Nuclear modification factor of non-photonic electrons in heavy-ion collisions and the heavy-flavor baryon to meson ratio

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The nuclear modification factor $R_{AA}$ of non-photonic electrons in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV is studied by considering the decays of heavy-flavor hadrons produced in a quark coalescence model. Although an enhanced $\Lambda_c/D^0$ ratio is predicted by the coalescence model, it is peaked at small transverse momenta ($\sim 2$ GeV) due to the large difference between heavy and light quark masses. As a result, the enhanced $\Lambda_c/D^0$ ratio, which is expected to suppress the electron $R_{AA}$ as the branching ratio of $\Lambda_c$ decay into electrons is smaller than that of $D^0$, does not lead to additional suppression of the electron $R_{AA}$ at large transverse momenta ($\geq 5$ GeV), where the suppression is mainly due to heavy quark energy loss in produced quark-gluon plasma. Also, the enhanced $\Lambda_b/B^0$ ratio predicted by the coalescence model has even smaller effect on the non-photonic electron $R_{AA}$ as bottom baryons and mesons have similar branching ratios for semi-leptonic decays into electrons.

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Heavy-flavor hadrons are useful for probing the properties of the dense matter produced in relativistic heavy-ion collisions. Although $D$ mesons were measured in $d + Au$ collisions at the Relativistic Heavy Ion Collider (RHIC) \cite{1}, there is not yet direct measurement of open charm or open bottom hadrons in heavy-ion collisions. Instead, heavy-flavor hadron production in heavy-ion collisions was studied through measurements of non-photonic electrons from their decays \cite{2}. The transverse momentum ($p_T$) spectrum of these electrons in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV were measured for several centralities by the PHENIX Collaboration \cite{2}. The resulting nuclear modification factor $R_{AA}$, defined by the ratio of the $p_T$ spectrum of non-photonic electrons in heavy-ion collisions $dN_{e}/dp_{T}$ to that from proton-proton collisions $dN_{e}/dp_{T}$ multiplied by the initial number of $NN$ binary collisions $\langle N_{\text{coll}} \rangle$, i.e.,

$$R_{AA} = \frac{dN_{e}^{AA}/dp_{T}}{(N_{\text{coll}}^{AA})/dN_{pp}/dp_{T}}, \tag{1}$$

shows that the production of heavy-flavor hadrons in heavy-ion collisions is suppressed as much as that of pions. This has raised a challenging question on heavy quark interactions in medium as perturbative Quantum Chromodynamics (pQCD) predicts that heavy quarks lose less energy in the quark-gluon plasma than gluons and light quarks, which is responsible for the observed large suppression of high $p_T$ pions. Various ideas have been suggested to explain the observed small non-photonic electron $R_{AA}$, and these include the introduction of very large medium opacity \cite{3}, two-body \cite{4,5,6} and three-body collisional energy loss \cite{8}, and the collisional dissociation of heavy mesons in medium \cite{9}. It is also proposed that an enhancement of the $\Lambda_c/D^0$ ratio would reduce the $R_{AA}$ of non-photonic electrons \cite{10,11,12}. This is based on the observation that the branching ratio for $\Lambda_c \rightarrow e$ decay is smaller than that for $D^0 \rightarrow e$ decay. Therefore, if the $\Lambda_c/D^0$ ratio is enhanced as in the case of $p/\pi$ and $\Lambda/K^0$ ratios, the $R_{AA}$ of non-photonic electrons would be smaller than that only due to heavy quark energy loss. In Ref. \cite{11}, it was claimed that this effect may explain about 20\% of the suppression of $R_{AA}$. Since the origin of the $\Lambda_c/D^0$ enhancement is unknown, this ratio is assumed in Refs. \cite{10,11} to have either the same $p_T$ dependence as in the $\Lambda/K$ data or a Gaussian form.

Recently, the enhancement of $\Lambda_c$ yield in relativistic heavy ion collisions was suggested as a possible test of the diquark model for the structure of heavy baryons \cite{12,13}. Estimates based on the quark coalescence model for heavy-flavor hadron production show that the existence of diquarks in both the quark-gluon plasma and the $\Lambda_c$ would enhance the $\Lambda_c/D^0$ ratio by a factor of ten and five, respectively, compared to those of PYTHIA simulation for $pp$ collisions and of a simple thermal model. (See, e.g., Ref. \cite{14} for the quark coalescence model.) Furthermore, it was shown that the enhancement of the $\Lambda_c/D^0$ ratio could be better seen at low $p_T$ region where heavy quark fragmentation is less important. Therefore, the enhancement of $\Lambda_c/D^0$ ratio is expected to result in the suppression of $R_{AA}$ only at low $p_T$ region. This is in contrast to the assumption of Refs. \cite{10,11} that the $\Lambda_c/D^0$ enhancement continues to the large $p_T$ region. In this report, we calculate the non-photonic electron $R_{AA}$ based on the results from Ref. \cite{13}. We also discuss the contribution from the enhanced $\Lambda_b/B^0$ ratio to the non-photonic electron $R_{AA}$.

For calculating the electron spectrum from heavy hadron decays, information on the branching ratios of semi-leptonic decays of heavy hadrons into electrons is needed. The experimental data compiled by the Particle Data Group \cite{15} for the branching ratios of these de-
cays are, however, ambiguous as shown in Table I. One can estimate the effect of the $\Lambda_c/D^0$ enhancement on the electron $R_{AA}$ roughly by considering semi-leptonic decay of heavy hadrons in each channel as in Ref. [11],

$$R_{AA} = \left\{ \frac{n_e(D^0) + n_e(D^+) + n_e(D_s) + n_e(\Lambda_c)}{n_e(D^0) + n_e(D^+) + n_e(D_s) + n_e(\Lambda_c)} \right\}_{pp},$$

(2)

where $n_e(H)$ is the number of electron produced by the decay of hadron $H$, and the number of binary collisions is included in the numerator. Since the branching ratio of $\Lambda_c$ decay into electron is smaller than that of charged mesons, the enhanced $\Lambda_c/D^0$ ratio indeed suppresses the electron $R_{AA}$ if the momentum difference between electrons and the decayed charged hadrons is neglected. In Ref. [11], it was claimed that if the enhancement factor, $C = (\Lambda_c/D^0)_{AA}/(\Lambda_c/D^0)_{pp}$, is 12, the electron $R_{AA}$ is reduced by about 20%. More quantitative understanding of the effect of enhanced $\Lambda_c/D^0$ ratio on the $R_{AA}$ of non-photonic electrons requires, however, a better understanding of the branching ratios of heavy hadron decays, including the decays to four-body final states, as well as the production mechanism of heavy-flavor hadrons in both $pp$ and $AA$ collisions. The latter is addressed in the present study.

We use the coalescence model calculation presented in Ref. [13], which is based on the coalescence formulas

$$\frac{dN_B}{dp_B} = g_B \left( \frac{2\sqrt{\pi} \sigma_{dG}}{V^2} \right)^3 \int dp_1 dp_2 dp_3 \frac{dN_1 dN_2 dN_3}{dp_1 dp_2 dp_3} \times \exp \left( -\frac{k^2}{\sigma_1^2} - \frac{k^2}{\sigma_2^2} \right) \delta(p_B - p_1 - p_2 - p_3),$$

(3)

for baryon production from three-quark coalescence and

$$\frac{dN_M}{dp_M} = g_M \left( \frac{2\sqrt{\pi} \sigma_{dG}}{V} \right)^3 \int dp_1 dp_2 dN_1 dN_2 \frac{dN_1 dN_2}{dp_1 dp_2} \times \exp \left( -\frac{k^2}{\sigma_0^2} \right) \delta(p_B - p_1 - p_2),$$

(4)

for both baryon and meson production from diquark-quark coalescence and from quark–anti-quark coalescence, respectively. For the details on the model and parameters used in the calculations, we refer to Ref. [13].

For the heavy quark energy loss, we use the parametrization given in Ref. [8],

$$L_c = 0.8 \exp(-p/1.2) + 0.6 \exp(-p/15),$$

$$L_b = 0.36 + 0.84 \exp(-p/10),$$

(5)

for charm and bottom quarks, respectively, where $p$ is the transverse momentum in units of GeV. As shown in Ref. [13], compared with charged hadron production via fragmentation of charm quarks, the yield of $D^0$ mesons in heavy ion collisions is suppressed in the quark coalescence model as a result of enhanced production of $\Lambda_c$. (See the small window in Fig. 1 for the $\Lambda_c/D^0$ ratios.) This happens in models based on both the three-quark coalescence and the diquark-quark coalescence. In Fig. 1 we plot the electron spectrum from charm hadron decays for central Au + Au collisions at mid-rapidity ($|y| < 0.5$). As a reference, results from the decays of charged hadrons produced via $\delta$-function fragmentation of charm quarks, i.e., charm quark and produced hadrons have same $p_T$, without and with energy loss are given by the solid line and dashed line, respectively. These electron spectra include contributions from decays of $D^0$, $D^+$, $D_s$, $\Lambda_c$ and their anti-particles, as production of electrons from charm hadrons other than $D^0$ is not negligible, particularly if there is a large enhancement of the $\Lambda_c/D^0$ ratio [10]. Compared with the case that these charged hadrons are produced from fragmentation of charm quarks via a $\delta$-function fragmentation, coalescence models are seen to give a somewhat suppressed electron spectrum. We note that the uncertainties in the branching ratios as shown in Table I can affect the electron spectrum. More discussions on these uncertainties can be found in Ref. [10].

Our results for the non-photonic electron $R_{AA}$ are presented in Fig. 2. Here, we consider five cases for investigating the role of the enhancement of the $\Lambda_c/D^0$ ratio in the electron $R_{AA}$. First, the solid line is the electron $R_{AA}$ for the case with charm quark energy loss in the $\delta$-function fragmentation approximation as discussed in Ref. [8]. Shown by the dotted line is the result from the coalescence model when only $D$ mesons are allowed to be produced. If other charmed hadrons are allowed to be produced, the contribution from the $D^0$ mesons to the electron spectrum is suppressed and leads to the suppressed electron $R_{AA}$ as can be seen by the dot-dashed line. The dashed and dot-dot-dashed lines are obtained

| Decay channel          | $D^0$       | $D^+$       | $D^{+}_{s}$ | $\Lambda_c$ |
|------------------------|-------------|-------------|-------------|-------------|
| $\text{BR}(e^+ + \text{anything})$ | $6.53 \pm 0.17\%$ | $16.0 \pm 0.4\%$ | $8 -5\%$ | $4.5 \pm 1.7\%$ |
| $\text{BR}(K^e^+ \nu_e)$   | $3.58 \pm 0.06\%$ | $8.6 \pm 0.5\%$ |             |             |
| $\text{BR}(K^e^+ \nu_e)$   | $2.18 \pm 0.16\%$ | $3.66 \pm 0.21\%$ | $2.9 \pm 0.6\%$ |             |
| $\text{BR}(\eta e^+ \nu_e)$ |             |             | $1.02 \pm 0.33\%$ |             |
| $\text{BR}(\eta e^+ \nu_e)$ |             |             |             | $2.1 \pm 0.6\%$ |
| $\text{BR}(\pi e^+ \nu_e)$   |             |             | $\Lambda_c$ | $1.8 \pm 0.9\%$ |

**TABLE I**: Branching ratios of major semi-leptonic charm hadron decays into electrons as listed by the Particle Data Group [13].
by allowing the decays of all charmed hadrons into electrons in diquark and three-quark coalescence, respectively, and are the main results of this study. Therefore, by comparing the dotted line and the dashed line, one can see that the enhanced $\Lambda_c/D^0$ leads to suppression of the electron $R_{AA}$.

However, when we compare our result for the electron $R_{AA}$ with that of fragmentation with energy loss, the enhancement of the $\Lambda_c/D^0$ ratio does not cause the suppression of the electron $R_{AA}$. This is because the enhancement of $\Lambda_c/D^0$ ratio in the coalescence model appears mainly in the region of $p_T \leq 5$ GeV. In addition, we found that the crossover of the coalescence and fragmentation is at $p_T \sim 0.75$ GeV. As a result, the suppression of the $R_{AA}$ for non-photonic electrons appears also at low $p_T$ region ($p_T \leq 3$ GeV). Thus, the calculated $R_{AA}$ underestimates the data [3] at low $p_T$ and overestimates it at large $p_T$. Including the decay of $\Lambda_c$, whose branching ratio of decaying into an electron is not small in comparison to that of $D^0$, increases the electron $R_{AA}$. We also found that the difference between the results of the three-quark and the diquark-quark coalescence models is not large. Therefore, in the coalescence model considered here, more quenched charm quark spectrum is needed to explain the small electron $R_{AA}$ observed in experiments.

Our results that the enhancement of $\Lambda_c/D^0$ ratio does not cause the suppression of $R_{AA}$ is in sharp contrast with those of Refs. [10, 11]. The reason for this is due to the difference in the $\Lambda_c/D^0$ ratio at large $p_T$ region. In both Refs. [10, 11], a constant enhancement factor is assumed for the $\Lambda_c/D^0$ ratio at large $p_T$. Besides the assumption that the $\Lambda_c/D^0$ ratio is the same as the $\Lambda/K_S^0$ ratio, it is further assumed in Ref. [10] that $\Lambda_c/D^0 = 0.33$ for large $p_T$, where no data for $\Lambda/K_S^0$ exist. In Ref. [11], an even larger constant enhancement factor $C \simeq 12$ was introduced to the $\Lambda_c/D^0$ ratio that was assumed to have a Gaussian shape in $p_T$. This large enhancement of $\Lambda_c/D^0$ at large $p_T$ would then lead to the suppression of $R_{AA}$ at intermediate and large $p_T$ ($\geq 5$ GeV).

In our case, although the $\Lambda_c/D^0$ ratio is enhanced compared to that in $pp$ collisions, the enhancement is mainly at small $p_T$ and the $\Lambda_c/D^0$ ratio remains comparable to that of $pp$ collisions at large $p_T$ ($> 7 \sim 8$ GeV) region. Therefore, the effect of the $\Lambda_c/D^0$ enhancement on the electron $R_{AA}$ cannot be seen in the intermediate electron $p_T$ region. Furthermore, charmed hadrons produced by coalescence with light quarks have larger values of $p_T$ than that of the charm quark inside a hadron, which results in the shift of charmed hadron $p_T$ spectra to the larger $p_T$ region. Therefore, at large $p_T$ region, we have more charm hadrons than those produced by $\delta$ function fragmentation of charm quarks. Although this effect is not large compared to the case for light hadrons, it increases the electron $R_{AA}$. As a result, we have a larger $R_{AA}$ at intermediate electron $p_T$ compared to that from the fragmentation of quenched heavy quarks.

As the electron $p_T$ increases, electrons from bottom hadron decays become important. The $p_T$ at which electrons from charmed hadron decays and from bottom hadron decays intercepts depends on the model for heavy quark energy loss in the quark-gluon plasma. Since heavy quark energy loss is suppressed as its mass increases [17], this momentum becomes smaller once heavy quark energy loss is included. Therefore, semi-leptonic decays of bottom hadrons should be considered at large electron $p_T$ region, and this would further increase the electron $R_{AA}$.

The decays of bottom hadrons into electrons are not well-known. There are two processes through which ele-
trons are produced from bottom hadron decays. One is the direct production of electrons from bottom hadron decays, such as $B \to e^+\nu_e X_c$, where $X_c$ denotes any charm meson. The produced $X_c$ can again decay into electrons. Therefore, bottom hadrons produce primary and secondary electrons. In addition, for vector mesons, $B^*$ and $B^*_0$, they first decay into $B\gamma$ and $B_s\gamma$, respectively, and electrons are then produced from the decay of resulting pseudoscalar mesons. Currently available experimental data show that the branching ratios of bottom hadrons decaying into electrons are nearly independent of the light quark content of bottom hadrons \cite{15},

\[
\begin{align*}
\text{BR}(B^\pm \to e^+\nu_eX_c) &= 10.8 \pm 0.4 \%, \\
\text{BR}(B^0 \to e^+\nu_eX_c) &= 10.1 \pm 0.4 \%, \\
\text{BR}(B_s \to \ell^+\nu_{\ell}D_s + \text{anything}) &= 7.9 \pm 2.4 \%, \\
\text{BR}(\Lambda_b \to \ell^+\nu_{\ell}\Lambda_c^+ + \text{anything}) &= 9.9 \pm 2.6 \%. \quad (6)
\end{align*}
\]

The paucity of experimental data for the branching ratio of each channel in semi-leptonic decays of bottom hadrons makes it difficult to compute the electron spectrum from bottom hadron decays. Nevertheless, one can estimate the effect of $\Lambda_b/B^0$ enhancement to the electron $R_{AA}$ in a qualitative way by using the formula given in Eq. (2). In Ref. \cite{13}, we have observed a large enhancement of the $\Lambda_b/B^0$ ratio in the coalescence model. However, since the branching ratio of $B \to e$ and $\Lambda_b \to e$ are similar, enhancement of $\Lambda_b$ baryon produces more electrons, which compensates almost the reduced number of electrons from $B$ decays. This can also be verified through Eq. (2). Namely, if we use the branching ratios given in Eq. (6), $R_{AA}$ changes from 1.0 with $C = 0$ to 0.95 with $C \to \infty$. This shows that the effect of the $\Lambda_b/B^0$ enhancement on the electron $R_{AA}$ is very small compared to that for charm hadrons. This is shown explicitly in Fig. 3. By considering the large uncertainty in the branching ratio of $\Lambda_b$ decays, the effects of $\Lambda_b/B^0$ enhancement is small, in particular at large $p_T$ region, where the electron $R_{AA}$ is expected to be governed by bottom hadron decays.

Although the multiplicities of multi-heavy-quark baryons are very small, production of heavy baryons containing one heavy quark and one or two strange quarks is not negligible. In the coalescence model of Ref. \cite{13}, we found that the sum of the multiplicities of $\Xi_Q$, $\Xi_Q'$, and $\Omega_Q$ is as large as $30 \sim 50\%$ of the multiplicity of $\Lambda_Q$, where $Q$ stands for $c$ or $b$. However, the branching ratios of these hadrons have not been measured and the electron spectrum from the decays of these baryons thus can not be estimated.

In summary, we have studied the transverse momentum spectrum and the nuclear modification factor $R_{AA}$ of non-photonic electrons from heavy hadron decays in relativistic heavy ion collisions. Contrary to the models of Refs. \cite{14, 11}, which assume an enhanced $\Lambda_c/D^0$ ratio at large $p_T$ region, the large enhancement of $\Lambda_c/D^0$ ratio predicted in the coalescence model \cite{13} occurs mainly in the low $p_T$ region and the heavy quark fragmentation remains dominant at large $p_T$ region. As a result, no additional suppression to the electron $R_{AA}$ due to enhanced $\Lambda_c/D^0$ ratio is obtained at large $p_T$ region. We have also estimated the role of $\Lambda_b/B^0$ enhancement in the electron $R_{AA}$ and found that the enhancement of $\Lambda_b$ baryon production does not affect the electron $R_{AA}$ produced by bottom hadron decays because of similar branching ratios of bottom meson and $\Lambda_b$ decays into electrons.

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