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Charmed hadron production in an improved quark coalescence model

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We study the production of charmed hadrons $D^0$ and $\Lambda_c^+$ in relativistic heavy ion collisions using the charm quark coalescence. Besides taking into consideration of changing hadron sizes in hot dense medium, which results in an enhanced coalescence probability for charm quarks of very low transverse momenta, we also include the collective flow effect on heavier resonances, which leads to a shift of massive charmed resonances to larger transverse momenta. Including the conversion of charm quarks not undergoing coalescence to hadrons by independent fragmentation, we obtain a good description of the measured yield ratio $\Lambda_c^+/D^0$ as a function of transverse momentum in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration at the Relativistic Heavy Ion Collider.

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I. INTRODUCTION

The main goal of relativistic heavy ion collisions, such as those being carried out at Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), is to explore the phase diagram of the matter described by Quantum Chromodynamics, especially the properties of deconfined quark-gluon plasma (QGP) that could be created in these collisions, and its transition to hadronic matter [1, 2]. Although the bulk properties of the created QGP are governed by light quarks and gluons, the rare heavy charm and bottom hadrons, such as the $D$ ($B$) mesons and $\Lambda_c$ ($\Lambda_b$), $\Sigma_c$ ($\Sigma_b$), $\Xi_c$ ($\Xi_b$) baryons in relativistic heavy ion collisions, has thus been a topic of great interest [19–21]. In recent experiments by the STAR Collaboration, the transverse momentum spectrum of $D^0$ mesons and also the $\Lambda_c/D^0$ ratio from Au + Au collisions have been measured [22–25]. The experimental data from collisions at 10-80% centrality shows the ratio $\Lambda_c^+/D^0 \simeq 0.8$–1.1 in the transverse momentum region of $3 < p_T < 6$ GeV, which is a very large enhancement compared to the value predicted from the fragmentation of charm quarks or from the PYTHIA results for $p+p$ collisions [26, 27]. Such a ratio is also much larger than the prediction for the integrated yield from the statistical hadronization model, where $\Lambda_c^+/D^0 \simeq 0.25$ – 0.3 [28–30].

Similar enhancements of the baryon to meson ratios of hadrons consisting of light and strange quarks in relativistic heavy ion collisions compared to those from $p+p$ collisions were previously seen in experiments at RHIC [31–34], and they were successfully explained in terms of the quark coalescence model for the production of hadrons of intermediate momenta [35–39]. Extending the quark coalescence model to charm quarks, it was shown in Refs. [40, 41] that the $\Lambda_c^+/D^0$ ratio in relativistic heavy ion collisions is also enhanced when compared with that in $p+p$ collisions at the same energy. An improved study using a more realistic charm quark spectrum was later carried out in Ref. [19]. The predicted ratio $\Lambda_c^+/D^0$ at $p_T \sim 6$ GeV from this study is found to be about 0.4, which is still a factor of two smaller than the measured value in the STAR experiments. Recently, it was found that this ratio could be explained by the resonance recombination model (RRM) [20] after including a large number of missing charm-baryon states [42].

In the present study, we improve the work of Ref. [41] by employing a more realistic charm quark spectrum and also including in the quark coalescence model the flow effect on produced heavy particles. In the usual coalescence model, such as the one employed in Refs. [19, 41],

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the transverse momentum of a produced hadron is equal to the total momentum of coalesced quarks. As a result, hadrons of different masses formed from these quarks all have same momentum, which is in contrast to the hydrodynamical picture that hadrons of large masses are shifted to higher transverse momentum as a result of collective flow. To include this effect, we boost a produced hadron from the center of mass of coalescing quarks, where its Wigner function is calculated to give its formation probability, back to the fireball frame using the physical mass of the hadron. In this way, the momenta of produced hadrons, particularly resonances of large masses, are increased by the effect of parton collective flow. With this improved approach as well as after including possible increase of hadron sizes in hot dense medium and the fragmentation contribution from charmed quarks not used in coalescence, we obtain a good description of the measured charmed quarks not used in coalescence, we obtain a good description of the measured $D^0$ momentum spectrum and the predicted $\Lambda^+/D^0$ ratio as a function of $p_T$ also agrees nicely with the available data from RHIC without assuming the existence of missing high mass charmed baryon resonances as in Ref. [42]. In addition, we find that the total yield ratio $\Lambda^+/D^0$ at $p_T = 8$ GeV can be as large as 0.6, which is much larger than the predictions from previous studies reported in Refs. [19, 41].

II. QUARK MOMENTUM SPECTRA

A. Light quarks

For the light quark momentum spectra, we adopt a similar approach as employed in Ref. [41] by using more realistic ones from Ref. [19]. Specifically, the longitudinal momentum distribution of light quarks is assumed to be boost-invariant in the rapidity range of $|y| \leq 0.5$. To take into account the collective flow of quark-gluon plasma, we assume that light partons have a radial flow profile of $\beta_T(r_T) = \beta_{\text{max}} r_T / R$ in the transverse plane of a heavy ion collision, where $R$ is the transverse radius of the quark-gluon plasma at hadronization proper time $\tau$. The transverse momentum distribution of light quarks is taken to be a thermal one at temperature $T = 165$ MeV, that is

$$\frac{dN_{q,\bar{q}}}{d^2p_T} = \frac{g_{q,\bar{q}} \tau m_T}{(2\pi)^3} \int \exp \left[ -\frac{\gamma_T (m_T - p_T \cdot \beta_T) \pm \mu}{T} \right] d^2r_T, \quad \text{(1)}$$

In the above, $g_{q,\bar{q}} = 6$ are the spin-color degeneracies of light quarks and antiquarks, $\mu$ is the quark baryon chemical potential with the plus and minus signs for quarks and antiquarks, respectively, $m_T = \sqrt{p_T^2 + m_{q,\bar{q}}^2}$ is the transverse mass with $m_{q,\bar{q}}$ being the constituent light quark and strange quark masses, which are taken to be 300 MeV and 475 MeV, respectively, and $\gamma_T = 1/\sqrt{1 - \beta_T^2}$. As in

| $N_u (N_d)$ | $N_s$ | $R$ (fm) | $\tau$ (fm/c) | $T$ (MeV) | $\beta_{\text{max}}$ | $\mu$ (MeV) |
|------------|-----|---------|-------------|----------|----------------|---------|
| 243 (224)  | 143 | 8.5     | 4.5         | 165      | 0.5            | 10      |

Ref. [19], which is based on results from a transport model study of charm quark energy loss and flow. It has the form

$$\frac{dN_c}{d^2p_T} = \begin{cases} a_0 \exp \left[ -a_1 p_T^2 \right], & p_T \leq p_0 \\ a_0 \exp \left[ -a_1 p_T^2 \right] + a_3 \left( 1 + 2 a_4 p_T^2 \right)^{-a_5}, & p_T > p_0 \end{cases}, \quad \text{(2)}$$

where $p_0 = 1.85$ GeV and the values of the parameters $a_i$ with $i = 1, \ldots, 5$ are given in Table II. They are slightly different from those in Ref. [19] to achieve a better description of the measured $D^0$ spectrum at large transverse momentum. Integrating the above transverse momentum spectrum gives the total number of heavy quarks of $dN_c/dy \simeq 2.1$ for the collisions at RHIC considered in the present study. For the charm quark mass, we use $m_c = 1.5$ GeV in the present study.

B. Charm quarks

For the charm quark momentum spectrum in heavy ion collisions at RHIC, we use the one parametrized in Ref. [19], which is based on results from a transport model study of charm quark energy loss and flow. It has the form

| RHIC | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ |
|------|------|------|------|------|------|------|
| $p_T \leq p_0$ | 0.69 | 1.15 | 1.57 | —    | —    | —    |
| $p_T > p_0$  | 1.08 | 3.04 | 0.71 | 9.914| 2.5  | 3.48 |

TABLE II: Parameters used in the parametrization of charm quark transverse momentum spectrum at mid-rapidity of central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV.
III. QUARK COALESCENCE

For simplicity, we assume as in Ref. [41] that the spatial distribution of quarks is uniform in the thermalized QGP inside a fire cylinder of volume \( V = \pi R^2 \tau \). Taking the Wigner function of hadrons to be Gaussian in space and in momentum and neglecting the space and velocity correlation of light quarks due to collective flow, we can integrate out the spatial part of the coalescence formula and obtain the transverse momentum spectrum of produced heavy mesons of certain species as

\[
\frac{dN_M}{dp_T} = g_M \frac{(2\sqrt{\pi})^3}{V} \int dp_1 dp_2 dp_3 \frac{dN_1}{dp_1} \frac{dN_2}{dp_2} \frac{dN_3}{dp_3} \times \exp \left( -k^2 \sigma^2 \right) \delta(p_M - p_1' - p_2' - p_3').
\]

In the above, \( g_M \) is the statistical factor for colored spin-1/2 quark and antiquark to form a color neutral meson, e.g., \( g_{D^0} = 1/36 \) and \( g_{D^{*0}} = 1/12 \) for \( D^0 \) and \( D^{*0} \), respectively. As to \( p_1', p_2', \) and \( p_M' \), they are the transverse momenta of heavy quark, light quark, and produced heavy meson, respectively, defined in the center-of-mass frame of the heavy meson. The \( \delta \)-function in the above equation ensures the momentum conservation. The relative transverse momentum \( k \) between the heavy quark mass \( m_1 \) and light antiquark of mass \( m_2 \) is defined as

\[
k = \frac{1}{m_1 + m_2} (m_2 p_1' - m_1 p_2'),
\]

where \( m_{1,2} \) are the quark masses. The width parameter \( \sigma \) is related to the harmonic oscillator frequency \( \omega_M \) by \( \sigma = 1/\sqrt{\omega_M} \) with \( \mu = m_1 m_2 / (m_1 + m_2) \) being the reduced mass.

Similarly, the momentum spectrum of heavy baryons from the coalescence of a charm quark and two light quarks can be calculated according to

\[
\frac{dN_B}{dp_T} = g_B \frac{(2\sqrt{\pi})^6 (\sigma_1 \sigma_2 \sigma_3)^3}{V^2} \int dp_1 dp_2 dp_3 \frac{dN_1}{dp_1} \frac{dN_2}{dp_2} \frac{dN_3}{dp_3} \times \exp \left( -k_1^2 \sigma_1^2 - k_2^2 \sigma_2^2 - k_3^2 \sigma_3^2 \right) \delta(p_B' - p_1' - p_2' - p_3'),
\]

where the index 3 refers to the heavy quark and indices 1 and 2 refer to light quarks, and \( g_B \) is the statistical factor, which, for example, is 1/108 for \( \Lambda_c \), 1/36 for \( \Sigma_c \), 1/54 for \( \Xi_c(\Xi_c^*) \), and 1/8 for \( \Sigma_c^* \) and \( \Xi_c^* \). The relative transverse momenta are defined as

\[
k_1 = \frac{1}{m_1 + m_2} (m_2 p_1' - m_1 p_2'),
\]

\[
k_2 = \frac{1}{m_1 + m_2 + m_3} [m_3 (p_1' + p_2') - (m_1 + m_2) p_3'].
\]

The width parameters \( \sigma_i \) are related to the oscillator parameter \( \omega_B \) by \( \sigma_i = 1/\sqrt{\mu_i \omega_B} \) with

\[
\mu_1 = \frac{m_1 m_2}{m_1 + m_2}, \quad \mu_2 = \frac{(m_1 + m_2) m_3}{m_1 + m_2 + m_3}.
\]

As in Ref. [41], we take the oscillator constants \( \omega_M \) for \( D_0 \) meson and \( \omega_B \) for \( \Lambda_c^+ \) baryon as parameters, and determine their values by fitting the spectrum of \( D_0 \) meson and letting all the charm quarks at low momentum hadronize through quark coalescence. Although the flow effect is taken into account in the light quark distribution through Eq. (1), its effect on produced heavy hadrons can be included by carrying out the coalescence calculation at the medium rest frame and then boosting these hadrons to the fireball frame. Because of the smaller quark thermal velocity than the flow velocity, the flow effect can be approximately included by first calculating the formation probability of a charmed hadron from coalescing charm and light quarks using its Wigner function evaluated in the center of mass of these quarks and then boosting the resulting charm hadron to the fireball frame using its physical mass. In this case, heavy resonances with large masses would have large transverse momenta in the rest frame of the expanding QGP, which is consistent with the hydrodynamic picture that the additional momenta acquired by particles due to the collective flow are larger if they are more massive. This effect has been neglected in previous studies based on the coalescence approach [19, 41] where the transverse momentum spectrum of produced particles is independent of their masses. The present approach is thus more appropriate for studying the production of massive resonances in relativistic heavy ion collisions. We note that the production of massive hadrons is not suppressed in the coalescence model as it is based on the sudden approximation. This is in contrast to that in the resonance recombination model of Ref. [20] used in Ref. [42] due to the required energy conservation in this approach.

IV. CHARM QUARK FRAGMENTATION

Similar to Refs. [19, 41], charm quarks that are not used for producing hadrons via coalescence with light quarks are converted to hadrons by fragmentation. In terms of the fragmentation probability \( P_{\text{frag}}(p_T) = 1 - P_{\text{coal}}(p_T) \) of a charm quark of transverse momentum \( p_T \), where \( P_{\text{coal}}(p_T) \) is its probability to coalesce with light quarks, the momentum spectrum of certain hadron species from the fragmentation of non-coalesced charm quarks is given by

\[
\frac{dN_{\text{had}}}{dp_T} = \sum_z \int dz P_{\text{frag}}(p_T) \frac{dN_{\text{had}}}{dz} \frac{D_{\text{had}/c}(z, Q^2)}{z^2}.
\]

In the above, \( z = p_{\text{had}}/p_c \) is the fraction of charm quark momentum carried by the produced hadron and \( Q^2 = (p_{\text{had}}/2z)^2 \) is the momentum scale for the fragmentation process. For the fragmentation function \( D_{\text{had}/c}(z, Q^2) \), we use the one from Ref. [44]

\[
D_{\text{had}}(z) \propto 1/ \left[ z \left( 1 - \frac{1 - \epsilon_c}{1 - z} \right)^2 \right].
\]
### TABLE III: Charmed mesons considered in the present study.

The branching ratios (B.R.) of resonances decaying to the ground states are taken from Ref. [45]. They are assumed to be 100%.

| Resonances | Decay modes | B.R. |
|------------|-------------|------|
| $D^{++} = dc$ | $D^0\pi^+$ | 68% |
| $D^0 = uc$ | $D^+ X$ | 32% |
| $D^+ = sc$ | $D^0\pi^0$ | 62% |
| $D^+ = sc$ | $D^0\gamma$ | 38% |

### TABLE IV: Same as Table III for charmed baryons.

| Baryon | Mass (MeV) | $I(J)$ |
|--------|------------|--------|
| $\Lambda^+ = udc$ | 2266 | $1/2(1)$ |
| $\Xi^0 = usc$ | 2467 | $1/2(1)$ |
| $\Xi^-$ = dsc | 2470 | $1/2(1)$ |
| $\Sigma^0 = ddc$ | 2455 | $1/2(1)$ |
| $\Sigma^+ = udc$ | 2455 | $1/2(1)$ |
| $\Sigma^+ = duc$ | 2520 | $1/2(1)$ |
| $\Sigma^+= udc$ | 2520 | $1/2(1)$ |
| $\Sigma^+ = uuc$ | 2520 | $1/2(1)$ |
| $\Xi^+ = usc$ | 2645 | $1/2(1)$ |
| $\Xi^0 = dsc$ | 2645 | $1/2(1)$ |
| $\Xi^0 = usc$ | 2580 | $1/2(1)$ |
| $\Xi^0 = dsc$ | 2580 | $1/2(1)$ |

with $\epsilon_c$ being a free parameter to fix the shape of the fragmentation function. In the present study, we choose $\epsilon_c = 0.006$ for $D$ mesons and $\epsilon_c = 0.02$ for $\Lambda_c$ baryons, which leads to the fragmentation branching ratios to $D^0$, $D^+$, $D^+_c$, and $\Lambda^+_c$ to be 0.607, 0.196, 0.121, and 0.076, respectively [41].

### V. RESULTS

As shown in Ref. [41], the contributions from resonances to the yield of ground state hadrons are important and should be taken into account. Tables III and IV summarize the charmed hadrons considered in the present study, which include the ground states and the resonance states of $D$ mesons, $\Lambda_c$, and $\Xi_c$ baryons, as given in the Particle Data Group [45]. For the branching ratio of $\Xi^+_c$ and $\Xi^0_c$ baryons decaying by strong or electromagnetic interactions to the $\Xi_c$ baryon, which are not given in Ref. [45], they are assumed to be 100%. We note that all charmed meson and baryon resonances in Tables III and IV have their orbital wave functions in the $L = 0$ states.

![FIG. 1: Transverse momentum spectrum of $D^0$ mesons at mid-rapidity from Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and (0–10%) centrality. Dashed and dash-dotted lines are the $D^0$ spectra from charm quark coalescence and fragmentation, respectively, and their sum is given by the solid line. The experimental data shown by solid squares are taken from Ref. [46].](image-url)
to hadronize by fragmentation than coalescence, only $D_0$ mesons of $p_T > 10$ GeV are mainly produced by charm quark fragmentation as shown in Fig. 1. This is because the charm quark in $D^0$ from coalescence (fragmentation) mainly comes from those with momentum smaller (larger) than that of $D^0$.

We also compute the spectra of produced $D_s^+$ and $D^+$ mesons, and the results are presented in Fig. 3. It is found that although the fragmentation contribution dominates at $p_T > 10$ GeV for $D^+$, which is similar to that for $D_0$ shown in Fig. 1, it becomes important already at $p_T > 7$ GeV for $D_s^+$. This is due to the softer $D_s$ transverse momentum spectrum than that of $D_0$ from charm quark coalescence, which is also seen in Ref. [43]. The yields of various charmed hadrons are summarized in Table V, which shows that the total number of charmed mesons is about 1.36 with the number of $D_0$ about three times that of $D^+$ because of the dominant contribution from the decay of charmed meson resonances. For the remaining 0.74 charm quarks, they are converted to charmed baryons by coalescence and fragmentation as shown below.

Shown in Fig. 4 is the $\Lambda^+_c$ spectrum, which includes those from coalescence (dashed line), fragmentation (dash-dotted line), and their sum (solid line). These results are obtained with the oscillator parameter $\omega_B = 0.16$ GeV for $\Lambda^+_c$ and $\Xi_c$, which again corresponds to an increase of their sizes than those for $\omega_B = 0.33$ GeV, to ensure that the remaining charm quarks of very low transverse momenta, which are not used in the production of charmed mesons from the coalescence of charm quark with light antiquarks, are all used in the production of charmed baryons. This leads to the yields of 0.547 and 0.175 for $\Lambda^+_c$ and $\Xi_c$, respectively. The total integrated yield ratio $\Lambda^+_c/D_0$ is then about 0.64, which is slightly larger than the value of about 0.54 measured in $p + p$ collisions at $\sqrt{s} = 7$ TeV at LHC [21, 48]. We note that the oscillator constant used here for charmed baryons is larger than that for charmed mesons, which is different from that in Ref. [41] where they are taken to have the same value.

In Fig. 5, we show the yield ratio $\Lambda^+_c/D^0$ as a function of transverse momentum in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and 0-10% centrality. It is seen that the fragmentation contribution suppresses this ratio, and the results from the sum of coalescence and fragmenta-

| yield | $D^0$ | $D^+$ | $D_s^+$ | $\Lambda^+_c$ | $\Xi_c$ |
|-------|-------|-------|--------|-------------|--------|
| RHIC  | 0.85  | 0.275 | 0.236  | 0.547       | 0.175  |

TABLE V: Charmed hadron yields in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and 0-10% centrality.
baryon resonances to larger transverse momenta, and this the flow effect on the momenta of hadrons formed from the present study is less important due to the inclusion of 41, the contribution from charm quark fragmentation in + ratio $\Lambda^+$ to use up all the charm quarks at $p_T = 0$ GeV and 0-10% centrality. For $p_T \approx 6$ GeV, the ratio $\Lambda^+_c/D^0$ is predicted to be close to 1.0, which is much higher than the value of less than 0.4 obtained in Refs. [19, 41]. In particular, we find that the ratio $\Lambda^+_c/D^0$ at $p_T = 8$ GeV can be as large as 0.6, while it was predicted to be around 0.2 in Ref. [19]. Compared to the previous studies reported in Refs. [19, 41], the contribution from charm quark fragmentation in the present study is less important due to the inclusion of the flow effect on the momenta of hadrons formed from quark coalescence, which shifts higher mass charmed baryon resonances to larger transverse momenta, and this helps describe the ratio $\Lambda^+_c/D^0$ in the transverse momentum region of $4 < p_T < 6$ GeV.

VI. CONCLUSIONS

Using the charm quark coalescence and fragmentation model with the inclusion of the effect of collective flow on the transverse momentum spectra of produced charmed hadrons, we have studied the transverse momentum spectra of charmed mesons and baryons as well as the $\Lambda_c/D_0$ ratio. By tuning the oscillator constants in the charmed hadron Wigner functions in the quark coalescence model, which models their changing sizes in hot dense matter, to use up all the charm quarks at $p_T \approx 0$ GeV and fragmenting the remaining charm quarks into charmed hadrons, we have obtained the ratio $\Lambda^+_c/D^0$ as a function of $p_T$ that successfully describes the experimental data measured at RHIC. This is in contrast to previous studies that did not include the effect of collective flow on charmed hadrons formed from quark coalescence, which underestimated substantially this ratio at $p_T > 4.5$ GeV. Compared to results from these studies, the contribution from fragmentation is less important in the present approach. As a result, we have obtained a much larger value for $\Lambda^+_c/D^0$ at $p_T > 6$ GeV than that from the conventional approach. Our study thus provides an alternative description of the measured $p_T$ dependence of the ratio $\Lambda^+_c/D^0$ at RHIC without the inclusion of a large number of unknown charmed baryon resonances as assumed in Ref. [42]. We have, however, neglected in the present study the space-momentum correlations of both light and charm quarks, which are shown in Ref. [42] to also help shift the peak of the $\Lambda^+_c/D^0$ ratio to higher transverse momentum. Also, the present study is based on a blast-wave model for light quarks. It is thus important to verify the validity of the results and conclusions from the present study by using the phase-space distributions of light and charm quarks from more realistic models. Since the light or strange baryon to meson ratio at $p_T \sim 4 - 7$ GeV in the quark coalescence approach without the flow effect is very small compared to the experimentally measured value [39], it will also be very interesting to check if the inclusion of the flow effect can help resolve this discrepancy.
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