Ratios of heavy baryons to heavy mesons in relativistic nucleus-nucleus collisions

Yongseok Oh,[1,*] Che Ming Ko,[1,†] Su Houng Lee,[2,‡] and Shigehiro Yasui[3,§]

[1]*Cyclotron Institute and Physics Department, Texas A&M University, College Station, Texas 77843, USA*

[2]*Institute of Physics and Applied Physics, Yonsei University, Seoul 120-749, Korea*

[3]*High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 302-0801, Japan*

Heavy baryon/meson ratios Λ_c/D^0 and $\Lambda_b/\bar{B}^0$ in relativistic heavy ion collisions are studied in the quark coalescence model. For heavy baryons, we include production from coalescence of heavy quarks with free light quarks as well as with bounded light diquarks that might exist in the strongly coupled quark-gluon plasma produced in these collisions. Including the contribution from decays of heavy hadron resonances and also that due to fragmentation of heavy quarks that are left in the system after coalescence, the resulting Λ_c/D^0 and $\Lambda_b/\bar{B}^0$ ratios in midrapidity ($|y| \leqslant 0.5$) from central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV are about a factor of five and ten, respectively, larger than those given by the thermal model, and about a factor of ten and twelve, respectively, larger than corresponding ratios in the PYTHIA model for pp collisions. These ratios are reduced by a factor of about 1.6 if there are no diquarks in the quark-gluon plasma. The transverse momentum dependence of the heavy baryon/meson ratios is found to be sensitive to the heavy quark mass, with the $\Lambda_b/\bar{B}^0$ ratio being much flatter than the Λ_c/D^0 ratio. The latter peaks at the transverse momentum $p_T \simeq 0.8$ GeV but the peak shifts to $p_T \simeq 2$ GeV in the absence of diquarks.

I. INTRODUCTION

Recent measurements on nonphotonic electrons from decays of midrapidity heavy-flavored mesons in central heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) have shown that the nuclear modification factor R_{AA}^e relative to pp collisions is significantly smaller than theoretical predictions based on radiative energy loss of heavy quarks in produced quark-gluon plasma [1–4]. To explain the observed small value of R_{AA}^e or large suppression of heavy meson production in relativistic heavy ion collisions, other mechanisms for energy loss of heavy quarks in quark-gluon plasma have been proposed [5–10]. Also, it was suggested that the enhancement of charmed baryon production over charmed meson production, i.e., the Λ_c/D^0 ratio, would suppress the R_{AA}^e of the electrons from heavy mesons [11,12]. This is due to the fact that enhanced charmed baryon production reduces the production of charmed mesons and thus their contribution to decay electrons.

In fact, experiments at RHIC have shown that in central heavy ion collisions there is an enhanced production of midrapidity baryons in the intermediate transverse momentum region not only in light hadrons but also in strange hadrons. This enhancement could be described by multiquark dynamics through quark coalescence or recombination [13–15], baryon junction loops [16–18], or long-range coherent fields [19]. Therefore, one might expect enhanced heavy baryon production in the intermediate transverse momentum region as well.

Since the Λ_c/D^0 ratio has not been measured in heavy ion collisions, it was assumed in Ref. [11] to be the same as the measured Λ/K_S^0 ratio or in Ref. [12] to have a Gaussian form with a maximum value peaked at the transverse momentum $p_T = 5$ GeV. It was then claimed that a value of $\Lambda_c/D^0 \sim 1$, which is about a factor of ten larger than that in pp collisions at same energy, could result in an additional 20–25% suppression of R_{AA}^e apart from the suppression due to the collisional energy loss of heavy quarks in quark-gluon plasma. However, it is not yet known what kind of underlying physics can cause such a large enhancement of the Λ_c/D^0 ratio.

Recently, enhancement of the Λ_c/D^0 ratio due to the existence of $[ud]$ diquarks in strongly coupled quark-gluon plasma (QGP) was suggested by Lee *et al.* [20]. This was based on the idea of possible existence of quasi bound states of quarks and gluons including diquarks in QGP when the temperature is between T_C and $4T_C$ [21], where T_C is the critical temperature for the quark-gluon plasma to hadronic matter transition. Based on the quark coalescence model, it was shown in Ref. [20] that the Λ_c/D^0 ratio could be enhanced by a factor of 4–8 relative to the case without diquarks in QGP, depending on the binding energy of the light diquark at $T_C = 175$ MeV. The question whether diquarks can exist as quasi bound states in cold quark matter was raised earlier in Ref. [22], where the quark-diquark matter was claimed to be energetically more favorable than the free quark matter. The idea of enhancement of Λ_c baryon production in heavy-ion collisions was then suggested in Ref. [23]. Based on the assumption that the number of diquarks present in a collision is mainly determined by that in the initial nuclei, the author of Ref. [23] considered the Λ_c/Σ_c ratio and estimated that it could be enhanced by a factor of as large as 80. Since the Σ_c cannot be directly measured in near-future heavy-ion experiments, the more phenomenologically accessible Λ_c/D^0 ratio is thus addressed in Ref. [20].

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*yoh@comp.tamu.edu
†ko@comp.tamu.edu
‡suhoung@phya.yonsei.ac.kr
§yasuis@post.kek.jp

The idea of diquarks [24–26] has been widely used in hadron physics for describing the mass spectrum, electromagnetic properties, and many other properties of hadrons (for a review, see, for example, Ref. [27]), although the properties and even the existence of diquarks are still under debate [28]. Among possible signatures of diquarks in hadrons, the observed large ratio of $\Lambda_c/\Sigma_c \sim 7$ in e^+e^- collisions was pointed out in Ref. [29], which implies a significantly larger production of scalar diquarks than vector diquarks [30]. (See also Ref. [31].) In spite of the lack of concrete consensus on the diquark nature, it is well-known that the (isoscalar) scalar light $[ud]$ diquark of color antitriplet is the most probable diquark state. Evidence for such scalar diquarks has been confirmed by a recent lattice QCD simulation [32]. (See, however, Ref. [33] for other lattice QCD calculation on diquarks.)

In diquark models, the Λ_c is usually considered as a system consisting of a charm quark and a scalar light $[ud]$ diquark. On the other hand, the structure of Σ_c and Σ_c^* is model-dependent: they may have an axial-vector light diquark but they also may contain diquarks $[Qq]$ made of one heavy quark (Q) and one light quark (q) [34,35]. In Ref. [36], it is claimed that the ground state baryons favor the $[Qq]$ diquark. This is based on the observation that the $[Qq]q$ system gives a Λ_c mass closer to that from the three-quark calculation, although it has a larger mass than that based on the $Q[qq]$ configuration. Since the color-spin interaction between quarks is inversely proportional to the quark masses, the binding energies of $[Qq]$ diquarks are smaller than those of scalar light $[qq]$ diquarks, and it is not clear whether such $[Qq]$ diquarks can exist, in particular, in QGP. (See Ref. [37] for a recent discussion on the diquark picture for heavy baryons.)

In this paper, we calculate the Λ_Q/H^0 ratios ($Q = b, c$ and H^0 stands for D^0 or $\bar{B}^0$) in relativistic heavy ion collisions based on the quark coalescence model. We consider the two cases of Λ_Q being a pure three-quark state and of Λ_Q being made of a heavy quark and one scalar light diquark. In addition to the direct formation of Λ_Q and H^0, we also take into account the contribution from decays of heavy hadron resonances. Namely, we consider the decay of D^* mesons for D^0 production and Σ_Q and Σ_Q^* baryon decays for Λ_Q production. As we have discussed before, we assume that Σ_Q and Σ_Q^* baryons are made of three quarks and that neither vector light diquarks nor scalar heavy-light diquark exists in QGP.

This paper is organized as follows. In the next section, we briefly discuss heavy hadron production in pp collisions. A simple thermal model is then used in Sec. III to show the role of heavy hadron resonances in the Λ_Q/H^0 ratios. The difference between the ratios for charmed hadrons and for bottom hadrons is also discussed. In Sec. IV, the coalescence model used in this work is given together with both light and heavy quark distribution functions. Also described are the calculational methods and the contributions from fragmentation of heavy quarks that are not used in coalescence. We then show in the same section the results for the relative production fractions of heavy hadrons and their p_T spectra as well as the transverse momentum dependence of the Λ_Q/H^0 ratios. Section V contains the conclusions and discussions.

II. HEAVY HADRON PRODUCTION IN PROTON-PROTON COLLISIONS

Before studying the production of heavy hadrons in heavy ion collisions, we briefly discuss their production in pp collisions by using the PYTHIA model [38]. For pp collisions at $\sqrt{s} = 200$ GeV, the PYTHIA model gives the following relative production fractions of charmed hadrons in midrapidity ($|y| \leqslant 0.5$)[1]:

$$f(D^+) \simeq 0.196, \qquad f(D^0) \simeq 0.607,$$
$$f(D_s^+) \simeq 0.121, \qquad f(\Lambda_c) \simeq 0.076. \qquad (1)$$

This leads to the particle number ratios

$$\left(\frac{D^0}{D^+}\right)_{pp} \simeq 3.1, \qquad \left(\frac{\Lambda_c}{D^0}\right)_{pp} \simeq 0.13. \qquad (2)$$

The above estimated D^0/D^+ ratio can be understood largely by considering resonance decays, namely, decays of D^* mesons into D mesons. First, the D^{*0} meson decays into D^0 meson by 100% [39] since the decay of D^{*0} into $D^+\pi^-$ is prohibited by energy conservation.[2] Second, the D^{*+} meson can decay either into D^+ or D^0. The branching ratios are $BR(D^{*+} \to D^0\pi^+) \approx 68\%$ and $BR(D^{*+} \to D^+X) \approx 32\%$, where sum over any state X is understood. If the production rates are equal for D and D^* mesons aside from the factor due to different spin degeneracies, we then would have

$$\left(\frac{D^0}{D^+}\right)_{pp} \approx \frac{1 + 3 + 3 \times 0.68}{1 + 3 \times 0.32} = \frac{6.04}{1.96} \approx 3.1, \qquad (3)$$

where the spin degeneracy of D^* is included. We also note that the estimated Λ_c/D^0 ratio is close to that (≈ 0.16) in the SELEX measurement [40].

For bottom hadron production in pp collisions at $\sqrt{s_{NN}} = 200$ GeV, the relative production fractions in midrapidity from the PYTHIA model are

$$f(B^-) \simeq 0.101, \quad f(\bar{B}^0) \simeq 0.101, \quad f(B_s^-) \simeq 0.030,$$
$$f(B^{*-}) \simeq 0.302, \quad f(\bar{B}^{*0}) \simeq 0.301, \quad f(B_s^{*-}) \simeq 0.089,$$
$$f(\Lambda_b) \simeq 0.076, \qquad (4)$$

leading to[3]

$$\Lambda_b/\bar{B}^0 \approx 0.7, \qquad (5)$$

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[1] We have confirmed the results reported in Ref. [12]. These values are also close to the values quoted by Particle Data Group (PDG) [39] for e^+e^- annihilation at $\sqrt{s} = 91$ GeV: $f(D^+) \simeq 0.21$, $f(D^0) \simeq 0.54$, $f(D_s^+) \simeq 0.16$, and $f(\Lambda_c) \simeq 0.093$.

[2] Note that $m(D^{*0}) = 2007$ MeV, $m(D^{*+}) = 2010$ MeV, $m(D^0) = 1865$ MeV, $m(D^+) = 1869$ MeV, while $m(\pi^\pm) = 139.6$ MeV and $m(\pi^0) = 135$ MeV.

[3] We note that the average fractions of bottom mesons and bottom baryons in $p\bar{p}$ annihilation at $\sqrt{s} = 1.5$ TeV have been estimated to be $f(b\bar{u}) = f(b\bar{d}) = 0.399$ and $f(\text{baryon}) = 0.092$ [39]. If we assume that $b\bar{q}$ mesons include equal number of B and B^* mesons apart from the spin degeneracy and the number of bottom baryons is mostly due to Λ_b, then we would have $\Lambda_b/\bar{B}^0 \approx 1.1$ in $p\bar{p}$ collisions.

which is significantly larger than the Λ_c/D^0 ratio given in Eq. (2).

III. THE THERMAL MODEL

In relativistic heavy-ion collisions, the Λ_c/D^0 and $\Lambda_b/\bar{B}^0$ ratios are expected to be different from those given in Eqs. (2) and (5) for pp collisions. This can be seen using a simple thermal model which assumes that in relativistic heavy ion collisions charmed and bottom hadrons are produced during hadronization of the quark-gluon plasma and that they are in both thermal and chemical equilibrium at the phase transition temperature T_C. The total charm and bottom numbers are, however, determined by initial hard scattering as thermal production of heavy quarks from created quark-gluon plasma is negligible in heavy ion collisions at RHIC [41]. The number of heavy hadrons of mass m inside a fireball of volume V at T_C is then given by

$$N = \gamma_Q \frac{gV}{2\pi^2} m^2 T K_2(m/T_C), \qquad (6)$$

where γ_Q is the heavy-quark fugacity, g is the degeneracy of the particle, and K_2 is the modified Bessel function.

For charmed hadrons, we would then have $(D^0/D^+)_0 = 1$, where the subscript 0 means the ratio without resonance contributions, if the $D^* \to D$ decay is not included. Since

$$\frac{D^{*0}}{D^0} = \frac{3m_{D^*}^2 K_2(m_{D^*}/T_C)}{m_{D_0}^2 K_2(m_{D_0}/T_C)} \simeq 1.47 \qquad (7)$$

at $T_C = 175$ MeV, including decays of D^* mesons changes the ratio to

$$\frac{D^0}{D^+} \approx \frac{1 + (1 + 0.68) \times 1.47}{1 + 0.32 \times 1.47} \approx 2.36, \qquad (8)$$

if we assume that the same branching ratios for D^* decay to D as in free space. The D^0/D^+ ratio in heavy-ion collisions is thus about 25% smaller than that in pp collisions.

For the Λ_c/D^0 ratio, we have, by using $m_{\Lambda_c} = 2285$ MeV and $m_{D^0} = 1865$ MeV,

$$\left(\frac{\Lambda_c}{D^0}\right)_0 = \frac{2m_{\Lambda_c}^2 K_2(m_{\Lambda_c}/T_C)}{m_{D_0}^2 K_2(m_{D_0}/T_C)} \simeq 0.24, \qquad (9)$$

where the factor 2 is the spin degeneracy of Λ_c baryon. Since the ratio D^*/D is 1.47, inclusion of D^* resonance decays causes a strong reduction of the Λ_c/D^0 ratio. On the other hand, baryon resonances can also contribute to the production of Λ_c baryon through their decays and can enhance the Λ_c/D^0 ratio. The major resonance contribution to Λ_c comes from $\Sigma_c^*(2520)$ of spin-3/2. In thermal model, we have

$$\frac{\Sigma_c^*(2520)}{\Lambda_c} \approx 2 \times 3 \times \frac{m_{\Sigma_c^*}^2 K_2(m_{\Sigma_c^*}/T_C)}{m_{\Lambda_c}^2 K_2(m_{\Lambda_c}/T_C)} = 1.8, \qquad (10)$$

where the factor 2 comes from the difference in the spin degeneracies of Λ_c and Σ_c^*, and the factor 3 is due to the isospin 1 of Σ_c^*. Since $\Sigma_c^*(2520)$ decays almost 100% into Λ_c, inclusion of its contribution gives 180% enhancement to the number of Λ_c. Another important contribution to Λ_c

production is from the decay of Σ_c ground state, $\Sigma_c(2455)$ of spin-1/2, via the $\Sigma_c \to \Lambda_c \pi$ decay.[4] In thermal model, its abundance relative to that of Λ_c is

$$\frac{\Sigma_c(2455)}{\Lambda_c} \approx 3 \times \frac{m_{\Sigma_c}^2 K_2(m_{\Sigma_c}/T_C)}{m_{\Lambda_c}^2 K_2(m_{\Lambda_c}/T_C)} = 1.26. \qquad (11)$$

Therefore, the contribution from $\Sigma_c(2455)$ and $\Sigma_c^*(2520)$ decays increases the Λ_c number by a factor of 3.1 and brings the Λ_c to D^0 ratio close to the naive expectation given in Eq. (9) based only on directly produced Λ_c and D^0, i.e.,

$$\frac{\Lambda_c}{D^0} = \left. \frac{\Lambda_c\{1 + \Sigma_c^*(2520)/\Lambda_c + \Sigma_c(2455)/\Lambda_c\}}{D^0(1 + 1.68D^*/D)} \right|_{\text{ther}}$$

$$\simeq \left(\frac{\Lambda_c}{D^0}\right)_0 \frac{1 + 1.8 + 1.26}{1 + 1.68 \times 1.47} \approx 0.28. \qquad (12)$$

The contribution from higher mass charmed resonances is negligibly small in the thermal model. For D meson production, the next higher state is $D_1(2420)$ of $J^P = 1^+$. The branching ratio of the decay of this meson is not well-known except that it decays into $D^*\pi$ but not into $D\pi$. If we assume that it decays into D^0 via an intermediate D^*, i.e., $D_1 \to D^*\pi \to D\pi\pi$, the denominator of Eq. (12) is then modified by the addition of $1.68 \times 3 \times 0.06 \simeq 0.3$, where the factor 0.06 is the $D_1(2420)/D^0$ ratio, giving thus less than 10% enhancement to D^0 production. For higher baryon resonances, the next excited state is $\Lambda_c(2593)$. Its contribution to the numerator of Eq. (12) is about 0.2, since there is no difference in its spin and isospin degeneracy from that of Λ_c. Thus it again gives an effect less than 5% to Λ_c production. The final value of the Λ_c/D^0 ratio then essentially does not change, i.e., the ratio is modified from 0.28 to 0.27, which is about twice of that in pp collisions.

The estimated value of the Λ_c/D^0 ratio from our simple thermal model is close to the value obtained in the more sophisticated thermal or statistical model of Ref. [42], which gives a charmed baryon to meson ratio $(cqq)/(c\bar{q}) \leqslant 0.25$. It is also consistent with the statistical model predictions of Ref. [43], which has $\Lambda_c/D^0 \sim 0.2$ at the RHIC energy.

The $\Lambda_b/\bar{B}^0$ ratio in the thermal model can be estimated in the same way as for the Λ_c/D^0 ratio. The main difference between $\bar{B}^0$ and D^0 productions is that the bottom quark is much heavier than the charm quark. As a result, the mass difference between B^* and B is much smaller than that between D^* and D because of the manifestation of heavy quark spin symmetry. In fact, the mass difference between D^* and D is about 140 MeV, while that between B^* and B is only [39]

$$m(B^*) - m(B) \approx 5325 \text{ MeV} - 5279 \text{ MeV} = 46 \text{ MeV}. \qquad (13)$$

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[4]In the strange quark sector, the small mass difference between Λ and Σ does not allow the strong decay of Σ into Λ, and only $\Sigma^0 \to \Lambda\gamma$ is allowed. But in heavy quark sector, the mass difference between Λ_c and Σ_c is well above the pion mass.

Therefore, unlike D^0 production, B^* mesons cannot decay into B mesons by strong interaction.[5] This leads to a large suppression of B meson production compared with the case for D meson production. With $m(\Lambda_b) = 5620$ MeV, our simple thermal model then gives

$$\frac{B^{*+}}{B^+} \approx 0.78, \quad \left(\frac{\Lambda_b}{\bar{B}^0}\right)_0 \approx 0.32. \quad (14)$$

It indeed shows that $\left(\Lambda_b/\bar{B}^0\right)_0$ is somewhat larger than $\left(\Lambda_c/D^0\right)_0$.

Unlike B production, the production of Λ_b is affected by resonance decays. This is because the mass difference between Λ_b and Σ_b approaches to a finite value (~ 195 MeV [44]) in the infinite mass limit, although the mass difference between Σ_b of spin-1/2 and Σ_b^* of spin-3/2 becomes smaller as the heavy quark mass increases. By using the recent experimental information for the Σ_b baryons [45],

$$M(\Sigma_b) = 5812 \text{ MeV}, \quad M(\Sigma_b^*) = 5833 \text{ MeV}, \quad (15)$$

the $\Lambda_b/\bar{B}^0$ ratio becomes

$$\frac{\Lambda_b}{\bar{B}^0} = \left(\frac{\Lambda_b}{\bar{B}^0}\right)_0 (1 + 3 \times 0.35 + 3 \times 2 \times 0.31) \approx 1.25, \quad (16)$$

where the factors 0.35 and 0.31 are the Σ_b/Λ_b and Σ_b^*/Λ_b ratios, respectively. The $\Lambda_b/\bar{B}^0$ ratio is seen to be larger than the Λ_c/D^0 ratio by a factor of about 5. Compared to its value in pp collisions, the $\Lambda_b/\bar{B}^0$ ratio in thermal model for heavy ion collisions is close to a factor of two larger, similar to the case for the Λ_c/D^0 ratio.

There are other higher charmed and bottom resonances listed by the PDG [39]. These include heavy baryons that contain strange quarks such as Ξ_Q, Ξ_Q', Ω_Q, and their resonances. Although most of corresponding bottom baryons are yet to be discovered, their existence has been predicted by the quark model [46]. Using the masses listed by the PDG and from the quark model, we find that the yield of these baryons is about 60% of the Λ_Q yield in the thermal model and is thus appreciable. Including these higher resonances in the thermal model changes the baryon/meson ratios to

$$\frac{\Lambda_c}{D^0} \simeq 0.27, \quad \frac{\Lambda_b}{\bar{B}^0} \simeq 0.86. \quad (17)$$

IV. THE COALESCENCE MODEL

In the thermal model, the relative abundance of particles depends only on their masses. Whether diquarks exist in QGP thus does not affect the Λ_c/D^0 and $\Lambda_b/\bar{B}^0$ ratios in the thermal model. This is not the case in the quark coalescence model as to be shown in the rest of this paper.

A. Formalism

As in the coalescence model described in Refs. [13,47], which has been used in Ref. [48] to study the D meson

transverse momentum spectrum in relativistic heavy ion collisions, we assume that quarks, antiquarks, and gluons in the produced QGP are uniformly distributed in a fire cylinder of volume V. Their momentum distributions are taken to be thermal in the transverse direction but uniform in midrapidity. For the Wigner functions of hadrons, they are expressed in terms of Gaussian functions. Modeling the effect of transverse radial flow of the fire cylinder by an effective temperature, the produced heavy meson transverse momentum spectrum is then given by

$$\frac{dN_M}{d\boldsymbol{p}_M} = g_M \frac{(2\sqrt{\pi}\sigma)^3}{V} \int d\boldsymbol{p}_1 d\boldsymbol{p}_2 \frac{dN_1}{d\boldsymbol{p}_1} \frac{dN_2}{d\boldsymbol{p}_2}$$
$$\times \exp(-k^2\sigma^2)\delta(\boldsymbol{p}_M - \boldsymbol{p}_1 - \boldsymbol{p}_2), \quad (18)$$

where g_M is the statistical factor for colored 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, and similarly for $\bar{B}^0$ and $\bar{B}^{*0}$. The distribution of heavy quarks with transverse momentum $\boldsymbol{p}_1$ and light antiquarks with transverse momentum $\boldsymbol{p}_2$ in the fire cylinder frame are denoted by $dN_1/d\boldsymbol{p}_1$ and $dN_2/d\boldsymbol{p}_2$, respectively. The $\boldsymbol{p}_M$ is the transverse momentum of produced heavy meson. The relative transverse momentum $\boldsymbol{k}$ between the heavy quark and light antiquark is defined as

$$\boldsymbol{k} = \frac{1}{m_1 + m_2}(m_2\boldsymbol{p}_1' - m_1\boldsymbol{p}_2'), \quad (19)$$

where $m_{1,2}$ are quark masses, and $\boldsymbol{p}_1'$ and $\boldsymbol{p}_2'$ are heavy quark and light antiquark transverse momenta, respectively, defined in the center-of-mass frame of produced heavy meson. The width parameter σ is related to the harmonic oscillator frequency ω by $\sigma = 1/\sqrt{\mu\omega}$, where $\mu = m_1 m_2/(m_1 + m_2)$ is the reduced mass and can be related to the size of produced hadrons. Namely, the charge rms radius of produced meson is given by

$$\langle r^2 \rangle_{\text{ch}} = \frac{3}{2} \frac{1}{\mu\omega} \frac{Q_1 m_2^2 + Q_2 m_1^2}{(m_1 + m_2)^2}, \quad (20)$$

with Q_i being the charge of the ith (anti)quark. To reproduce the root-mean-square charge radii 0.43 fm of D^+ and 0.62 fm of B^+ as predicted by the light-front quark model of Ref. [49], an oscillator frequency $\omega = 0.33$ GeV is needed.

We note that contrary to that for mesons consisting of only light quarks, the coalescence formula, Eq. (18), does not require heavy and light quarks to have similar momenta to form heavy hadrons. Instead, quarks of similar velocities have the most probable chance to form hadrons.

Similarly, the coalescence formula for forming Λ_Q, Σ_Q, Ξ_Q, Ξ_Q', and Ω_Q as well as their resonances from three quarks are given by

$$\frac{dN_B}{d\boldsymbol{p}_B} = g_B \frac{(2\sqrt{\pi})^6(\sigma_1\sigma_2)^3}{V^2} \int d\boldsymbol{p}_1 d\boldsymbol{p}_2 d\boldsymbol{p}_3 \frac{dN_1}{d\boldsymbol{p}_1} \frac{dN_2}{d\boldsymbol{p}_2} \frac{dN_3}{d\boldsymbol{p}_3}$$
$$\times \exp\left(-k_1^2\sigma_1^2 - k_2^2\sigma_2^2\right)\delta(\boldsymbol{p}_B - \boldsymbol{p}_1 - \boldsymbol{p}_2 - \boldsymbol{p}_3), \quad (21)$$

where the index 3 refers to the heavy quark and indices 1 and 2 to light quarks, and the statistical factor g_B has values 1/108, 1/36, and 1/18 for Λ_Q, Σ_Q, and Σ_Q^*, respectively, and

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[5]The decay of B^* into B is caused by electromagnetic interactions, $B^* \to B\gamma$, and can thus be distinguished in experiments.

1/54, 1/18, 1/108, and 1/36 for Ξ_Q (Ξ'_Q), Ξ^*_Q, Ω_Q, and Ω^*_Q, respectively. The relative transverse momenta defined in the center of mass frame of produced baryon are

$$\boldsymbol{k}_1 = \frac{1}{m_1 + m_2}(m_2 \boldsymbol{p}'_1 - m_1 \boldsymbol{p}'_2),$$

$$\boldsymbol{k}_2 = \frac{1}{m_1 + m_2 + m_3}[m_3(\boldsymbol{p}'_1 + \boldsymbol{p}'_2) - (m_1 + m_2)\boldsymbol{p}'_3].$$

$$(22)$$

The width parameters σ_i are $\sigma_i = 1/\sqrt{\mu_i \omega}$, where

$$\mu_1 = \frac{m_1 m_2}{m_1 + m_2}, \qquad \mu_2 = \frac{(m_1 + m_2)m_3}{m_1 + m_2 + m_3}, \qquad (23)$$

and the oscillator frequency ω is related to the baryon charge radius by

$$\langle r^2 \rangle_{\text{ch}} = \frac{3}{2\omega} \frac{1}{m_1 + m_2 + m_3}$$
$$\times \left(\frac{m_2 + m_3}{m_1} Q_1 + \frac{m_3 + m_1}{m_2} Q_2 + \frac{m_1 + m_2}{m_3} Q_3 \right). \qquad (24)$$

The root-mean-square charge radii of Λ_c and Λ_b predicted by the quark model have similar values of about 0.39 fm [50], and they are reproduced by the oscillator frequencies 0.43 GeV and 0.41 GeV, respectively. These values are 25–30% larger than the ones for heavy mesons. As we shall show in the next subsection, to convert as many heavy quarks of small p_T into heavy hadrons via coalescence as possible[6] requires, however, smaller oscillator frequencies or larger heavy hadron radii.

For production of Λ_Q baryons from the coalescence of heavy quarks and $[ud]$ diquarks, we consider Λ_Q baryons as made of a heavy quark and a light diquark only. Their spectrum can thus be obtained from Eq. (18) by replacing g_M with $g'_B = 1/9$. Explicitly, it is written as

$$\frac{dN_B}{d\boldsymbol{p}_B} = g'_B \frac{(2\sqrt{\pi}\sigma_{dq})^3}{V} \int d\boldsymbol{p}_1 d\boldsymbol{p}_2 \frac{dN_1}{d\boldsymbol{p}_1} \frac{dN_2}{d\boldsymbol{p}_2}$$
$$\times \exp\left(-k^2 \sigma_{dq}^2\right) \delta(\boldsymbol{p}_B - \boldsymbol{p}_1 - \boldsymbol{p}_2). \qquad (25)$$

The width parameter σ_{dq} or corresponding oscillator frequency ω_{dq} is determined by fitting the sizes of heavy baryons used in the three-quark model, i.e., $\omega = 0.25$ GeV and 0.26 GeV for Λ_c and Λ_b, respectively.

The scalar diquarks can also lead to formation of excited states of Λ_Q baryons with $j^\pi = \frac{1}{2}^-$ and $\frac{3}{2}^-$, which can decay into Λ_Q by emitting pions. We note that the mass differences between $j^\pi = \frac{1}{2}^-$ and $\frac{3}{2}^-$ states are small because of heavy quark spin symmetry, e.g., the lowest excited states of Λ_c are $\Lambda(2593)$ of $j^\pi = \frac{1}{2}^-$ and $\Lambda_c(2625)$ of $j^\pi = \frac{3}{2}^-$, and thus have a mass difference of only 32 MeV. Although the number of these resonances is rather small in the thermal model due to their higher masses compared to those of ground state Λ_Q baryons, it is not the case in the coalescence model if diquarks

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[6]This is similar to the assumption introduced in the thermal model that all charmed quarks are converted into heavy hadrons.

exist in QGP. Since excited Λ_Q baryons have negative parities, the scalar diquark inside them is in a relative P-wave state with respect to the heavy quark. The coalescence formula for the production of such hadrons is

$$\frac{dN_B}{d\boldsymbol{p}_B} = g'_B \frac{2(2\sqrt{\pi}\sigma_{dq})^3}{3V} \int d\boldsymbol{p}_1 d\boldsymbol{p}_2 \frac{dN_1}{d\boldsymbol{p}_1} \frac{dN_2}{d\boldsymbol{p}_2} \sigma_{dq}^2 k^2$$
$$\times \exp\left(-k^2 \sigma_{dq}^2\right) \delta(\boldsymbol{p}_B - \boldsymbol{p}_1 - \boldsymbol{p}_2), \qquad (26)$$

using the Wigner function given in Refs. [51,52]. In the above, k is similarly defined as in Eq. (19) and the width parameter σ_{dq} is taken to have same value as that for the ground state Λ_Q.

B. Quark distribution functions in QGP

For the quark distribution functions in quark-gluon plasma, we use the thermal distribution for light quarks, namely,

$$\frac{dN_q}{d\boldsymbol{p}} = \lambda_q \frac{g_q V}{(2\pi)^3} m_T \exp(-m_T/T_{\text{eff}}), \qquad (27)$$

where $g_q = 6$, $m_T = \sqrt{\boldsymbol{p}^2 + m_q^2}$, and $\boldsymbol{p}$ is the transverse momentum. Instead of the local temperature and transverse flow velocity, we use an effective temperature T_{eff} ($= 200$ MeV) and introduce a normalization factor λ_q to fix the total number of quarks as in Ref. [53]. Following Ref. [54], we assume that the phase transition temperature is $T_C = 175$ MeV and the volume of the quark-gluon plasma formed in rapidity $|y| \leqslant 0.5$ is $V = 1,000$ fm^3 for central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC. This gives the light quark numbers $N_u = N_d \approx 245$ and the strange quark number $N_s \approx 149$ if the constituent light quark and strange quark masses are taken to be 300 MeV and 475 MeV, respectively. The resulting normalization factors λ_q for light and strange quarks are then 0.95 and 0.81, respectively.

Diquarks are also assumed to be in thermal equilibrium and their distribution $dN_{[ud]}/d\boldsymbol{p}$ is then the same as given in Eq. (27) with $g_{[ud]} = 3$. The number of diquarks depends on the diquark mass and is in the range of $77 \sim 44$ with $m_{[ud]} = 455 \sim 600$ MeV [20]. If diquarks exist in QGP, the number of free light quarks is reduced by twice the number of diquarks so that the total number of light quarks is preserved. This would cause a reduction of meson yields and an enhancement of baryon yields and thus induces larger Λ_Q/H^0 ratios. Results to be presented below are obtained by using the diquark mass $m_{[ud]} = 455$ MeV, which is in the range of diquark mass estimated in Ref. [55]. The sensitivity of these results to the diquark mass will, however, be briefly discussed.

For heavy quark transverse momentum distributions in midrapidity, we adopt those parameterized in Ref. [8] for central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC, i.e.,

$$\frac{dN_c}{d\boldsymbol{p}} = \frac{19.2[1 + (p/6)^2]}{(1 + p/3.7)^{12}[1 + \exp(0.9 - 2p)]},$$
$$\frac{dN_b}{d\boldsymbol{p}} = 0.0025 \left[1 + \left(\frac{p}{16}\right)^5\right] \exp(-p/1.495), \qquad (28)$$

with the transverse momentum p in units of GeV. These distributions were obtained from heavy quark p_T spectra from

pp collisions at same energy by the number of binary collisions (∼960) in Au + Au collisions. For bottom quarks, it was taken from the upper limit of the uncertainty band of the pQCD predictions in Ref. [56] for *pp* collisions, as no experimental measurements are available at RHIC. The charm quark p_T spectrum in *pp* collisions is, on the other hand, determined from fitting simultaneously measured p_T spectrum of charmed mesons from $d +$ Au collisions [57] and of electrons from heavy meson decays in *pp* collisions.

Including heavy quark energy loss as estimated in Ref. [8], the resulting heavy quark transverse momentum distribution in midrapidity can be parametrized as

$$\frac{dN_Q^{\rm EL}}{d\bm{p}} = \frac{dN_Q}{d\bm{p}} L_Q(p), \tag{29}$$

with

$$L_c = 0.8 \exp(-p/1.2) + 0.6 \exp(-p/15),$$
$$L_b = 0.36 + 0.84 \exp(-p/10), \tag{30}$$

for charm and bottom quarks, respectively, and p again in GeV. The heavy quark numbers are then estimated to be $N_c \simeq 9.23$ and $N_b \simeq 0.035$. The charm quark number used here is about a factor three larger than that used in Ref. [20] based on perturbative QCD calculations. This, however, does not affect the Λ_Q/H^0 ratios. For the heavy quark masses, we use $m_c = 1.5$ GeV and $m_b = 5.0$ GeV.

C. Results

To calculate the spectra of H^0 and Λ_Q produced in relativistic heavy ion collisions, we consider two scenarios for Λ_Q production. In the first model, we assume that the Λ_Q baryons have no diquark structure and there are no diquarks in QGP either. Therefore, $\Lambda_Q, \Sigma_Q, \Sigma_Q^*, \Xi_Q, \Xi_Q', \Xi_Q^*, \Omega_Q$, and Ω_Q^* baryons are all formed by three-quark coalescence. We further include heavy mesons that consist of strange quarks such as D_s and B_s and their resonances. Using the same oscillator frequency for both heavy mesons and baryons as shown approximately in the quark model, we adjust its value to convert all heavy quarks of small p_T into heavy hadrons via coalescence as in the thermal model. This leads to $\omega = 0.106$ GeV for charmed hadrons and $\omega = 0.059$ GeV for bottom hadrons. The resulting D^+ and B^+ charge radii are 0.74 fm and 1.44 fm, respectively, which are factors of 1.7 and 2.3 larger than those predicted by the light-front quark model of Ref. [49]. The required smaller oscillator frequencies may be partly due to the change in hadron radii in medium [58] and partly due to the incomplete treatment of production and decay of hadron resonances in the present study.

The second model assumes the diquark structure in Λ_Q and the existence of diquarks in QGP as in Ref. [20]. In this case, Λ_Q baryons are formed by diquark–heavy-quark coalescence in addition to three-quark coalescence.[7] Together with the

Σ_Q and Σ_Q^* resonance contributions as well as those from $\Xi_Q, \Xi_Q', \Xi_Q^*, \Omega_Q$, and Ω_Q^* resonances, which are formed only from three-quark coalescence as they do not contain the scalar diquark structure, excited $\Lambda_Q(\frac{1}{2}^-)$ and $\Lambda_Q(\frac{3}{2}^-)$ baryons are also included using the *P*-wave diquark–heavy-quark coalescence.[8] As in the three-quark coalescence model, the oscillator frequencies or width parameters are determined by requiring that all low p_T heavy quarks are converted to hadrons. Besides the common oscillator frequency ω for mesons and three-quark baryons, the additional oscillator frequency for the heavy-quark and diquark system is fixed by reproducing the same Λ_Q radius used in the three-quark configuration. Then we have $\omega = 0.09$ GeV for charmed hadrons and $\omega = 0.049$ GeV for bottom hadrons, leading to 0.81 fm and 1.58 fm for the D^+ and B^+ charged radii, respectively. These values lead to $\omega_{dq} = 0.053$ GeV and 0.029 GeV, respectively, for charmed and bottom baryons consisting of diquarks. In obtaining the contribution of resonances to the ground state H^0 and Λ_Q spectra, we neglect for simplicity the small momentum shift in their decays.

In both models, remaining heavy quarks that are not converted to hadrons via coalescence, which mostly have high p_T, are converted to heavy hadrons by fragmentation. This is achieved by assuming that a heavy quark of transverse momentum p_T fragments into Λ_Q and H^0 of same momentum and with a ratio similar to that given by the PYTHIA model, i.e.,

$$\left(\frac{\Lambda_c}{D^0}\right)_{\rm fr} = 0.05 \exp[-(p_T - 4.0)^2/8.0] + 0.1,$$
$$\left(\frac{\Lambda_b}{\bar{B}^0}\right)_{\rm fr} = 0.75, \tag{31}$$

with p_T in units of GeV.

1. Relative production fractions of heavy hadrons and Λ_Q/H^0 ratios

Our results for the relative production fractions of heavy hadrons produced in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV are presented in Table I together with those from the PYTHIA model and the thermal model. It is seen that the relative production fraction of D^0 among all produced charmed hadrons in the three-quark coalescence model is 0.35, while it is 0.44 and 0.61 for the thermal model and the PYTHIA model, respectively. This fraction reduces to 0.28 in the diquark model. For $\bar{B}^0$, its relative production fractions among all produced bottom hadrons are 0.101, 0.097, 0.052, and 0.043 in the PYTHIA model, the thermal model, the three-quark model, and the diquark model, respectively.

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[7] Strictly speaking, the three quarks should coalesce to form the Λ_Q in diquark structure. Here we simply approximate this production process by three-quark coalescence to form non-diquark Λ_Q. This

thus gives an upper bound for the yield of Λ_c from three independent quarks in QGP as pointed out in Ref. [20].

[8] In general, coalescence of three independent quarks can also form negative parity baryons. Since this process has a smaller contribution than that due to the production of positive parity baryons [59], it is not considered in present work.

TABLE I. Relative production fractions of midrapidity heavy hadrons produced in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The heavy-strange baryon (Ξ_Q, Ξ'_Q, and Ω_Q) yield is suppressed in the PYTHIA model and thus neglected in this work.

Model	Charmed hadrons					Bottom hadrons					
	D^0	D^+	D_s	Λ_c	$\Xi_c/\Xi'_c/\Omega_c$	$\bar{B}^0 (B^-)$	$\bar{B}^{*0} (B^{*-})$	B_s^0	B_s^{*0}	Λ_b	$\Xi_b/\Xi'_b/\Omega_c$
PYTHIA model	0.607	0.196	0.121	0.076		0.101	0.3015	0.030	0.089	0.076	
Thermal model	0.435	0.205	0.179	0.118	0.063	0.111	0.229	0.049	0.113	0.096	0.062
Coalescence model (three-quark model)	0.348	0.113	0.113	0.288	0.138	0.053	0.158	0.027	0.080	0.316	0.155
(ground state contribution)	0.051	0.051	0.0264	0.028	0.066	0.052	0.155	0.026	0.079	0.032	0.073
(fragmentation)	0.043	0.014	0.009	0.005		0.001	0.003	0.0003	0.001	0.001	
Coalescence model (diquark model)	0.282	0.091	0.123	0.378	0.126	0.044	0.131	0.031	0.092	0.385	0.142
(ground state contribution)	0.039	0.039	0.028	0.016	0.059	0.040	0.120	0.029	0.088	0.019	0.066
(diquark contribution)				0.205						0.192	
(fragmentation)	0.048	0.015	0.010	0.005		0.004	0.011	0.002	0.004	0.003	

For the Λ_Q/H^0 ratios, we find that without resonance contribution $\Lambda_c/D^0 = 0.55$ in the three-quark model and $\Lambda_c/D^0 = 2.2$ in the diquark model. These results are different from those of Ref. [20], namely, the Λ_c/D^0 is larger and the enhancement of this ratio due to the presence of diquarks is about 4 while it was about 8 in Ref. [20]. These differences come from the different values for the oscillator frequencies or width parameters as well as the fact that in Ref. [20] the number of free quarks in the quark-gluon plasma is not reduced by the presence of diquarks. For bottom hadrons, we obtain $\Lambda_b/\bar{B}^0 = 0.6$ in the three-quark model, which increases by a factor of 3.5 to $\Lambda_b/\bar{B}^0 = 2.1$ in the diquark model.

Including resonances enhances both Λ_Q and H^0 production. We find that in the three-quark model, about 70% of D^0 and about 90% of Λ_Q are produced through resonance decays. The importance of resonances is also seen in the diquark model. In particular, the diquark contribution through negative parity Λ_Q resonances is non-negligible. The number of negative parity Λ_Q resonance of spin-1/2 turns out to be about half of the ground state Λ_Q baryon number. Since $\Lambda_Q(\frac{1}{2}^-)$ and $\Lambda_Q(\frac{3}{2}^-)$ resonances are almost degenerate in mass, the number of negative parity Λ_Q resonances is about two times that of the ground state Λ_Q after taking into account the spin degeneracy. This should be contrasted with the thermal model which predicts suppressed yields of negative parity Λ_Q resonances due to their large masses. As a result, we find that about 70% of D^0 and about 75% of Λ_Q are produced through resonance decays in the diquark model.

The contribution from heavy quark fragmentation is small, particularly to the ratios of particle numbers. This is because we have assumed that most hadrons are produced by coalescence of low p_T heavy quarks. The fragmentation contribution is thus non-negligible only for high p_T hadrons, which constitute less than 8% of produced total heavy hadrons.

The final Λ_Q/H^0 ratios after including fragmentation and resonance contributions are

$$\Lambda_c/D^0 = 0.83, \qquad \Lambda_b/\bar{B}^0 = 6.00, \tag{32}$$

for the three-quark model, and

$$\Lambda_c/D^0 = 1.34, \qquad \Lambda_b/\bar{B}^0 = 8.79, \tag{33}$$

for the diquark model. Therefore, the enhancement factor for these ratios due to diquarks in QGP is about 1.6 for both charmed and bottom hadrons.

Our results thus indicate that the Λ_c/D^0 ($\Lambda_b/\bar{B}^0$) ratio in heavy ion collisions predicted by the coalescence model is about a factor of 6.4 (8.6) larger than the predictions of the PYTHIA model in Sec. II and about a factor of 3.1 (7.0) larger than that from the thermal model in Sec. III. The existence of diquarks in QGP further enhances this factor to 10.3 (12.6) and 5.0 (10.2), compared to those from the PYTHIA and thermal models, respectively.

2. Transverse momentum spectra of heavy hadrons

The transverse momentum spectra of Λ_Q and H^0 are shown in Figs. 1 and 2 for charmed and bottom hadrons, respectively, together with the transverse momentum dependence of the Λ_Q/H^0 ratio. Solid lines are results for the three-quark model and dashed lines are those for the diquark model. Compared with the PYTHIA results shown by filled circles, the enhancement of Λ_Q yield and the suppression of H^0 yield are evident. The bottom hadron spectra are seen to be harder than the charmed hadron spectra due to the flatter bottom quark spectrum than the charm quark spectrum.

Compared with measured $\bar{p}/\pi^-$ and Λ/K_S^0 ratios [60–62], the obtained Λ_Q/H^0 ratios show very different behavior. Although the Λ_c/D^0 ratio has a similar shape as the $\bar{p}/\pi^-$ and Λ/K_S^0 ratios, which could be approximated by a Gaussian
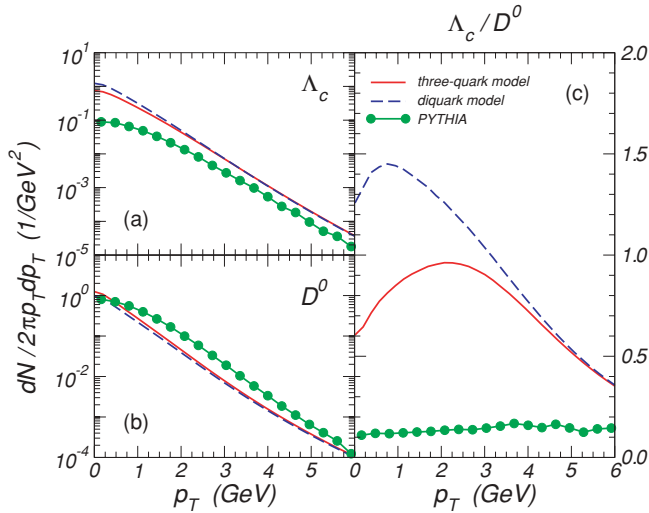
FIG. 1. (Color online) Spectra of (a) Λ_c and (b) D^0, and (c) the ratio Λ_c/D^0 in midrapidity ($|y| \leqslant 0.5$) for central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Solid lines are for the three-quark model and dashed lines are for the diquark model. Results from the PYTHIA model are shown by filled circles.

shape as assumed in Ref. [12], it has a much larger width and is thus much flatter than the light baryon/meson ratios. Furthermore, the $\Lambda_b/\bar{B}^0$ ratio is even flatter than the Λ_c/D^0 ratio. This behavior can also be found in the spectra of Λ_Q and H^0. Namely, while the spectra of Λ_b and $\bar{B}^0$ have very similar p_T dependence (Fig. 2), those of Λ_c and D^0 show somewhat different p_T dependence (Fig. 1). All these behaviors originate from the large mass of heavy quarks. In the infinite mass limit, the momentum of a heavy hadron is completely carried by the heavy quark, and the role of light quarks or diquarks is just to give different production probability depending on the heavy hadron wave function. Therefore, the Λ_Q/H^0 ratio in the infinite heavy mass limit becomes a constant and shows no momentum dependence. In the case of the Λ_c/D^0 ratio,
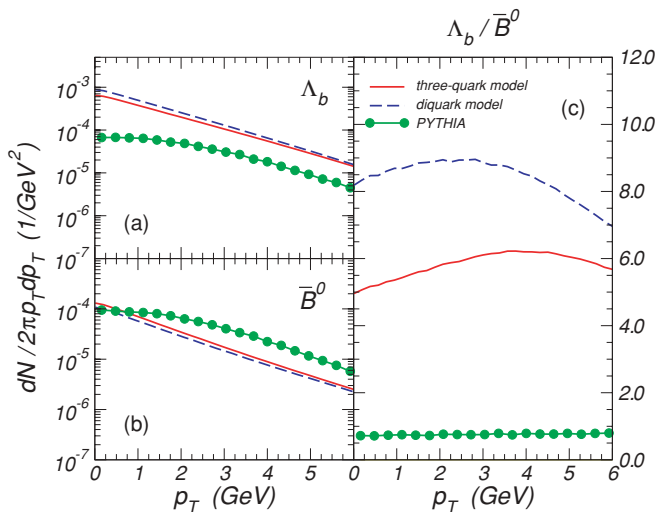

FIG. 2. (Color online) Same as Fig. 1 for (a) Λ_b spectrum, (b) $\bar{B}^0$ spectrum, and (c) the $\Lambda_b/\bar{B}^0$ ratio.

finite mass effects are not negligible but its dependence on the transverse momentum is less strong than in the Λ/K_S^0 ratio. This is clearly seen in pp collisions as shown by the PYTHIA model results in Figs. 1 and 2. Although the coalescence model shows a p_T dependence of the Λ_Q/H^0 ratio, this dependence weakens as the heavy quark mass increases.

We also find that inclusion of diquarks in QGP causes a shift of the peak positions in the Λ_Q/H^0 ratios to lower values of p_T. In the three-quark model, the Λ_c/D^0 ratio peaks at $p_T \simeq 2$ GeV, which shifts to $p_T \simeq 0.8$ GeV in the diquark model. The change of the peak position is caused by both the reduction of the D^0 meson spectrum and the enhancement of the Λ_c spectrum in the diquark model. We find, however, that the latter has a larger effect on the peak position in the Λ_c/D^0 ratio. Since the enhancement of Λ_c due to light diquarks is more appreciable in the low p_T region, the peak of the Λ_c/D^0 ratio in the diquark model thus appears at a lower value of p_T compared to that in the three-quark model. The $\Lambda_b/\bar{B}^0$ ratio also shows a shift in the peak position, i.e., from $p_T \simeq 3.5$ GeV in the three-quark model to 2 GeV in the diquark model, but it is still much flatter than the Λ_c/D^0 ratio.

For a more realistic momentum distribution of heavy hadrons in relativistic heavy ion collisions after their production from QGP, their production and annihilation due to collisions of and with surrounding particles should be investigated by a transport model like the AMPT model [63,64]. However, cross sections for reactions involving open charmed hadrons are small [65,66], and it has been shown in Ref. [51] that the effects of multiple scattering would be small with such small cross sections. Since this work is at the level of an exploratory study, such an elaborated investigation is not yet called for.

V. CONCLUSIONS AND DISCUSSIONS

In this paper, we have studied the Λ_Q/H^0 (Λ_c/D^0 and $\Lambda_b/\bar{B}^0$) ratios in heavy ion collisions, particularly the enhancement of these ratios due to coalescence of heavy quarks with light quarks as well as diquarks that might exist in the produced QGP. We have also considered the resonance decay effects which are shown to be important for understanding the particle production ratios in pp collisions. Our simple estimate based on the thermal model as well as predictions of more sophisticated statistical models [42,43] show that resonance decays also plays a crucial role for heavy hadron production in heavy ion collisions. We have, therefore, included the contribution from resonances in estimating these ratios.

We have determined the width parameters of hadron Wigner functions used in the coalescence model by requiring that the majority of heavy hadrons at low p_T are formed from coalescence, which is similar to that assumed in the thermal model. The remaining heavy quarks are then converted to heavy hadrons via fragmentation as in pp collisions. The resulting Λ_c/D^0 and $\Lambda_b/\bar{B}^0$ ratios in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV are found to be 1.34 and 8.79, respectively, which are about 10.3 and 12.6 larger than the predictions of the PYTHIA model, and about a factor of 5.0 and

10.2 larger than those of the thermal model. The enhancement of the Λ_Q/H^0 ratio due to diquarks is, however, only about 1.6 for both charmed and bottom hadrons, which is smaller than that predicted in Ref. [20]. The difference mainly arises from the different constraints used here and in Ref. [20] for determining the oscillator frequencies or width parameters in the hadron Wigner functions and from maintaining the same total light quark numbers in both the three-quark model and diquark model in the present study.

The enhancement due to diquarks would have been larger if we do not take into account the resonance contribution. This is because of the enhancement of Λ_Q baryons from Σ_Q and Σ_Q^* decays, whose production is not affected by the presence of diquarks in QGP. This is different from the production of strange Λ to which Σ can not decay by strong interactions. Furthermore, including the resonance contribution increases the $\Lambda_b/\bar{B}^0$ ratio much more than the Λ_c/D^0 ratio because B^* cannot decay into B by strong interactions as a result of heavy quark spin symmetry. Finally, this model leads to the reduction of D^0 and $\bar{B}^0$ mesons by factors of about 2.2 compared to the PYTHIA model.

Contrary to the PYTHIA model, we have found that the yields of heavy baryons with strange quark(s) are not small. Their yield was estimated to be about 60% of the Λ_Q yield in the thermal model. In the coalescence model, this is about 50% and 35% of the Λ_Q yield in the three-quark model and diquark model, respectively.

We have also compared the transverse momentum dependence of the Λ_Q/H^0 ratios with that of measured Λ/K_S^0 ratio and found that the Λ_Q/H^0 ratios have a weaker dependence on the transverse momentum because of the massive quarks inside heavy hadrons. In particular, this leads to a very weak dependence of the $\Lambda_b/\bar{B}^0$ ratio on the transverse momentum.

We have further found that the Λ_Q/D^0 ratio peaks at $p_T \simeq$ 2 GeV in the three-quark model and at $p_T \simeq 0.8$ GeV in the diquark model. Therefore, the enhancement of heavy baryon production over heavy meson production due to diquarks can mostly be observed at low p_T region. We have also estimated that the ratio $\Lambda_c/\Sigma_c^0 \simeq 23$, which is less than that of Ref. [23] by a factor of ~ 4.

These results are based on a diquark mass of 445 MeV or a binding energy of 145 MeV. Because of the thermal factor, the number of diquarks decreases as the diquark mass increases. This would reduce both Λ_c and Λ_b production and increase that of D^0 and $\bar{B}^0$, reducing thus the Λ_Q/H^0 ratios. For example, if

the diquark mass is 550 MeV, the enhancement of the Λ_c/D^0 ratio due to diquarks would reduce from 1.6 to 1.3. The peak position in the ratio changes, however, very little.

In studying resonance production in the coalescence model, we have assumed that the effect due to energy mismatch between quarks and produced hadron is small. Since the coalescence model can be viewed as formation of bound states from interacting particles in the system with energy mismatch balanced by other particles in the system, this would be reasonable if the energy mismatch is small. Otherwise, the correction factor can, in principle, be determined by evaluating the transition probability in the presence of other particles. Also, the coalescence model can be further improved by imposing energy conservation using Breit-Wigner type spectral functions for the produced hadrons [67]. This would naturally lead to suppressed production rate due to the energy mismatch between quarks and produced hadron. Improving the coalescence model, therefore, deserves further studies.

One may also consider contributions to heavy hadron production from other diquark states. It is well-known that the color-spin interaction for color-sextet diquark of spin-1 is, although not strong, attractive. (See, e.g., Ref. [33].) This diquark, of course, cannot form a color-singlet baryon with one heavy quark, and color-sextet diquarks are thus disfavored in phenomenological models [31]. However, color-sextet diquarks in QGP can produce color-singlet baryons by first forming color-octet or color-decuplet baryons and then neutralizing their colors by interacting with quarks and gluons in QGP. Therefore, if we assume the existence of (weakly-bound) color-sextet vector diquarks in QGP, it may bring in additional enhancement of Λ_Q baryon production. Since this mechanism is very model-dependent, the existence and properties of such diquark states in QGP should be understood before estimating their contributions to heavy hadron production.

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