon$ (1S+2S+3S)

PHENIX has observed $\Upsilon$ counts in central and muon arms in $p+p$, $d+Au$ and $Au+Au$ collisions. Given the limited mass resolution obtained in both PHENIX spectrometers and the small distance in mass between the $\Upsilon$ 1S, 2S and 3S, the measurement is made for the sum of these states. According to results from $p+\bar{p}$ collisions in CDF [17] and $p+p$ collisions in LHCb [18], 1S, 2S and 3S states contribute with the total $\Upsilon$ yield in $\sim 73\%$, 17\% and 10\% respectively. Decays of the 2S, 3S and $\chi_b(1P+2P)$ states corresponds to 11\%, 1\% and 37\% respectively of the 1S yield in $p+p$ and $p+\bar{p}$ collisions.

Di-lepton invariant mass distributions measured in the $\Upsilon$ mass range also contain correlated bottom decays and principally Drell-Yan. These contributions are accounted for in $p+p$ and $d+Au$ collisions by using PYTHIA simulations, NLO calculations for Drell-Yan [19] and also including cold nuclear matter effects in heavy ion collisions [20].

Figure 6 shows the $\Upsilon$ peaks in $p+p$ and $Au+Au$ collisions and the nuclear modification factor $R_{AA}$ at mid-rapidity. PHENIX result is in agreement with STAR result at the same energy and rapidity [21]. For simplicity let’s ignore cold nuclear matter effects for now, if $\Upsilon$ (2S+3S) are totally dissociated in $Au+Au$ collisions, $R_{AA}$ of the measured $\Upsilon$ would be around 0.64. If $\chi_b$ also disappear in QGP, $R_{AA}$ would be around 0.37. The most central STAR result supports that only the 1S state survive, however, parton distribution modifications and breakup in hadrons can also be important in the strong suppression observed in $Au+Au$ collisions. Upcoming measurements of the rapidity dependence of $\Upsilon$ nuclear modification factors in $d+Au$ collisions can provide a more quantitative measurement of the cold nuclear matter effects.

![Figure 6. $\Upsilon$ (1S+2S+3S) yields in $p+p$ and $Au+Au$ collisions and nuclear modification factor measured in $Au+Au$ collisions compared to STAR results [21].](image)

4. Future Measurements

PHENIX has now entered in the vertex detectors era opening the possibility to explore many more aspects of quarkonia production at RHIC. The two vertex detectors are already in operation in the central and (VRTX) muon arms (FVTX). The VTX can improve significantly the signal/background of the di-electron measurements. A direct measurement of the $B$-meson contribution to the high $p_T J/\psi$ and $\psi'$ yields can now be done. Finally, VTX can be used as
a photon converter to low-mass di-electrons suitable for the measurement of low energy $\gamma$ in radiative $\chi_c$ decays.

Currently, di-muon invariant mass is measured by using the muon tracker in front of thick hadron absorbers. Multiple scattering in these absorbers limits the measurement of the opening angle of di-muons. The FVTX is installed between the collision point and the absorbers allowing it to improve the measurement of the di-muon opening angle. With this improvement we expect to discriminate $\psi'$ from $J/\psi$ peaks in the di-muon invariant mass spectrum. Rapidity dependent $\psi'$ measurements can help to understand the role of the pre-resonant state in our results.

Future high luminosity runs will provide a better statistical precision in the $\Upsilon$ measurements at RHIC. The current PHENIX apparatus is going to be replaced by a solenoidal detector (sPHENIX) with 2T magnetic field covering $|y| < 1.1$ [22] which can resolve the $\Upsilon$ states. Detector studies to resolve $\Upsilon$ states are also being carried on in the forward rapidity ($1.1 < y < 4$). These upgrades will open a new field of study in quarkonia at RHIC.

References
[1] Matsui T and Satz H 1986 Phys. Lett. B 178 416
[2] Abreu M et al. (NA50) 1997 Physics Letters B 410 337 – 343 ISSN 0370-2693
[3] Adare A et al. (PHENIX Collaboration) 2007 Phys. Rev. Lett. 98 232301
[4] Adare A et al. (PHENIX Collaboration) 2011 Phys. Rev. Lett. 107(14) 142301
[5] Adare A et al. (PHENIX Collaboration) 2012 (Preprint 1204.0777)
[6] Thews R L, Schroedter M and Rafelski J 2001 Phys. Rev. C 63(5) 054905
[7] Suzuki K, Gubler P, Morita K and Oka M 2012 (Preprint 1204.1173)
[8] Adare A et al. (PHENIX Collaboration) 2010 Phys. Rev. C 81 034911
[9] Leitch M J et al. ((FNAL E866/NuSea Collaboration)) 2000 Phys. Rev. Lett. 84(15) 3256–3260
[10] Alessandro B et al. (NA50) 2006 Eur. Phys. J. C 48 329 (Preprint nucl-ex/0612012)
[11] Arleo F, Gossiaux P B, Gousset T and Aichelin J 2000 Phys. Rev. C 61(5) 054906
[12] Adare A et al. (PHENIX Collaboration) 2012 Phys. Rev. D 85(9) 092004
[13] Adare A et al. (PHENIX Collaboration) 2008 Phys. Rev. Lett. 101(12) 122301
[14] Adare A et al. (PHENIX Collaboration) 2011 Phys. Rev. C 84(5) 054912
[15] da Silva C L (PHENIX Collaboration) 2011 J.Phys.G G38 124031
[16] Sjostrand T, Mrenna S and Skands P 2006 JHEP 05 026
[17] Papadimitriou V (CDF Collaboration) 1994 (Preprint hep-ex/9501010)
[18] Aaij R et al. (LHCb Collaboration) 2012 Eur.Phys.J. C72 2025 (Preprint 1202.6579)
[19] Kubar J, Le Bellac M, Meunier J and Plant G 1980 Nucl.Phys. B175 251
[20] Neufeld R, Vitev I and Zhang B W 2011 Phys.Lett. B704 590–595 (Preprint 1010.3708)
[21] Kesich A (STAR Collaboration) 2012 (Preprint 1207.7166)
[22] Aidala C et al. 2012 (Preprint 1207.6378)