Directed flow of open charm in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using a quark coalescence model

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The directed flow ($v_1$) of open charm meson ($D^0$) is studied in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using A Multi-Phase Transport (AMPT) model framework with partonic interactions (string melting version). Within this framework, it is found that although the initial spatial eccentricity ($e_1$) of charm quark is smaller than light quarks, the charm quark $v_1$ magnitude is found to be approximately 7 times larger than that of the light u quark at large rapidity. This indicates that the charm quarks can retain more information from initial condition than the light quarks. We have studied the directed flow of $D^0$ as a function of rapidity and transverse momentum using quark coalescence as the mechanism for hadron production. Like charm quark, the $D^0$ $v_1$ magnitude is found to be about 7 times larger than that of the light ($\pi$) hadrons at large rapidity.

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I. INTRODUCTION

The main purpose of relativistic heavy-ion experiments is to understand the formation and evolution of a strongly interacting matter, called Quark Gluon Plasma (QGP) [1], which is expected to be formed micro-second after the big bang. Experiments at the Brookhaven Relativistic Heavy Ion Collider (RHIC) and at CERN Large Hadron Collider (LHC) facilities established the existence of such strongly interacting matter [2], but the complexity in dynamics of the medium is still being explored. Collective motion of the particles emitted from these collisions is of special interest because it is sensitive to the equation of state of the system. Directed flow ($v_1$) is characterized by the first harmonic coefficient in the Fourier decomposition of the momentum distribution of emitted particles [3, 4].

$$v_1 = \langle \cos(\phi - \Psi_{RP}) \rangle,$$

(1)

where $\phi$ denotes the azimuthal angle of emitted particles and $\Psi_{RP}$ is the reaction plane subtended by the $x$-axis and impact parameter direction. In this paper we consider the rapidity-odd component of directed flow ($v_1^{\text{odd}}(y) = -v_1^{\text{odd}}(-y)$), which refers to a sideward collective motion of emitted particles, and is a repulsive collective deflection in the reaction plane. Whereas, the fluctuations in the initial-state of the colliding nuclei can generate a rapidity-even component of $v_1$ ($v_1^{\text{even}}(y) = v_1^{\text{even}}(-y)$) and it is unrelated to the reaction plane [5]. In this paper $v_1$ denotes the rapidity-odd component.

Model calculation [6] suggested that the directed flow near the beam rapidity is initiated during the passage of two colliding nuclei. The typical time scale of passing is $\sim 2R/\gamma \sim 0.1$ fm/c for a Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV, where $R$ and $\gamma$ are the radius of nuclei and Lorentz factor respectively. So the observable of directed flow is sensitive to the dynamics in the early stages of nuclear collisions [7]. Both hydrodynamic [8, 10] and transport model [11] calculations have shown that the directed flow at mid-rapidity, especially the baryons, are sensitive to the equation of state of the system [9, 10]. Several hydrodynamic calculations suggested that the negative $v_1$-slope near mid-rapidity (called “wiggle” [10, 12] or “anti-flow” [13]) could be a possible QGP signature [10]. However, there are the hadronic models with partial baryon-stopping and positive space momentum correlations [12], and a hydro model full stopping with a tilted source [14] can also explain the anti-flow nature of $v_1$. Recently, the STAR experiment at the RHIC has reported the measurements of directed flow of several light hadron species ($\pi$, K, $K^0_S$, p, A and their anti-particles, and $\phi$) over the beam energy range 7.7–200 GeV [15, 16]. Number of Constituent Quark (NCQ) scaling has been observed in higher flow harmonics ($v_2$ and $v_3$) at both RHIC and LHC energies [17–19]. Such scaling is interpreted as evidence of quark degrees of freedom in the early stages of heavy-ion collisions. The recent $v_1$ measurements reported by STAR [16] found to be consistent with the particles being formed via coalescence of constituent quarks.

The heavy quarks play a crucial role in probing the QGP medium, because its mass is significantly larger than the typical temperature achieved in such a collision. They are produced in hard partonic scatterings during the early stages of collisions. The probability of thermally produced heavy quarks are expected to be small in the high temperature phase of QGP. Due to large mass, they decouple in the early stages of the collision. The total number of charm quarks is frozen quite early in the history of collision. So the heavy...
quarks are capable of retaining information of early time dynamics. The measurement of directed flow of heavy quarks can offer insight into the early time dynamics of the system. Apart from that, recent measurements at the RHIC [20] and LHC [21] have shown significant elliptic flow for the charm hadrons. The flow magnitude of charm hadrons seems to follow that of the light hadrons at mid-rapidity. The $D^0$ $v_2$ from the AMPT model [22] moderately explain recent STAR data at mid-rapidity [23, 24].

In this paper, we aim to study the directed flow of charm mesons ($D^0$($u\bar{c}$)) in Au+Au collisions at 200 GeV within the framework of AMPT model. Since the directed flow is generated in early times and also the charm quark production limited to the primordial stage of the collisions, the study of directed flow can offer insight into the initial dynamics of the system. In this work, we have used string melting version (ver 2.26) of AMPT model [22] (which includes parton coalescence) for the estimation of directed flow. We have studied the $v_1(y,p_T)$ of both heavy and light quarks. We have employed dynamic coalescence mechanism to form hadrons from those quarks.

This paper is organized as follows. In the section II, we discuss briefly AMPT model and dynamic coalescence of partons. Section III describes the directed flow $v_1$ of heavy and light flavor mesons at 200 GeV Au+Au collisions using the AMPT framework. (version 2.26). The section IV presents a summary of the results.

II. THE AMPT MODEL

The AMPT is a hybrid transport model [22]. It uses the initial conditions from Heavy Ion Jet Interaction Generator (HIJING) [25]. However the mini-jet partons are made to undergo scattering before they are allowed to fragment into hadrons. The string melting (SM) version of the AMPT model (labeled here as AMPT-SM) is based on the idea that for energy densities beyond a critical value of $\sim 1$ GeV/fm$^3$, it is difficult to visualize the coexistence of strings (or hadrons) and partons. Hence the need to melt the strings to partons. Scattering among partons are modelled by Zhang’s parton cascade [26]. Once the interactions stop, the partons then hadronizes through the mechanism of parton coalescence. The parton-parton interaction cross section in the string-melting version of the AMPT is given by

$$\sigma_{pp} = \frac{9\pi\alpha_s^2}{2\mu^2}$$

For this study we set the strong coupling constant as $\alpha_S = 0.47$ and the parton screening mass to be $\mu = 3.22$ fm$^{-1}$. This leads to $\sigma_{pp} = 3$ mb. As the hadronization of heavy quarks is not implemented in AMPT-SM, we use a dynamical coalescence model to form open charm mesons. Such a model has been extensively used at both intermediate and high energies. In this model we use phase-space information of partons at the freezeout to form open charm mesons based on Wigner phase space function [27].

The probability to form a meson from a pair of quark and anti-quark is given by,

$$\rho^W(r,k) = \int \psi\left(r + \frac{R}{2}\right)\psi^\ast\left(r - \frac{R}{2}\right)exp(-i\mathbf{k} \cdot \mathbf{R})d^3\mathbf{R} = 8\exp\left(\frac{r^2}{\sigma^2} - \frac{\sigma^2}{2}\right)$$

where $R$ is the center-of-mass coordinate of the quarks or anti-quarks and $\Psi$ is the quark wave function. The relative momentum between the two quarks is $\mathbf{k} = \frac{1}{m_1 + m_2}(m_2\mathbf{p}_1 - m_1\mathbf{p}_2)$. Here $m_i$ is the mass of $i^{th}$ quark, and $p_1$ and $p_2$ are heavy quark and light antiquark transverse momenta, respectively, defined in the center-of-mass frame of produced meson [28]. For quarks, the Wigner phase-space densities are obtained from the spherical harmonic oscillator wave functions,

$$\Psi(r_1, r_1) = \frac{1}{(\pi\sigma^2)^{3/4}}\exp\left[-\frac{r^2}{2\sigma^2}\right]$$

where $\mathbf{r} = \mathbf{r}_1 - \mathbf{r}_2$ and $\sigma$ is the size parameter related to the root mean square radius as $\langle r^2 \rangle = \langle 3/8 \rangle \sigma^2$ [29, 30]. In this paper, we have taken $\langle r^2 \rangle = 0.30$ fm$^2$ for $D^0$ and $\langle r^2 \rangle = 0.44$ fm$^2$ for pion as predicted by the light-front quark model [32].

III. RESULTS AND DISCUSSION

The flow harmonic, $v_1$, quantifies the 1$^{st}$ order anisotropy of particles of interest in the momentum space, and its magnitude is a response of the initial anisotropy, the expansion dynamics and the equation of state of the medium. Figure 4 presents the initial odd-eccentricity ($\epsilon_1$) of $u$ and c quarks as function of spatial rapidity ($y_s$) in Au+Au collisions at 200 GeV in three different transverse momentum ($p_T$) regions. The $\epsilon_1$ can be extracted following the equation [33, 34]:

$$\epsilon_1 = \langle \cos(\phi_s - \Psi_{RP}) \rangle,$$

where $\phi_s$ denotes the particle azimuthal angle, $\langle \ldots \rangle$ denotes the average at a given rapidity and $\Psi_{RP}$ is the reaction plane. In this paper, we have used the theoretical reaction plane $\Psi_{RP} = 0$ for the $v_1$. It is observed that the $\epsilon_1$ for c quarks is about 2–3 times smaller than that for the u quarks in all $p_T$ regions.
Next we try to see how this eccentricity is being transferred to the directed flow.

The Figure 2 presents the $p_T$ differential $v_1$ for the $c$ and $u$ quarks in the forward rapidity region. We observed that the $u$ quark $v_1$ has a very strong $p_T$ dependence, while the $c$ quark shows a weak dependence on $p_T$. Figure 3 shows the rapidity dependence of $v_1$ for $c$ and $u$ quarks in three different $p_T$ regions.

Motivation for showing $v_1(y)$ in three different $p_T$ intervals comes from $p_T$ dependence of $v_1$, as shown in Fig. 2. The panel (a) in Figure 3 presents $v_1(y)$ for $0 < p_T < 5$ GeV/c. The magnitude of $v_1$ (first order anisotropy in coordinate space) with opposite sign in the forward and backward rapidities. Whereas for the $c$ quarks the magnitude of $v_1$ is of similar order. This is due the effect of system evolution in the partonic phase in the AMPT model. All though the parton-parton interaction cross-section in the AMPT model is taken to be same (3mb) for all types of quarks, charm quark are less affected by the scattering due to its heavy mass. Therefore, change in momentum (or $v_1 = < p_x > / < p_T >$) of charm quarks are less during the interaction with other light quarks. We observe that full $p_T$ integrated $v_1$-values for $c$ quarks (0.02) is about 7 times larger than that of the $u$ quark (0.003) within the range $2.0 < |y| < 3.0$. This indicates that the heavy $c$ quarks retain more information about the initial anisotropy than light $u$ quarks, since initial $v_1$ of $u$ quarks is larger than $c$ quarks. However, we do not see any significant difference between $v_1$ of $u$ and $c$ quarks at mid-rapidity. Our model calculation suggested that rapidity dependence of flow harmonics of various identified hadrons need to measured in experiment to better understand the dynamics of the produced medium. In this paper, we have concentrated our calculation only on the $v_1$ co-efficient. The panel (b) and (c) presents the $p_T$ dependence of $v_1$, as shown in Fig. 2. The panel (a) in Figure 3 presents $v_1(y)$ for $0 < p_T < 5$ GeV/c. The magnitude of $v_1$ (first order anisotropy in momentum space) for $u$ quarks is few order smaller than the magnitude of $v_1$ (first order anisotropy in coordinate space) with opposite sign in the forward and backward rapidities. Whereas for the $c$ quarks the magnitude of $v_1$ is of similar order. This is due the effect of system evolution in the partonic phase in the AMPT model.
range $p_T > 1.0$ GeV/c, the $p_T$ integrated $v_1(y)$ for $p_T > 1.0$ GeV/c (Fig. 3(c)) shows nearly same magnitude for both “charm” and “up” quarks.

Next, we employ dynamic coalescence mechanism, as described in section II, to form mesons from the quarks at the freezeout. The $u$ and $\bar{d}$ quarks are used to form pions, while $c$ and $\bar{u}$ quarks are used to get the $D^0$. The Figure 4 presents $p_T$ differential $v_1$ for $D^0$ and $\pi$’s in the forward rapidity region ($y > 0$). The $\pi$’s have a stronger ($p_T$) dependence of $v_1$ than for the $D^0$’s, which reflects the similar behavior of the constituent quarks which is shown in Figure 2.

The Figure 5 shows the rapidity dependence of $v_1$ for $D^0$ and $\pi$’s in three different $p_T$ intervals. The panel (a), (b) and (c) present $v_1(y)$ for $0 < p_T < 5$ GeV/c, $0 < p_T < 1$ GeV/c and $1 < p_T < 5$ GeV/c, respectively. Fig. 5(a) shows that the $D^0$ $v_1$ has large magnitude than that of pions for $|y| > 1.0$. The full $p_T$ integrated $D^0$ $v_1$ is found to be factor 7 times larger than that of pions within the range $2.0 < |y| < 3.0$. The panel (b) and (c) represent similar observation as shows for partons in Fig. 3. Our observation from AMPT model calculation suggest that $D^0$ $v_1$ can be used as a useful probe, in addition to light hadrons $v_1$, to study the initial state effect in heavy ion collisions. There are recent hydro calculations [36] that suggests that the $v_1$-slope of heavy flavors can be sensitive probe of the initial matter distribution. The AMPT model with different dynamics for the charm quarks hints towards the same direction.

A recent paper [35] predicted that the transient magnetic field in heavy-ion collisions can induce a larger $v_1$ in heavy quarks than for light quarks. Model also predicts opposite sign for charm and anti-charm quarks due to the magnetic field. In future, one can study these effect on charm $v_1$ within the AMPT model framework. We also look forward to the measurement of charm $v_1$ at both RHIC and LHC energies.

IV. SUMMARY AND CONCLUSION

In summary, we have presented the directed flow of heavy and light flavor hadrons, and their constituent quark species in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV using the string melting version of AMPT model. Although the initial rapidity-odd eccentricity ($\epsilon_1$) in spatial coordinates for heavy quarks are smaller than for the light quarks, the $v_1$ magnitude for heavy flavor hadrons is approximately 7 times larger than that of the light hadrons.
at large rapidity. This is an interesting observation, which tells us that the charm hadrons are capable of retaining more information of the initial dynamics than the light ones. Any future measurement of $D^0 v_1$ in a large rapidity window would be interesting to understand the initial dynamics in heavy-ion collisions.

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