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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 $D^{\pm}$, 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.

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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 Λ_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 Λ_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 $\mathrm{d}E/\mathrm{d}x$ 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. $D^0 \to \pi^{\pm}K^{\mp}$, $D^{\pm} \to \pi^{\pm}\pi^{\pm}K^{\mp}$, $\Lambda_c^{\pm} \to p^{\pm}K^{\mp}\pi^{\pm}$, and $D_s^{\pm} \to \pi^{\pm}\phi(1020) \to \pi^{\pm}K^{\pm}K^{\mp}$, 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 1.1 B 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

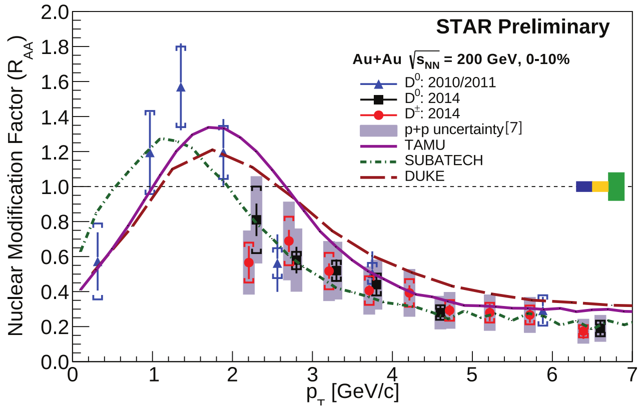

Figure 1: D^0 and $D^\pm$ meson R_{AA} as a function of p_T for 0–10 % central Au+Au collisions. The gray bands are systematic uncertainties from the p+p baseline and the blue, yellow, and green vertical bands around unity are uncertainties related to the N_{coll} in Au+Au collisions in 2010 and 2014, and the global normalization in p+p collisions, respectively.

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 $3 \le 2\pi T D_s \lesssim 11$ 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 $2 \le 2\pi T D_s \le 4$. 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 D^0 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 $3 \le 2\pi T D_s \le 6$ and $5 \le 2\pi T D_s \le 12$, respectively, describe both the measured R_{AA}

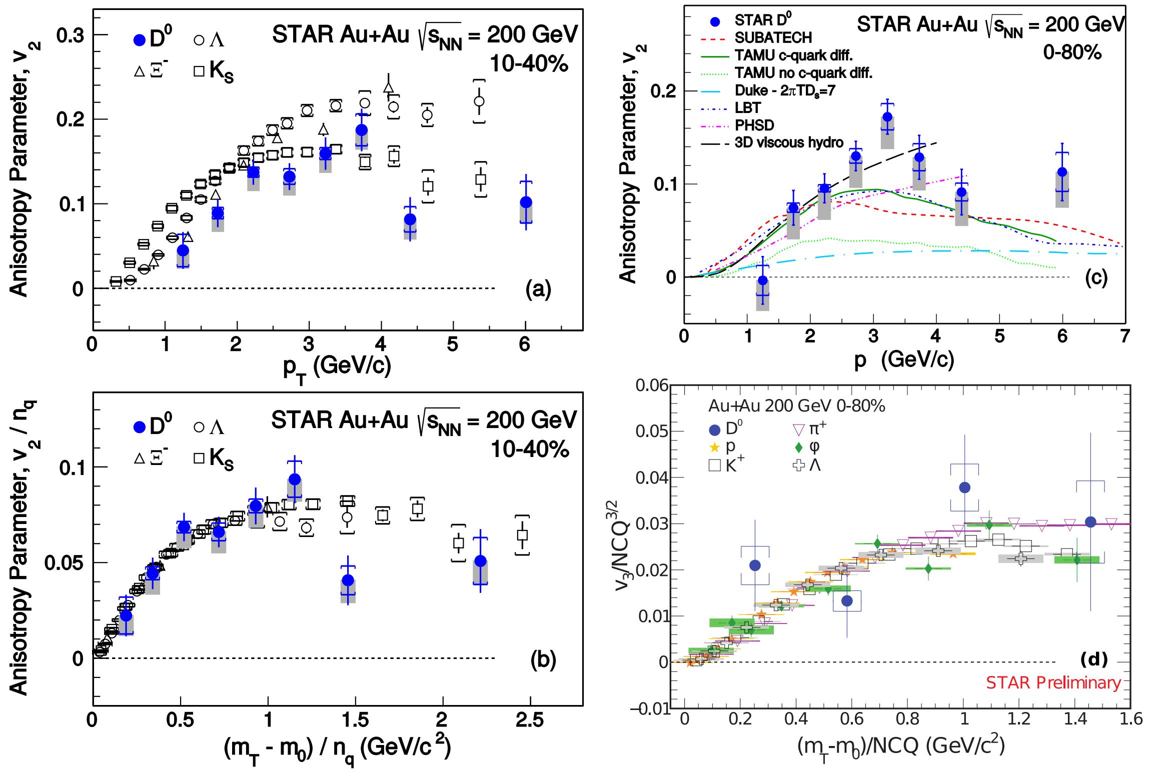

Figure 2: **(a)** D^0 v_2 as a function of p_T in 10–40 % central collisions [15], compared to light hadrons [16]; **(b)** v_2/n_q of D^0 and light hadrons as a function of $(m_T - m_0)/n_q$; **(c)** D^0 v_2 as a function of p_T in 0–80 % centrality bin; **(d)** $v_3/n_q^{3/2}$ of D^0 and light hadrons 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 $(m_T - m_o)/n_q$, 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 Λ_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.

Λ_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 Λ_c/D^0 to several theoretical

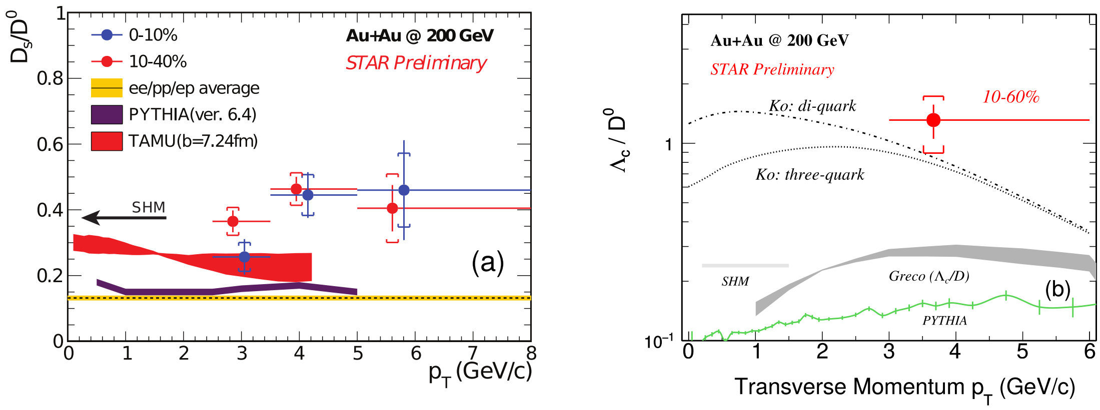

Figure 3: **(a)** Yield ratio of D_s/D^0 in 0–10 % and 10–40 % central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV; **(b)** Yield ratio of Λ_c/D^0 in 10–60 % central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

calculations. The calculation with no coalescence, obtained from PYTHIA, is significantly below the data. The SHM [10, 24] underpredicts the data as well. The Ko model [7] uses two coalescence calculations: one where the charm quark coalesces with a light di-quark structure and the other where three quarks coalesce. No rescattering in the hadron gas is considered in these two scenarios. The data are consistent with both the di-quark and three-quark coalescence scenarios. The Greco model [8, 9] employs the three-quark coalescence mechanism, and calculates the diffusions of Λ_c and D^0 in the hadron gas. Note that the denominator for this calculation is the sum of all D meson species rather than only D^0, and one expects it to increase if only the D^0 meson is considered.

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 Λ_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.

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