Heavy flavor in heavy ion collisions

Lijuan Ruan
Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
E-mail: ruan@bnl.gov, ruanlj@rcf.rhic.bnl.gov

Abstract. The recent results on heavy flavor at the Relativistic Heavy Ion Collider will be reviewed. The results on charm cross section, heavy flavor collectivity and energy loss, color screening effect and quarkonia production mechanism will be highlighted. Precise measurements with future detector upgrades will be discussed.

1. Introduction
Data taken in the last decade have demonstrated that the Relativistic Heavy Ion Collider (RHIC) has created a strongly interacting hot, dense medium with partonic degrees of freedom, the Quark Gluon Plasma (QGP) in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [1, 2, 3, 4]. Understanding the properties of this matter, such as the colored degrees of freedom and the equation of state, is the physics goal of RHIC and of broad interest. For example, we would like to study the temperature of QGP, the chemical composition, whether the system is thermalized and the color screening effect. Heavy flavor measurements serve as an ideal probe for the QGP and will directly address those above properties. The mass of charm and bottom quark is much larger than the possible temperature in QGP thus $c\bar{c}$ and $b\bar{b}$ pairs are believed to be produced at initial impact from hard processes with high $Q^2$ transfer and therefore they can be calculated in perturbative Quantum Chromodynamic (pQCD) framework [5]. Any modification on the heavy flavor production would be sensitive to the system evolution, light flavor thermalization, medium modifications and properties. On the other hand, heavy quarkonia are thought to be an excellent probe for the color screening effect in the medium. Different quarkonia states are predicted to dissolve at different temperatures due to different binding energies. Precise measurements of transverse momentum ($p_T$) distributions of quarkonia at different centralities, collision systems and energies will serve as a thermometer of the QGP [6, 7]. I will review recent heavy flavor results at RHIC. The results on charm cross section, heavy flavor collectivity and energy loss, color screening effect and quarkonia production mechanism will be highlighted. Precise measurements with future detector upgrades will be discussed. The results presented here were from collision energy at $\sqrt{s_{NN}} = 200$ GeV.

2. Open heavy flavor measurements at RHIC
At STAR, there are three measurements related to open heavy flavor production: $D^0$ reconstruction through $K\pi$ decay [8], single muons at low $p_T$ (0.17-0.25 GeV/c) from charm decay [9], and single electrons from charm and bottom decay (non-photonic electrons) in the range of 1-10 GeV/c [8]. The $D^0$ and muon measurements at low $p_T$ help constrain the cross section of $c\bar{c}$ production. The $D^0$ signal was obtained by mix-event technique. The muons
from charm decay were derived by a two-component fit to the distribution of its distance of closest approach to the collisions vertex (DCA) \cite{9}. The two components are muons from charm decay and from $\pi, K$ decay. The muons at low $p_T$ were found to be able to uniformly sample the charm cross section \cite{10}. The non-photonic electrons are the inclusive electrons after subtraction of the photonic backgrounds, which are dominantly from gamma conversion and $\pi^0, \eta$ Dalitz decays. The photonic electrons were reconstructed using the electron pair topology technique, in which the leading electrons, identified either through the Time of Flight detector or Electromagnetic Calorimeter, were combined with the other tracks from the Time Projection Chamber to reconstruct the opening angle or invariant mass distribution. By cutting on a small opening angle or a small invariant mass and correcting for the partner finding efficiency, the background was obtained and then subtracted from inclusive electrons \cite{8}. The three measurements together cover 90% kinematical range of total charm cross section at mid-rapidity.

At PHENIX, there are two ways to measure the non-photonic electrons: cocktail method and converter method \cite{11}. In the cocktail method, the photonic sources were simulated with PHENIX geometry and subtracted from inclusive electrons. In the converter method, the material with known radiation length were added in PHENIX experiment during the normal run and the non-photonic electrons were derived from the extrapolation. The electron measurements from these two are consistent. The $c\bar{c}$ cross section were derived from the electron measurements at $p_T > 0.4$ GeV/$c$ \cite{11}. In addition, there were also constraints from di-lepton measurements \cite{12} and it was found that the $c\bar{c}$ cross section derived from non-photonic electrons at $p_T > 0.4$ GeV/$c$ is consistent with that from di-lepton measurements in p+p collisions.

2.1. Charm cross section measurements at RHIC

There is a factor of two difference for the charm cross section measured by STAR and PHENIX. This is still under investigation. The low material run and the large Time of Flight detector coverage in year 2009 at STAR will help to solve this puzzle. However, the charm cross section from both experiments was found to follow the number of binary collision scaling from 200 GeV p+p, d+Au, peripheral Au+Au to central Au+Au collisions, which indicates that charm production is exclusively at the initial impact.

There was also a factor of two difference for high $p_T$ electrons measured by STAR and PHENIX between 3 and 10 GeV/$c$ without a significant $p_T$ dependence in 200 GeV p+p and Au+Au collisions. Recently the high $p_T$ electrons at 3-10 GeV/$c$ were updated at STAR in p+p collisions and it was found that the measurement is consistent with that from PHENIX in the overlapping $p_T$ region \cite{13}. The Au+Au results are under investigation and the low material run of 200 GeV Au+Au collisions during 2010 will be helpful to solve the puzzle.

2.2. heavy flavor modification and collectivity

Non-photonic electrons, which come from heavy flavor charm and bottom decay, show a similar magnitude of suppression as light hadrons \cite{8, 11}. The pQCD calculations including charm and bottom decay with collisional and radiative energy loss show a systematically higher $R_{AA}$ value than experimental data \cite{14, 15}. Further calculations indicate that with the charm contribution only, non-photonic electrons are expected to reproduce the data \cite{15}. Using the azimuthal angle correlations between non-photonic electrons and charged hadrons (e-h) and between non-photonic electrons and $D^0$ ($e - D^0$), the bottom contribution factor to non-photonic electrons were measured \cite{16}. It was found that at $p_T > 5$ GeV/$c$, the bottom contribution is very significant. This together with non-photonic electron $R_{AA}$ measurements challenge the pQCD energy loss model calculations; they may indicate collisional dissociation of heavy mesons \cite{17}, in-medium heavy resonance diffusion \cite{18}, and multi-body mechanisms \cite{19} might play an important role for heavy quark interactions with the medium.
In addition, it was found that charm freezeout earlier with moderate or smaller radial flow compared to stable particles from the non-photonic electron spectrum measurements in Au+Au collisions [9]. The elliptic flow of non-photonic electrons was found to be significant at low $p_T$, indicating the QGP created at RHIC is strongly-interacting [11].

3. Color screening effect on high $p_T$ $J/\psi$?
The dissociation of quarkonia due to color screening in a QGP is a classic signature of de-confinement in relativistic heavy-ion collisions [20]. Results at RHIC show that the suppression of the $J/\psi$ as a function of centrality (the number of participants) is similar to that observed at the SPS, even though the energy density reached in collisions at RHIC is significantly higher [21, 22]. Possible production mechanisms such as sequential suppression [23], $c\bar{c}$ recombination [24, 25, 26, 27] were proposed to explain this. Recent Lattice QCD calculations indicate that direct $J/\psi$ is not dissociated in the medium created at RHIC while the suppression observed for $J/\psi$ comes from the dissociation of $\chi_c$ and $\psi'$ [28]. However, the direct $J/\psi$ might be dissociated at RHIC at high $p_T$, which was predicted in the hot wind dissociation picture, in which the AdS/CFT approach was used and the dissociation temperature for $J/\psi$ was predicted to decrease as a function of $p_T$ [29]. The AdS/CFT approach was applied to hydro framework and predicted that $J/\psi R_{AA}$ decreases versus $p_T$ [30].

Figure 1 shows $J/\psi R_{AA}$ as a function of $p_T$ in 0-20% and 0-60% Cu+Cu collisions from STAR [31] and 0-20% Cu+Cu collisions from PHENIX [32]. The average of two STAR 0-20% data points at high $p_T$ is $R_{AA} = 1.4\pm0.4$ (stat.) $\pm0.2$ (syst.). Compared to low $p_T$ PHENIX measurements, the results indicate that $R_{AA}$ of $J/\psi$ increases from low $p_T$ to high $p_T$ with a 97% confidence level (C.L.). The $R_{AA}$ of high $p_T$ $J/\psi$ is in contrast to strong suppression for open charm [14, 17, 33], indicating that $J/\psi$ might be dominantly produced through color singlet configuration. However, even though there is significant improvement from the next-next-to-leading order (NNLO) pQCD calculations with the color singlet model, the calculation still fails to reproduce the high $p_T$ part [34]. The $R_{AA}$ trend of $J/\psi$ is contradictory to AdS/CFT+hydrodynamic calculations at the 99% C.L.. This might indicate two things: 1) Cu+Cu system is not big enough so that the calculation is not applicable. The larger system produced in Au+Au collisions may be necessary to observe or exclude the effect predicted by AdS/CFT; 2) the formation time effect for high $p_T$ $J/\psi$ is important since the AdS/CFT+hydrodynamic calculation shown in Fig. 1 requires that the $J/\psi$ is produced as an on-shell $J/\psi$ fermion pair, almost instantaneously, at the initial impact with no formation time. A calculation combining effects of $J/\psi$ formation time, color screening, hadronic phase dissociation, statistical $c\bar{c}$ coalescence and B meson feed-down contribution can describe the data [35]. The calculation suggests a slight increase in the $R_{AA}$ at higher $p_T$.

In addition to nuclear modification factors for heavy quarkonia, which can help further constrain their production mechanisms, it is important to understand the higher states and B decay contribution to $J/\psi$. For example, from $J/\psi - h$ correlations, it was found that B decay contributes to 13 $\pm$ 5% of the inclusive $J/\psi$ at $p_T > 5$ GeV/c [31]. Through the di-electron decay, it was found that $\psi'$ decay contributes to 8.5 $\pm$ 2.6% of the inclusive $J/\psi$ [36]. Besides, the recent spin alignment result for inclusive $J/\psi$ [37] is consistent with both CSM [38] and COM [39] calculations at low $p_T$, as shown in Fig. 2. The future higher $p_T$ measurement of the spin alignment will help distinguish these model calculations and thus further improve our understanding of $J/\psi$ production mechanisms.

4. Future upgrades and the related key measurements
STAR and PHENIX recently updated their data acquisition and trigger systems, which will help sample RHIC II luminosity. With several detector upgrades, heavy flavor collectivity and energy loss as well as color screening effects will be studied with better precision at RHIC.
Figure 1. $J/\psi R_{AA}$ versus $p_T$. The box about unity on the left shows $R_{AA}$ normalization uncertainty, which is the sum in quadrature of p+p normalization and binary collision scaling uncertainties. The solid line and band show the average and uncertainty of the two 0-20% data points. The uncertainty band of 10% for the dotted curve is not shown. Figure is taken from ref. [31].

Figure 2. $J/\psi$ spin alignment versus $p_T$ in 200 GeV p+p collisions. Boxes are correlated systematic uncertainties. Figure is taken from ref. [37].

4.1. Heavy flavor collectivity and energy loss
The non-photonic electron analyses suffer from large systematic uncertainties, which are related to photonic background reconstruction and/or subtraction from hadronic decays. In the future, with the Heavy Flavor Tracker upgrade at STAR, the direct topological reconstruction of heavy flavor hadron decays will be feasible and direct charmed hadron measurements will be obtained with good precision [40]. With the Silicon Vertex Detector upgrades, PHENIX will be able to measure non-photonic electrons from charm and bottom decay separately [41]. These measurements are crucial to understand heavy flavor energy loss thus further constrain the details of jet quenching. The collectivity measurements from heavy flavor will be important to understand the thermalization for light flavor.
4.2. Quarkonia production mechanisms, color screening, collectivity and energy loss
To further understand the production mechanisms of quarkonia, color screening effects and medium properties, the precise measurements of the following are needed: nuclear modification factors of $J/\psi$ from low to high $p_T$ in Au+Au and d+Au collisions, $J/\psi v_2$, forward and backward $J/\psi$ production to address intrinsic charm contributions at large $x_F$ [42], $J/\psi - h$ correlations to access the feeddown contribution, the spin alignment of $J/\psi$ from low to high $p_T$, higher charmonia states and different $\Upsilon$ states [36, 43]. The Time of Flight system [44], fully installed in the summer of 2009, will enhance the $J/\psi$ capability at low $p_T$ significantly at STAR. The $\Upsilon$ states are also ideal tools to study the effect of color screening in hot and dense QCD matter since its ground state and excited states melt at different temperatures and all of them decay to dileptons [23]. Furthermore, since the $b\bar{b}$ cross section at RHIC energy is expected to be much smaller compared to $c\bar{c}$ cross section from FONLL calculations [45], the recombination contribution from QGP phase might be negligible to bottomonia production. This makes the $\Upsilon$ even a better probe for studying the color screening effect in QGP if sufficient statistics can be achieved experimentally. RHIC II luminosity enables the $\Upsilon R_{AA}$ measurements with good precision. With the possible Muon Telescope Detector upgrade, STAR can cleanly separate the ground state from the excited states even with the additional material from the upgraded inner tracker since the muons in $\Upsilon \rightarrow \mu^+\mu^-$ do not suffer from Bremsstrahlung radiation [46].

With the Silicon Vertex Detector upgrade, PHENIX can measure different upsilon states as well through $\Upsilon \rightarrow e^+e^-$ since the silicon vertex detector brings better mass resolution to quarkonia measurement. The different state $\Upsilon$ measurements will shed more light on the study of the temperature of the QGP created at RHIC.

5. Summary
The recent results on heavy flavor at RHIC are reviewed. The results on charm cross section, heavy flavor collectivity and energy loss, color screening effect and quarkonia production mechanisms are highlighted. Precise measurements with future detector upgrades are discussed.

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