

Heavy Flavor Production at STAR

Haibin Zhang (for the STAR[†] Collaboration)

Physics Department, Brookhaven National Laboratory, Upton, NY, 11973, USA

E-mail: haibin@bnl.gov

Abstract. We present measurements on D^0 meson production via direct reconstruction of its hadronic decay channel $D^0 \rightarrow K\pi$ in minimum bias d +Au and Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV with p_T up to ~ 3 GeV/ c . Non-photonic electron spectra from the charm semi-leptonic decays are analyzed from the same data set as well as in $p+p$ collision at $\sqrt{s}=200$ GeV using the STAR Time-of-Flight (TOF) and Barrel EMC (BEMC) detectors, respectively. Results of the charm-decayed single muon (prompt muon) spectra are also presented at low p_T in Au+Au collisions measured by the TOF detector. The charm production total cross-section per nucleon-nucleon collision is measured to be $1.26 \pm 0.09(\text{stat.}) \pm 0.23(\text{sys.})$ mb in minimum bias Au+Au collisions, which is consistent with the N_{bin} scaling compared to $1.4 \pm 0.2 \pm 0.4$ mb in minimum bias d +Au collisions, and supports the idea that charm quarks should be produced mostly via parton fusion at early stage in relativistic heavy-ion collisions. A Blast-Wave model fit to the low p_T (< 2 GeV/ c) non-photonic electrons, prompt muons and D^0 spectra shows that charm hadrons may kinetically freeze-out earlier than light hadrons with a smaller collective velocity. The nuclear modification factors (R_{AA}) of the non-photonic electrons in central Au+Au collisions are significantly below unity at $p_T > \sim 2$ GeV/ c , which indicates a significant amount of energy loss for heavy quarks in Au+Au collisions. The charm transverse momentum distribution must have been modified by the hot and dense matter created in central Au+Au collisions at RHIC.

PACS numbers: 25.75.Dw, 13.20.Fc, 13.25.Ft, 24.85.+p

1. Introduction

Recent experimental studies at the Relativistic Heavy-Ion Collider (RHIC) have given strong evidences that the nuclear matter created in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV has surprisingly large collectivity and opacity as reflected by its hydrodynamic behavior at low p_T [1] and its particle suppression behavior at high p_T [2]. This has led to the famous name of this high energy density and high temperature nuclear matter, sQGP, which can be interpreted as either strongly-interacting Quark Gluon Plasma [3], or super/perfect-fluid Quark Gluon Plasma [4]. However, many of its important properties are still remain unclear so far, such as whether the newly-created partonic matter has been thermalized or not, etc.

[†] For the full list of STAR authors and acknowledgements, see appendix ‘Collaboration’ of this volume

Charm quarks can provide a unique tool to probe the partonic matter created in relativistic heavy-ion collisions at RHIC energies. First, charm quarks are produced in the early stages of high-energy heavy-ion collisions due to its relatively large mass [5]. Thus the charm total cross-section is believed to follow the N_{bin} scaling from $p+p$, $d+Au$ collisions to Au+Au collisions at RHIC energies if the nuclear modification to the parton structure function, the so-called EMC effect [6], is small. The direct measurement of D^0 mesons with low p_T coverage in Au+Au collisions will allow us to extract this important information on the scaling properties of the charm production cross-section by comparing with the same measurement in $d+Au$ collisions. Second, theoretical calculations have shown that the charm quarks interacting with the surrounding partons in the medium could change its flow properties [7, 8], such as its p_T spectra shape, and could boost the elliptic flow (v_2) of the final observable charmed hadrons besides the v_2 effect picked up by their light constituent quarks. Thus experimental measurements for the p_T spectra of the charmed hadrons and/or its decayed non-photonic electrons/positrons together with their elliptic flow properties in Au+Au collisions are particularly interesting to interpret the thermalization processes of the light quarks in the partonic matter. Third, charm quarks are believed to lose much smaller energies compared to light quarks in the partonic matter due to the famous so-called “dead-cone” effect [9, 10, 11]. A measurement of the nuclear modification factor for the charmed hadrons and/or their decayed non-photonic electrons/positrons compared to light hadrons is valuably important to complete the picture of the observed jet-quenching phenomenon and help us better understand the energy-loss mechanisms at parton stage in Au+Au collisions at RHIC.

2. Analysis

The data used for this analysis were taken with the STAR experiment during the $\sqrt{s_{NN}}=200$ GeV Au+Au run in 2004 and the $\sqrt{s_{NN}}=200$ GeV $d+Au$ and $p+p$ run in 2003 at RHIC. A minimum bias (minbias) Au+Au collision trigger was defined by requiring coincidences between two zero degree calorimeters (ZDCs). A 0-12% central Au+Au collision trigger was defined using the scintillator CTB (Central Trigger Barrel) and both the ZDCs. A 0-5% central data set is further selected by cutting on the event multiplicity in the 0-12% central data sample. The minimum bias event sample is subdivided into two centrality bins: 10-40% and 40-80% for the BEMC non-photonic electron analysis. A minbias $d+Au$ collision trigger was defined by requiring at least one spectator neutron in the outgoing Au beam direction depositing energy in a ZDC. A minbias $p+p$ collision trigger was defined by coincidences between two BBCs (Beam-Beam Counter).

The low p_T (< 3 GeV/ c) D^0 mesons were reconstructed in minbias Au+Au and $d+Au$ collisions through their decay $D^0 \rightarrow K^- \pi^+$ ($\bar{D}^0 \rightarrow K^+ \pi^-$) with a branching ratio of 3.83%. Analysis details can be found in Ref. [12, 13]. Panel (a) of Fig. 1 shows the p_T distributions of invariant yields for the D^0 mesons in minbias Au+Au (solid stars)

and d +Au (open stars) collisions.

The charm-decayed prompt muons (μ^\pm) at $0.17 < p_T < 0.25$ GeV/ c were analyzed by combining the energy-loss information measured by the STAR Time Projection Chamber (TPC) and the mass-square (m^2) information measured by the TOF detector. Analysis details can be found in Ref. [14]. The p_T distribution for μ^\pm invariant yields in 0-12% central and minbias Au+Au collisions is shown in panel (a) of Fig. 1.

By using the combined information from the STAR TPC and TOF detectors, electrons can be identified and measured. Detailed analysis for the inclusive, photonic and non-photonic electron reconstruction can be found in Ref. [12]. The p_T spectra for non-photonic electrons measured by TOF in 0-12% central Au+Au (solid squares), minbias Au+Au (solid circles), d +Au (open circles) and p + p (open squares) collisions are shown in panel (a) of Fig. 1.

Electrons can also be identified by using the STAR TPC and BEMC detectors as shown in Ref. [15, 16]. Panel (b) of Fig. 1 shows the non-photonic electron spectra measured by BEMC for 0-5% central (stars), 10-40% (pink crosses), 40-80% (triangles) Au+Au, d +Au (circles) and p + p (squares) collisions.

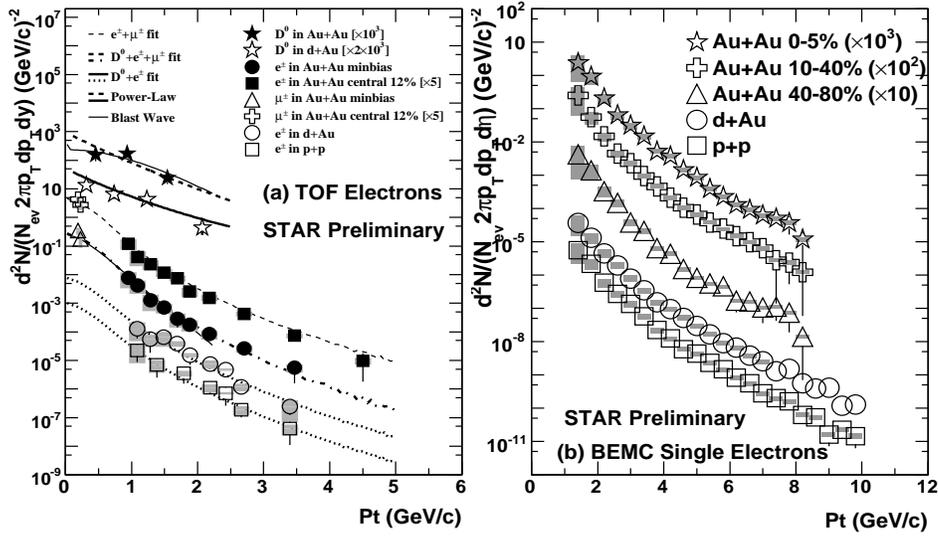


Figure 1. (a) p_T distributions of invariant yields for D^0 mesons in minbias Au+Au (solid stars) and d +Au (open stars) collisions, charm-decayed prompt muons in 0-12% central Au+Au (open crosses) and minbias Au+Au (open triangles) collisions and non-photonic electrons in 0-12% central Au+Au (solid squares), minbias Au+Au (solid circles), d +Au (open circles) and p + p (open squares) collisions measured by the TOF detector. (b) p_T distributions of invariant yields for single electrons in 0-5% central (stars), 10-40% (crosses), 40-80% (triangles) Au+Au, d +Au (circles) and p + p (squares) collisions measured by the BEMC detector.

3. Results

Using a combined fit applied to the directly reconstructed D^0 spectra, charm-decayed prompt muon spectra and the non-photonic electron spectra in 0-12% central Au+Au, minbias Au+Au and d +Au collisions, the mid-rapidity D^0 yield is then obtained and converted to the mid-rapidity charm total cross-section per nucleon-nucleon collision ($d\sigma_{c\bar{c}}^{NN}/dy$) and the charm total cross-section per nucleon-nucleon collision ($\sigma_{c\bar{c}}^{NN}$) following the method addressed in Ref. [12]. $\sigma_{c\bar{c}}^{NN}$ is measured to be $1.33 \pm 0.06(\text{stat.}) \pm 0.18(\text{sys.})$ mb in 0-12% central Au+Au, $1.26 \pm 0.09 \pm 0.23$ mb in minimum bias Au+Au collisions and $1.4 \pm 0.2 \pm 0.2$ mb in minimum bias d +Au collisions at $\sqrt{s_{NN}}=200$ GeV. Panel (a) of Fig. 2 shows the $d\sigma_{c\bar{c}}^{NN}/dy$ as a function of N_{bin} for minbias d +Au, minbias Au+Au and 0-12% central Au+Au collisions. It can be observed that the charm total cross-section roughly follows the N_{bin} scaling from d +Au to Au+Au collisions which supports the conjecture that charm quarks are produced at early stages in relativistic heavy-ion collisions. Panel (b) of Fig. 2 shows the $\sigma_{c\bar{c}}^{NN}$ as a function of \sqrt{s} for minbias d +Au, minbias Au+Au and 0-12% central Au+Au collisions compared various collision systems at various collision energies as well as theoretical predictions. However, one can clearly see from Fig. 2 that the $d\sigma_{c\bar{c}}^{NN}/dy$ in the three measured collision systems are about a factor of 5 larger than the NLO predictions [17, 18] shown as the light green band in panel (a).

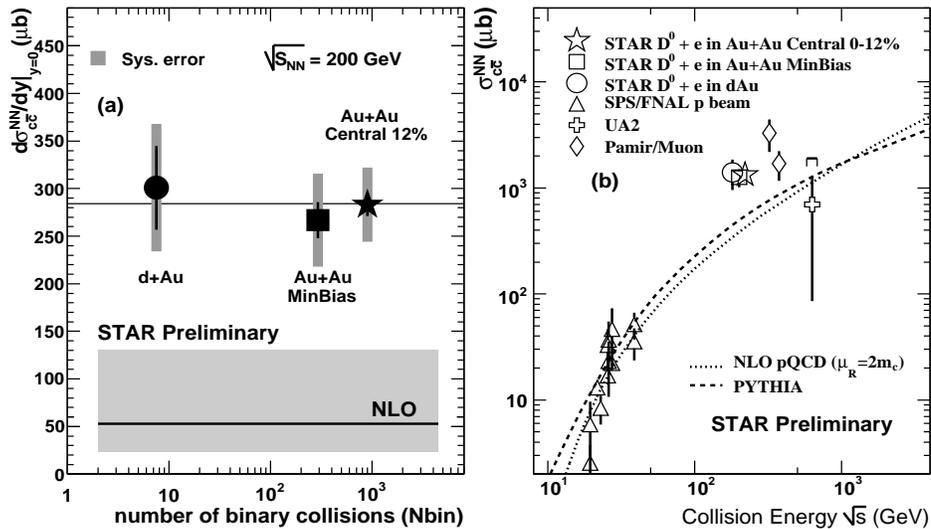


Figure 2. (a) Mid-rapidity charm total cross-section per nucleon-nucleon collision as a function of number of binary collisions (N_{bin}) in d +Au, minbias and 0-12% central Au+Au collisions. (b) Charm total cross-section per nucleon-nucleon collision as a function of collision energy (\sqrt{s}) in d +Au, minbias and 0-12% central Au+Au collisions compared various collision systems with various collision energies.

A Blast-Wave model [19] fit to the D^0 , prompt muons and non-photonic electron p_T spectra at $p_T < 2$ GeV/ c in minbias Au+Au collisions, from which the charm hadron kinetic freeze-out temperature T_{fo} and the maximum flow velocity β_m are derived. Fig. 3

shows the T_{fo} versus β_m for charm hadrons in minbias Au+Au collisions. The 1σ contour from the Blast-Wave fit with quadratic sum of statistical and systematic errors of the spectra is shown as the pink curve in Fig. 3. A larger T_{fo} (>140 MeV) and a smaller β_m compared to those of light hadrons [20] can be observed from the figure, which indicate that charm hadrons may kinetically freeze-out early and may not be in complete equilibrium with the rest of the system at kinetic freeze-out in minbias Au+Au collisions.

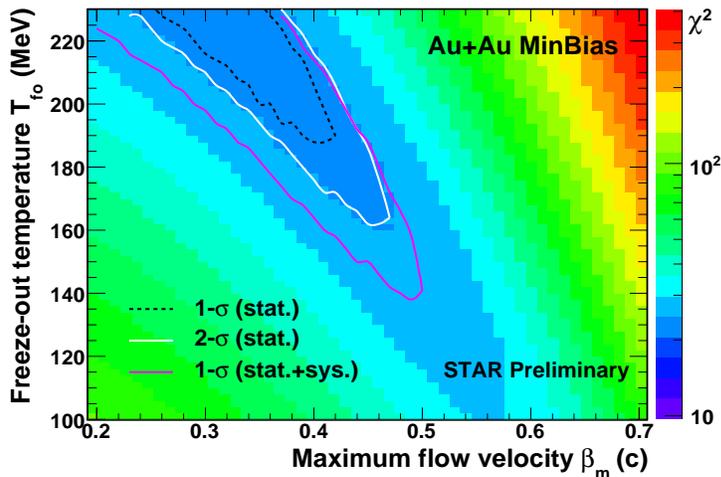


Figure 3. (a) Charm hadron freeze-out temperature (T_{fo}) versus maximum flow velocity (β_m) in minbias Au+Au collisions.

The $D^0 R_{AA}$ (stars in Panel (a) of Fig. 4) are calculated by dividing the D^0 data points in minimum bias Au+Au collisions by the power-law fit results of the $D^0 p_T$ spectrum in d +Au collisions scaled by N_{bin} . The prompt muon R_{AA} are calculated by dividing the p_T spectrum in 0-12% central Au+Au collisions to that in minbias Au+Au collisions with N_{bin} scaling, shown as triangles in panel (a) of Fig. 4. The TOF-measured single electron R_{AA} are also calculated by dividing the p_T spectra in 0-12% central Au+Au collisions to the $D^0 \rightarrow e^\pm$ decayed shape in d +Au collisions scaled by N_{bin} , shown as open circles in panel (a) of Fig. 4. The R_{AA} 's for D^0 and muons at low p_T are consistent with unity considering uncertainties. The non-photonic electron R_{AA} in 0-12% central Au+Au collisions is observed to be significantly below unity at $1 < p_T < 4$ GeV/ c .

The BEMC-measured non-photonic electron R_{AA} 's for 0-5% central (stars), 10-40% (crosses), 40-80% (triangles) Au+Au collisions and d +Au (circles) collisions are calculated by dividing the corresponding non-photonic electron p_T spectra to that in p + p collisions, respectively, and are shown in panel (b) of Fig. 4. The non-photonic electron R_{AA} in d +Au collisions (R_{dAu}) is close to/above unity indicating the Cronin effect in d +Au collisions. In Au+Au collisions, the R_{AA} in central collisions is smaller than in peripheral collisions. The R_{AA} in 0-5% central Au+Au collisions is significantly below

unity at $p_T > 2$ GeV/ c and is suppressed as strongly as that of light hadrons [2], which indicates a large amount of energy-loss for heavy quarks in central Au+Au collisions.

According to the famous “dead-cone” effect [9, 10, 11], bottom quarks should lose smaller energy than charm quarks due to their mass difference. Theoretical calculations [11, 21] considering only the charm contributions to the non-photonics electrons agree with the measured non-photonics electron R_{AA} , while calculations with single electrons decayed from both bottom and charm quarks give larger R_{AA} values. However, in most theoretical models, the amount of bottom quark and charm quark contributions to the non-photonics electron spectra, respectively, still remains uncertain. Thus, an experimental measurement of the R_{AA} ’s from directly reconstructed charm hadrons (D^0 , D^\pm , D_S , Λ_C , etc.) at high p_T is necessary. A detector upgrade plan for a silicon pixel detector, the Heavy Flavor Tracker (HFT) [22], at STAR will make it possible for the direct charm hadron R_{AA} measurements in the near future.

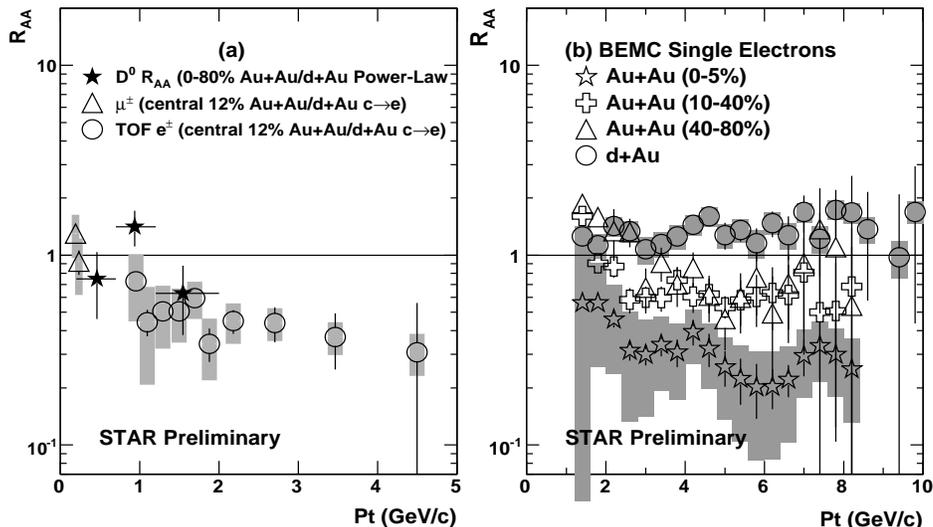


Figure 4. (a) p_T distributions of the nuclear modification factor (R_{AA}) for D^0 , charm-decayed prompt muons and single electrons measured by the TOF detector. (b) p_T distributions of R_{AA} for non-photonics electrons in 0-5% central, 10-40%, 40-80% Au+Au and d+Au collisions measured by the BEMC detector.

4. Conclusion

We present measurements on D^0 meson production via direct reconstruction of its hadronic decay channel $D^0 \rightarrow K\pi$ in minimum bias d+Au and Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV with p_T up to ~ 3 GeV/ c . Non-photonics electron spectra from the charm semi-leptonic decays are analyzed from the same data set as well as in $p+p$ collision at $\sqrt{s}=200$ GeV using the STAR Time-of-Flight (TOF) and Barrel EMC (BEMC) detectors, respectively. Results of the charm-decayed prompt muon spectra are also presented at low p_T in Au+Au collisions measured by the TOF detector. The

charm production total cross-section per nucleon-nucleon collision is measured to be $1.26 \pm 0.09(\text{stat.}) \pm 0.23(\text{sys.})$ mb in minimum bias Au+Au collisions, which is consistent with the N_{bin} scaling compared to $1.4 \pm 0.2 \pm 0.4$ mb in minimum bias d +Au collisions, and supports the idea that charm quarks should be produced mostly via parton fusion at early stage in relativistic heavy-ion collisions. A Blast-Wave model fit to the low p_T (< 2 GeV/ c) non-photonic electrons, prompt muons and D^0 spectra shows that charm hadrons may kinetically freeze-out earlier than light hadrons with a smaller collective velocity. The nuclear modification factors (R_{AA}) of the non-photonic electrons in central Au+Au collisions are significantly below unity at $p_T > \sim 2$ GeV/ c , which indicates a significant amount of energy loss for heavy quarks in Au+Au collisions. The charm transverse momentum distribution must have been modified by the hot and dense matter created in central Au+Au collisions at RHIC.

References

- [1] C. Adler et al. Phys. Rev. Lett. 87 (2001) 182301.
- [2] J. Adams et al. Phys. Rev. Lett. 91 (2003) 172302.
- [3] M. Gyulassy, nucl-th/0403032.
- [4] http://www.bnl.gov/bnlweb/pubaf/pr/PR_display.asp?prID=05-38.
- [5] Z. Lin et al. Phys. Rev. C 51 (1995) 2177.
- [6] J. J. Aubert et al., Phys. Lett. B 123 (1983) 275.
- [7] G. Moore et al. Phys. Rev. C 71 (2005) 064904.
- [8] H. van Hees et al. nucl-th/0508055.
- [9] Y. Dokshizer et al. Phys. Lett. B 519 (2001) 199.
- [10] M. Djordjevic et al. Phys. Rev. Lett. 94 (2005) 112301.
- [11] N. Armesto et al. Phys. Rev. D 71 (2005) 054027.
- [12] J. Adams et al. Phys. Rev. Lett. 94 (2005) 062301.
- [13] Haibin Zhang, nucl-ex/0510063, Quark Matter 2005 proceedings.
- [14] Yifei Zhang, nucl-ex/0607011, these proceedings.
- [15] Jaro Bielcik, nucl-ex/0511005, Quark Matter 2005 proceedings.
- [16] nucl-ex/0607012, STAR paper in preparation for PRL.
- [17] R. Vogt, Int. J. Mod. Phys. E 12, 211 (2003).
- [18] R. Vogt, hep-ph/0203151.
- [19] E. Schnedermann, et al. Phys. Rev. C 48, 2462 (1993).
- [20] J. Adams et al. Phys. Rev. Lett. 92 (2004) 112301.
- [21] M. Djordjevic et al. Phys. Lett. B 632 (2006) 81.
- [22] Kai Schweida, nucl-ex/0510003, Quark Matter 2005 proceedings.