Measurements of open charm hadrons in Au+Au collisions at the STAR experiment

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Charm quarks possess a large mass and thus they are expected to be primarily produced during the initial stages of heavy-ion collisions. Hot and dense nuclear matter, usually referred to as the Quark-Gluon Plasma (QGP), can also be created in these collisions. Therefore, the QGP can be studied using charm quarks as penetrating probes via measurements of the parton energy loss and collective behavior, which are directly related to the intrinsic properties of the medium. In particular, a mass ordering of the parton energy loss in the hot medium is predicted, i.e. heavy-flavor quarks are expected to lose less energy than light quarks. Moreover, STAR has measured several species of charm hadrons and, therefore, can probe several modes of charm quark hadronization in the medium. In these proceedings we report on the most recent measurements of the production of $D^0$ and $D^+_s$, as well as $D_s$, containing a strange quark, and the $Λ_c$ baryon in Au+Au collisions at the center-of-mass energy per nucleon–nucleon pair of $\sqrt{s_{NN}} = 200$ GeV. These particles are reconstructed via their hadronic decay channels, where the daughter particles are tracked and identified with excellent precision.
In ultra-relativistic heavy-ion collisions, such as those carried out at Relativistic Heavy Ion Collider (RHIC), a new state of matter, the so-called strongly-coupled quark-gluon plasma (sQGP), is expected to be created \[1\]. Charm quarks are mainly produced in hard processes during the early stages of such collisions since the charm quark mass is much larger than the temperature of the sQGP which makes the thermal production improbable. Therefore, charm quarks experience the whole evolution of the medium and can be used to probe the properties of the hot and dense strongly-interacting matter \[2\]. Analogous to the Brownian motion, charm quarks are sensitive to the transport properties of the sQGP and can be used to extract \(2\pi T D_s\), where \(T\) is the temperature of the system and \(D_s\) the spatial diffusion coefficient of the c-quark in the medium.

The \(D^0\) and \(D^\pm\) mesons, the lightest hadrons containing a charm quark, provide excellent probes to the medium properties. Previous measurements of the \(D^0\) meson production at RHIC \[3\] and the Large Hadron Collider (LHC) \[4,5\] show suppression of yields at high transverse momenta \((p_T)\) and suggest a non-zero elliptic flow coefficient \((v_2)\) at intermediate to high \(p_T\). Measurements of better precision are, however, needed to provide more stringent constraints on model calculations.

The \(D_s\) meson and the charmed baryon \(\Lambda_c\) provide additional handles on understanding the hadronization process of charm quarks. Model calculations \[6–10\] suggest enhancements of the \(D_s/D^0\) and \(\Lambda_c/D^0\) yield ratios in Au+Au collisions, because of the presence of the quark coalescence mechanism in contrast to only quark fragmentation in p+p collisions.

1. The STAR experiment and open charm hadron reconstruction

The Solenoidal Tracker at RHIC (STAR) is a large multi-purpose detector that covers the full azimuthal angle and pseudorapidity range of \(|\eta| < 1\) \[11\]. The main tracking detector of STAR is the Time Projection Chamber which also provides \(dE/dx\) information for particle identification (PID). The Time-Of-Flight detector is also used to improve the PID capabilities, especially at low \(p_T\).

In 2014–2016, a novel high-precision silicon vertex detector, the Heavy Flavor Tracker (HFT), was installed at STAR. The HFT provided excellent track pointing resolution and allowed for direct topological reconstruction of the secondary vertices of open charm hadron decays via hadronic channels, i.e. \(D^0 \rightarrow \pi^\pm K^\mp\), \(D^\pm \rightarrow \pi^\pm \pi^\pm K^\mp\), \(\Lambda_c^\pm \rightarrow p^\pm K^\mp \pi^\pm\), and \(D_s^\pm \rightarrow \pi^\pm \phi(1020) \rightarrow \pi^\pm K^\mp K^\mp\), which greatly reduced the combinatorial background. In the case of the \(D_s\) meson, the decay channel through \(\phi(1220)\) is used to place an additional constraint on the \(K^\pm + K^\mp\) invariant mass, reducing the background even further.

2. Results

2.1 \(D^0\) and \(D^\pm\) nuclear modification factor \(R_{AA}\)

Figure 1 shows the \(D^0\) and \(D^\pm\) nuclear modification factors \((R_{AA})\) as a function of \(p_T\) in the 0–10% most central Au+Au collisions. \(R_{AA}\) is a ratio between the particle yield in Au+Au collisions and that in p+p collisions scaled by the number of binary collisions \(N_{coll}\). The new results (black squares for \(D^0\) and red circles for \(D^\pm\)), which were obtained using the HFT, have a much better precision, compared to the published \(R_{AA}\) from 1.1B minimum-bias events taken in 2010 and 2011 without the HFT (blue triangles) \[3\], despite the less statistics used. The \(D^0\) and \(D^\pm\) yields are
consistent with each other after taking into account their different fragmentation ratios from charm quarks and are significantly suppressed at high-$p_T$, indicating strong interactions between charm quarks and the medium in this kinematic region.

Several theoretical calculations that use different approaches to describe charm quark transportation in the sQGP and correspond to different values of the diffusion coefficient can qualitatively describe the measured $R_{AA}$. The group from TAMU [12] predicts $3 \leq 2\pi T D_s \lesssim 11$ for $T_c < T < 2T_c$, where $T_c$ is the QCD critical temperature, while in the SUBATECH calculation [13] the diffusion coefficient is within $2 \leq 2\pi T D_s \leq 4$. The model by the Duke university group [14] uses $2\pi T D_s$ as a free parameter which is fixed for the RHIC energies to be 7 by matching to the $R_{AA}$ measured at the LHC.

### 2.2 D⁰ elliptic and triangular anisotropies

The HFT has enabled the measurement of the $D^0$ elliptic ($v_2$) [15] as well as triangular ($v_3$) anisotropies for the first time at RHIC. STAR results on $v_2$ are shown in Figs. 2a–2c. The vertical bars (brackets) indicate the statistical (systematic) uncertainties while the gray bands represent an estimate of the non-flow contribution inferred from $D^*$–hadron correlations in p+p collisions. The data show that the $v_2$ is significantly larger than 0 above 1.5 GeV/c.

Figures 2a and 2b show the $D^0 v_2$ for 10–40% central collisions, compared to those of light-flavor hadrons. In Fig. 2a a clear mass ordering is observed for $p_T < 2$ GeV/c. If divided by the number of constituent quarks $n_q$, as shown in Fig. 2b, and displayed as a function of $(m_T - m_0)/n_q$, where $m_0$ is the rest mass and $m_T = \sqrt{p_T^2 + m_0^2}$, the $D^0 v_2$ follows the same pattern as those of light-flavor hadrons. This observation points to strong collective behavior of the charm quarks.

Several model calculations are compared to the measured $D^0 v_2$ in Fig. 2c. A 3D viscous hydrodynamical calculation [17] is consistent with the data within the region of $p_T < 4$ GeV/c, suggesting thermalization of the c-quark. In addition to $R_{AA}$, the SUBATECH and TAMU models are consistent with the measured $v_2$ as well. The Duke model can describe the shape of the $R_{AA}$, however it systematically underestimates the $v_2$. The LBT [18] and PHSD [19] calculations, corresponding to $3 \leq 2\pi T D_s \leq 6$ and $5 \leq 2\pi T D_s \leq 12$, respectively, describe both the measured $R_{AA}$.
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Figure 2: (a) $D^0 v_2$ as a function of $p_T$ in 10–40% central collisions [15], compared to light hadrons [16]; (b) $v_2/n_q$ of $D^0$ and light hadrons as a function of $(m_T - m_0)/n_q$; (c) $D^0 v_2$ as a function of $p_T$ in 0–80% centrality bin; (d) $v_3/n_q^{3/2}$ of $D^0$ and light hadrons as a function of $(m_T - m_0)/n_q$ in 0–80% centrality bin.

and $v_2$. From these models, the range of $2 \leq 2\pi T D_s \lesssim 12$ can be inferred for $T_c < T < 2T_c$. This range is consistent with lattice QCD calculations [20, 21].

Figure 2d shows the triangular anisotropy $v_3$ of the $D^0$ compared to that of light flavor hadrons. A strong indication of non-zero $v_3$ is observed. Similarly to the $v_2$ measurement, the $D^0$ $v_3$ is scaled by $n_q^{3/2}$ (indicated NCQ$^{3/2}$ in Fig. 2d) and plotted as a function $(m_T - m_0)/n_q$, which is seen to follow the same trend for the $D^0$ meson and light hadrons.

2.3 Strangeness and baryon enhancements in open-charm hadrons

Thanks to the HFT, the $D_s$ meson is measured for the first time at RHIC and the $\Lambda_c$ baryon is measured for the first time in heavy-ion collisions.

In Fig. 3a, the yield ratio of produced $D_s$ to $D^0$ is shown as a function of $p_T$ in 0–10% and 10–40% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The measured $D_s/D^0$ yield ratio in Au+Au collisions is compared to the PYTHIA [22] prediction for p+p collisions, as well as the average of the fragmentation ratio from the measurements in p+p, e+e, and e+p collisions [23]. The $D_s/D^0$ yield ratio in Au+Au collisions is significantly enhanced compared to that in elementary collisions. The calculation by the TAMU group [6], including charm quark coalescence, underpredicts the data in the corresponding centrality interval of 10–40%. The Statistical Hadronization Model (SHM [24]) is consistent with the data.

$\Lambda_c$ baryons are reconstructed in the $p_T$ region of 3–6 GeV/$c$ in the 10–60% centrality interval. Figure 3b shows the comparison of the measured yield ratio of $\Lambda_c/D^0$ to several theoretical
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3. Summary and outlook

STAR has made a comprehensive study of the behavior of the charm quarks in the sQGP. We report measurements of the open charm hadrons using the state-of-the-art vertex detector HFT. The $D^0 v_2$ and $v_3$ are measured for the first time at RHIC and are significantly above zero, favoring models with charm diffusion. Moreover, the $D^0$ and $D^\pm R_{AA}$ are measured with much improved precision, compared to the previous measurements without the HFT. Comparing both the $R_{AA}$ and $v_2$ results to different models, the value of the charm quark spatial diffusion coefficient is inferred to be $2 \leq 2\pi T D_s \lesssim 12$ in the range of $T_c < T < 2T_c$, which is consistent with lattice QCD calculations.

The yield ratios of $D_s/D^0$ and $\Lambda_c/D^0$ are measured for the first time at RHIC. Compared to the fragmentation-only scenario, both ratios are strongly enhanced, suggesting that charm quarks also participate in the coalescence hadronization.

In addition to the data taken in 2014, on which the reported results are based, twice more minimum-bias Au+Au events were recorded at STAR with the HFT in 2016. All the measurements in these proceedings will benefit greatly from the increased statistics.

This work has been supported by the Czech Technical University in Prague grant no. SGS16/238/OHK4/3T/14 and by the grant LG15001 of the Ministry of Education of the Czech Republic.
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