In this report, we present the measurements of open charm production at mid-rapidity in p+p, d+Au, and Au+Au collisions at RHIC energies. The techniques of direct reconstruction of open charm via its hadronic decay and indirect measurements via its semileptonic decay are discussed. The beam energy dependence of total charm cross section, electron $p_T$ spectra, and their comparisons to theoretical calculations, including NLO pQCD, are presented. The electron spectra in p+p, d+Au, and Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV show significant variation. The open charm absolute cross section at midrapidity and its centrality dependence are compared to those of inclusive hadrons integrated over $p_T > 1.5$ GeV/c.

1. Introductions

Hadrons with heavy flavor are unique tools for studying the strong interaction described by Quantum Chromodynamics (QCD). Due to the large charm quark mass, which requires large energies ($\gtrsim 3$ GeV) for their creation, charm quark production can be evaluated by perturbative QCD (pQCD) even at low momentum with the introduction of additional scales related to its mass [1, 2]. Therefore, the theoretical calculations of the charm hadron production cross section integrated over momentum space are expected to be less affected by non-perturbative processes and hadronization than those of the light hadrons [3]. Charm production has been proposed as a sensitive measurement of parton(gluon) distribution function in nucleon and the nuclear shadowing effect by systematical studies of p+p, and p+A collisions [4]. The reduced energy loss of heavy quarks(“deadcone” effect) at momentum range $5 \lesssim p_T \lesssim 10$ GeV/c will help us study the energy loss mechanism within the partonic medium [5]. A possible enhancement of charmonium ($J/\psi$) production can be present at RHIC energies [6, 7, 8] through charm quark coalescence. This effect is opposed to the $J/\psi$ suppression in a Quark-Gluon Plasma(QGP) in the absence of that process [9]. The measurement of both open charm yield and charmonia may allow us to quantify the effects and study whether charms are in chemical equilibrium with the system.
In addition, the heavy flavor transverse momentum distributions and their anisotropic flow can be used to study the nature of early thermalization in A+A collisions [10].

Identification of charmed hadrons is difficult due to its short lifetime \(c\tau(D^0) = 124 \mu m\), low production rate and overwhelming combinatoric background. Most measurements of the total charm cross section in hadron-hadron collisions were performed at low center-of-mass energies (\(\lesssim 40 \text{ GeV}\)) in fixed target experiments [11, 12]. The measurements at high energy colliders were either at high \(p_T\) [13], with large uncertainty [14, 15] or inconsistency [16]. Theoretical predictions for RHIC energy region differ significantly [17, 18]. At RHIC, direct measurements of open charm from charm hadronic decays and indirect measurements from charm semileptonic decays in many beam conditions are possible. We will illustrate the techniques used in open charm measurements at RHIC and discuss the results.

2. Direct open charm reconstruction

- **Large acceptance, Large dataset**
  The data used in \(D^0\) direct reconstruction were taken during the 2003 RHIC run in d+Au collisions at \(\sqrt{s_{NN}} = 200 \text{ GeV}\) with the Solenoidal Tracker at RHIC (STAR) [19, 20]. A total of 15.7 million minimum bias triggered d+Au collision events were used in \(D^0\) analysis. The primary tracking device of the STAR detector is the Time Projection Chamber (TPC) which was used to reconstruct the decay of \(D^0 \rightarrow K^-\pi^+ (D^0 \rightarrow K^+\pi^-)\) with a branching ratio of 3.83%.

- **Event Mixing**
  The invariant mass spectrum of \(D^0(\bar{D}^0)\) was obtained by pairing oppositely charged kaon and pion in same event with the parent rapidity \(|y| < 1\). The kaon and pion tracks were identified through the ionization energy loss \((dE/dx)\) in the TPC. The track reconstruction in the TPC gives a single track projection resolution of \(\sim 1 \text{ cm}\) around the collision vertex and therefore does not allow to resolve the exact decay topology. The \(D^0\) signal in \(p_T < 3 \text{ GeV/c}\) and \(|y| < 1\) after mixed-event background subtraction [21] is shown in the left panel of Fig. 1.

In current STAR analyses, the total charm cross section is largely determined by directly reconstructed \(D(\bar{D})\) at low \(p_T\) [19, 20]. In addition, \(D^*\) has been measured at \(1.5 \lesssim p_T < 6 \text{ GeV/c}\) and \(D^\pm, D^0\) at \(p_T \simeq 10 \text{ GeV/c}\) [22]. In this presentation, we will focus on total charm cross section and its centrality dependence [19, 23].
3. Electron spectra from charm semileptonic decay

There are three techniques used to identify electrons in STAR and PHENIX:

1. Tracking+RICH+EMCAL
   This method is used by PHENIX collaboration to identify electrons [14, 23]. Tracking from drift chamber and pad chamber provides particle track with high momentum resolution. A Ring Image Cerenkov Detector (RICH) is used as veto counter, and an electromagnetic calorimeter confirms the track’s existence and provides a E/p measurement for electron selection.

2. Tracking+dE/dx+EMC
   This method is used by STAR collaboration to identify electron with $p > 1.5$ GeV/c [19, 20]. The STAR TPC not only provides tracking in a solenoidal field, but also has good particle identification capabilities through ionization energy loss at resolution of about 8%. Due to relativistic rise of dE/dx of electron at high $\beta\gamma$, its separation from
\[ \pi, K \text{ and } p \text{ are very good at hadron rejection of } > 10^{-2} \text{ at high } p_T. \] The addition of E/p=1.0 from EMC further reject \( \pi, K \) and p, and hadrons with high dE/dx (nuclei, ghost tracks). Since EMC can be used as a trigger detector, the electron spectra from this method can be extended to much higher \( p_T \) with high statistics [24].

3. Tracking+dE/dx+TOF

This new technique is developed by STAR collaboration. A prototype time-of-flight system (TOFr) [25] based on the multi-gap resistive plate chamber technology was installed in STAR. It covers \(-1 < \eta < 0\) and allows particle identification for \( p_T < 3.5 \text{ GeV/c} \). In addition to its capability of hadron identification [25], electrons could be identified at low momentum \((0.2 < p_T < 3 \text{ GeV/c})\) by the combination of velocity \((\beta)\) from TOFr and \( dE/dx \) from TPC measurements. The right panel of Fig. 1 demonstrates the clean separation of electrons from hadrons using their energy loss \((dE/dx)\) in the TPC after applying a TOFr cut of \(|1/\beta - 1| \leq 0.03\). This cut eliminated the hadrons crossing the electron \( dE/dx \) band. Electrons were required to originate from the primary vertex. Hadron contamination was evaluated to be about 10 − 15% in this selection.

Gamma conversions \( \gamma \to e^+e^- \) and \( \pi^0 \to \gamma e^+e^- \) Dalitz decays are the dominant photonic sources of electron background. There are again several methods used to study the background electron sources:

1. Cocktail Modeling
   This method was adapted by PHENIX Collaboration in their first publication [14]. The cocktail is a detailed detector simulation of electrons/positrons from \( \gamma \) conversion and Dalitz decays from \( \pi^0, \eta \) and other photonic sources.

2. Converter
   This method was adapted by PHENIX Collaboration in their latest report [23]. Two datasets with and without a converter with known thickness were taken and analyzed. The two measurements allows to untangle the sources associated with photon conversion and those without. Species-dependent Dalitz fraction per \( \gamma \) and contribution from other photonic sources \((\eta, \omega, \rho, \phi \text{ and } K)\) are evaluated by detailed detector simulations.

3. Invariant Mass Reconstruction
   The \( e^+e^- \) pairs from photon conversions and Dalitz decays are present mainly at small pair invariant mass and/or small opening angle [19, 20]. Due to the large coverage of the TPC, the efficiency of finding
pairs is very high for such processes. To measure the background, the invariant mass and opening angle of the pairs were constructed by first selecting an electron (positron) in TOFr and then matching it with every positron (electron) candidate reconstructed in the TPC without additional requirement of a secondary vertex at the conversion point. In this method, both inclusive electron spectra and background sources are taken from same dataset, and the reconstructed background spectrum is not sensitive to the detailed knowledge of the conversion and Dalitz decay. About 95% of electrons from sources other than charm semileptonic decays have been measured with this method, while the remaining fraction (<5%) from decays of \( \eta, \omega, \rho, \phi \) and \( K \) was determined from detailed detector simulations.

4. Discussions

Fig. 2 shows the energy dependence of the electron \( p_T \) spectra from ISR to Tevatron. Direct open charm measurements (STAR, CDF) are con-
Fig. 3. Total $c\bar{c}$ cross section per nucleon-nucleon collision vs. the collision energy (in $\sqrt{s_{NN}}$).

Verted to electron spectra. Several measurements at RHIC have shown to be consistent between (dE/dx+EMC), direct D, (dE/dx+TOF) at STAR, and to some extent, the measurements in p+p collisions between STAR and PHENIX. Fig. 2 shows significant dispersion of electron distribution at $\sqrt{s_{NN}}=200$ GeV at RHIC from Au+Au, d+Au to p+p at $p_T \simeq 2$ GeV/c where statistics are still high. The variation in spectra is possibly due to the interactions between the charm quark (hadron) and the medium. The deadcone effect would be most effective at $5 < p_T < 10$ GeV/c and not yet accessible at the $p_T$ range ($\simeq 2$ GeV/c) of electrons. The beam energy dependence of the cross section is shown in Fig. 3. The PHENIX results are derived from electron spectrum in Au+Au minbias collisions using the electron spectrum shape from PYTHIA6.205. The STAR result is from a combined fit of $D^0$ and electron spectra in d+Au minbias collisions. At $\sqrt{s} \sim 52 - 63$ GeV, the available measurements are inconclusive due to the inconsistency between different measurements and are omitted. At $\sqrt{s_{NN}} = 200$ GeV, both PYTHIA and NLO pQCD calculations underpredict the total charm cross section. This is evident from STAR data but less pronounced in PHENIX results. There
are indications that a large charm production cross section ($\sigma_{c\bar{c}}^{NN} \approx 2 - 3$ mb) at $\sqrt{s_{NN}} \approx 300$ GeV is essential to explain cosmic ray data [30]. The centrality dependence of charm $d\sigma/dy$ per binary nucleon-nucleon collision at midrapidity shows possible dependence on centrality with lower production cross section in central collisions as in Fig. 4. In the same figure, the cross sections per binary nucleon-nucleon collisions of inclusive hadrons [31] ($d\sigma_{h^+}/d\eta/3(\mu b)$), which were integrated over $p_T > 1.5$ GeV/c (close to the mass of charm hadron $m_D$) and scaled down by a factor of 3 for three light quark flavors, show same magnitude of absolute cross section and a similar trend. This may suggest that particle production rate is not sensitive to flavor when the momentum transfer is above the production threshold.

A direct reconstruction of open charm spectra in Au+Au collisions from $0 \lesssim p_T \lesssim 10$ GeV/c in future runs, when compared with those from d+Au data [19, 22], will enable us to study the thermalization at low $p_T$ and deadcone effect at high $p_T$. The elliptic flow $v_2$ measurements of charm

![Fig. 4. Charm differential cross section per binary nucleon-nucleon collision ($d\sigma_{c\bar{c}}^{NN}/d\eta$) at midrapidity as function of number of participant nucleons at RHIC $\sqrt{s_{NN}}=200$ GeV. Also plotted as open stars are cross section per binary nucleon-nucleon collisions ($d\sigma_{h^+}/d\eta/3(\mu b)$) of inclusive hadrons integrated over $p_T > 1.5$ GeV/c ($\approx m_D$) and scaled down by a factor of three.](image-url)
flow with higher statistics at the same $p_T$ range will further strengthen the case, since early thermalization will result in large $v_2$ at low $p_T$, and absence of large energy loss due to deadcone effect may result in smaller $v_2$ at high $p_T$ when compared to those of light hadrons.

5. Summary

In summary, charm cross section and transverse momentum distributions from $p+p$, $d+Au$ and $Au+Au$ collisions have been measured by the STAR and PHENIX collaborations at RHIC. The NLO calculation underpredicts the total cross section in this energy range. A possible centrality dependence of charm cross section can explain the marginally different cross sections observed by STAR in $d+Au$ collisions and PHENIX in $Au+Au$ collisions. We look forward to more results using charm as probe to the hot and dense medium created at RHIC from run4 and future runs.

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REFERENCES

[1] P.L. McGaughey et al., Int. J. Mod. Phys. A 10, 2999(1995).
[2] M.L. Mangano et al., Nucl. Phys. B 405 (1993) 507.
[3] S.S. Adler et al., (PHENIX Collaboration), Phys. Rev. Lett. 91 (2003) 241803; J. Adams et al., (STAR Collaboration), Phys. Rev. Lett. 92 (2004) 171801.
[4] Z. Lin and M. Gyulassy, Phys. Rev. Lett. 77 (1996) 1222.
[5] Y.L. Dokshitzer and D.E. Kharzeev, Phys. Lett. B 519 (2001) 199.
[6] A. Andronic et al., Phys. Lett. B 571 (2003) 36, and references therein.
[7] R.L. Thews, M. Schroedter, and J. Rafelski, Phys. Rev. C 63 (2001) 054905, and references therein.
[8] M.I. Gorenstein et al., J. Phys. G 28 (2002) 2151.
[9] T. Matsui and H. Satz, Phys. Lett. B 178 (1986) 416.
[10] N. Xu and Z. Xu Nucl. Phys. A 715 (2003) 587c; S. Batsouli et al., Phys. Lett. B 557 (2003) 26; Z.W. Lin and D. Molnar, Phys. Rev. C 68 (2003) 044901; X. Dong et al., Phys. Lett. B 597 (2004) 328.
[11] S.P.K. Tavernier, Rep. Prog. Phys. 50 (1987) 1439; and references therein.
[12] G.A. Alves et al., (E769 Collaboration), Phys. Rev. Lett. 77 (1996) 2388.
[13] D. Acosta et al., (CDF II Collaboration), Phys. Rev. Lett. 94 (2003) 241804.
[14] K. Adcox et al., (PHENIX Collaboration), Phys. Rev. Lett. 88 (2002) 192303.
[15] O. Botner it et al., (UA2 Collaboration), Phys. Lett. B 236 (1990) 488.
[16] F.W. Büsser et al., Nucl. Phys. B 113 (1976) 189.
[17] R. Vogt, hep-ph/0203151 and references therein. The curve in Fig. 3 is a NLO pQCD calculation with CTEQ5M, $\mu_F = \mu_R = 2m_c$, $m_c = 1.2$ GeV/c$^2$.
[18] J. Raufeisen and J.-C. Peng, Phys. Rev. D 67 (2003) 054008.
[19] J. Adams, et al. (STAR Collaboration), nucl-ex/0407006.
[20] L.J. Ruan, J. Phys. G 30 (2004) S1197-S1200; nucl-ex/0403054. H. Zhang, DNP 2003, Hot Quarks 2004.
[21] C. Adler et al., Phys. Rev. C66, 06190(R)(2002); H. Zhang, J. Phys. G 30 (2004) S577.
[22] A. Tai, J. Phys. G 30 (2004) S809-S818; nucl-ex/0404029
[23] PHENIX Collaboration, S.S. Adler, et al., nucl-ex/0409028
[24] A.A.P. Suaide, J. Phys. G 30 (2004) S1179-S1182; nucl-ex/0404019
[25] J. Adams et al., (STAR Collaboration), nucl-ex/0309012
[26] J. Adams et al., (STAR Collaboration), nucl-ex/0401008
[27] R. Averbeck, J. Phys. G 30 (2004) S943-S950.
[28] D. Teaney, BNL seminar; private communications.
[29] T. Sjöstrand, L. Lönnblad and S. Mrenna, hep-ph/0108264. In this paper we used PYTHIA 6.152 with CTEQ5M1.
[30] I.V. Rakobolskaya et al., Nucl. Phys. B 112 (2003) 353c.
[31] J. Adams et al., (STAR Collaboration), Phys. Rev. Lett. 91 (2003) 172302; Phys. Rev. Lett. 91 (2003) 072304.