Abstract: Charm quarks are primarily produced at the early stages of ultra-relativistic heavy-ion collisions and can therefore probe the quark-gluon plasma throughout its whole evolution. Final-state open-charm hadrons are commonly used to experimentally study the charm quark interaction with the medium. Thanks to the excellent secondary vertex resolution provided by the Heavy Flavor Tracker, STAR is able to directly reconstruct $D^\pm$, $D^0$, $D_s$, and $\Lambda^\pm_c$ via their hadronic decay channels. The topological cuts for signal extraction are optimized using supervised machine learning techniques. In these proceedings, we present an overview of recent open charm results from the STAR experiment. The nuclear modification factors of open-charm mesons and $\Lambda^\pm_c/D^0$ ratio are shown as functions of transverse momentum and collision centrality.

Keywords: quark-gluon plasma; STAR experiment; heavy-ion collisions; heavy-flavor mesons; nuclear modification factor; baryon/meson ratio

1. Introduction

At RHIC energies, charm and bottom quarks are produced predominantly through hard partonic scatterings at the early stage of a heavy-ion collision. Therefore, most open-charm hadrons observed at RHIC come from hadronization of primordial charm quarks or decays of $b$-hadrons. This makes them an ideal probe of the Quark-Gluon Plasma (QGP) because they experience the entire evolution of the medium. A selection of recent open-charm hadron results from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, measured by the STAR experiment using data recorded in 2014 and 2016, is presented and discussed in these proceedings.

The secondary vertices of charm hadrons are reconstructed topologically, utilizing the STAR Heavy Flavor Tracker (HFT) [1,2]. The specific decay channels used in the analysis and basic properties of the open-charm hadron decays are summarized in Table 1. These new measurements will provide insights into phenomena, such as the energy loss of partons inside the QGP and the hadronization process.
Table 1. Summary of open-charm hadrons measured at STAR using the HFT. The left column contains decay channels used for the reconstruction, $c\tau$ is the mean lifetime of a given hadron, and $BR$ is the branching ratio. Numbers are taken from Ref. [3].

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>$c\tau$ [µm]</th>
<th>$BR$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+ \rightarrow K^-\pi^+\pi^+$</td>
<td>311.8 ± 2.1</td>
<td>9.46 ± 0.24</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^-\pi^+$</td>
<td>122.9 ± 0.4</td>
<td>3.93 ± 0.04</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$</td>
<td>149.9 ± 2.1</td>
<td>2.27 ± 0.08</td>
</tr>
<tr>
<td>$\Lambda_c^+ \rightarrow K^-\pi^+p$</td>
<td>59.9 ± 1.8</td>
<td>6.35 ± 0.33</td>
</tr>
</tbody>
</table>

2. Open-Charm Measurements with the HFT

The main sub-systems for reconstruction of open heavy-flavor hadrons in STAR are the Time Projection Chamber (TPC) which is used for momentum determination and for particle identification, the Time Of Flight (TOF) which improves the particle identification, and the HFT which enables precise reconstruction of the decay topology.

To reconstruct the open-charm hadrons, a series of selection criteria has to be applied to the events and tracks first. The specific selection of the topological variables and values of the criteria depend on the open-charm hadron species and its decay channel. After applying all the selection criteria, the open-charm hadron raw yields ($Y_{\text{raw}}$) are extracted from the invariant mass spectrum. The invariant yield is then calculated from $Y_{\text{raw}}$ as:

$$
\frac{d^2N}{2\pi p_T dp_T dy} = \frac{Y_{\text{raw}}}{2\pi N_{\text{evt}} BR p_T \Delta p_T \Delta y (p_T)},
$$

where $N_{\text{evt}}$ is number of events, $BR$ is the branching ratio, $p_T$ is the transverse momentum, $y$ is the rapidity and $\epsilon (p_T)$ is the reconstruction efficiency. The nuclear modification factor ($R_{AA}$) is subsequently calculated according to formula:

$$
R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{(N_{coll}) dN^{pp}/dp_T},
$$

where $dN^{AA}/dp_T$ and $dN^{pp}/dp_T$ are the invariant yields measured in heavy-ion collisions and $p+p$ collisions respectively and $(N_{coll})$ is the mean number of binary nucleon-nucleon collisions computed from the Glauber model. The results presented in this proceedings use a combined measurement of $D^*$ and $D^0$ in $p+p$ collisions at $\sqrt{s} = 200$ GeV measured by the STAR experiment in 2009 [4] as a reference.

Figure 1 shows the nuclear modification factor $R_{AA}$ of $D^0$ and $D^\pm$ mesons as a function of transverse momentum $p_T$ for 0–10% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. As expected, the level of suppression of $D^0$ and $D^\pm$ is similar.
This result shows that open-charm mesons are significantly suppressed at high $p_T$, suggesting strong interaction between the charm quarks and the QGP. It is important to note that the Cold Nuclear Matter (CNM) effects may contribute to the suppression as well. Interestingly, the low $p_T D^0$ mesons also show a suppression. As a result, the integrated $R_{AA}$ of $D^0$ mesons is below unity which shows that the suppression is likely not only due to the shift in the $p_T$ spectrum, caused by the energy loss in the medium, but also other effects, such as a redistribution of charm quarks among different charm hadrons.

In order to understand the hadronization process in heavy-ion collisions, STAR has measured the $D_s/D^0$ ratio which is shown in Figure 2. This ratio is larger in Au+Au collisions than predicted by PYTHIA and than that in $e^+e^-$, p+p and e+p collisions [5]. A better prediction is achieved by the TAMU model [6], but it still underestimates the data. In contrast, the value predicted by the SHM [7] seems to be consistent with the data. This result indicates that the modification of open-charm hadron production in heavy-ion collisions depends on the quark content of the final state hadron.

For a full understanding of charm production and hadronization in heavy-ion collisions, it is important to study, besides the production of charm mesons, also production of charm baryons. STAR performed the first measurement of $\Lambda_c$ production in heavy-ion collisions as a functions of collision centrality and $p_T$. The left panel of Figure 3 shows $p_T$ dependence of the $\Lambda_c/D^0$ ratio. PYTHIA and the SHM clearly underestimate the data which indicates significant enhancement of $\Lambda_c$ production in Au+Au collisions. The coalescence models [8,9] are much closer to the data, but still are not quite able to describe the STAR result, especially at high $p_T$.

---

**Figure 2.** $D_s/D^0$ ratio as a function of $p_T$ for two centralities. The data is compared to combined $e^+e^-$, p+p and e+p data [5], PYTHIA, TAMU [6] and SHM [7] models.

**Figure 3.** (a) The $\Lambda_c/D^0$ ratio as a function of $p_T$ for semi-central Au+Au collisions at $\sqrt{s}_{NN} = 200$ GeV. The data is compared to coalescence models [8,9], SHM [7] and PYTHIA. (b) The $\Lambda_c/D^0$ ratio as a function of centrality. The STAR data is compared to ALICE measurement for p+p collisions at $\sqrt{s} = 7$ TeV [10].
It is very important to note here that, according to this measurement, the production of $\Lambda_c$ is significantly enhanced in heavy-ion collisions with respect to $p+p$ collisions. This, at least partially, explains the significant suppression of open-charm mesons shown in Figure 1. The right panel of Figure 3 shows that the $\Lambda_c/D^0$ ratio increases with the collision centrality which suggests that the larger and the more dense the medium is in a heavy-ion collision, the larger the enhancement of the $\Lambda_c$ production is observed. Finally, the STAR data are also compared to result from $p+p$ collisions at $\sqrt{s} = 7$ TeV measured by ALICE [10]. The value from the $p+p$ collisions is consistent with that in peripheral Au+Au collisions.

3. Summary

The STAR experiment has measured open-charm hadrons through their hadronic decay channels in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Topological reconstruction of secondary decay vertices has been used, utilizing the STAR Heavy Flavor Tracker, which has lead to results with exceptional precision. A significant suppression of $D^0$ and $D^\pm$ mesons is observed in central Au+Au collisions, indicating strong interaction of charm quarks with the QGP. The current STAR data also indicate an enhancement of $D_s$ production in Au+Au collisions with respect to $e^+e^-$, $p+p$ and $p+e$ collisions. This result will help better understand the hadronization process in heavy-ion collisions. The first measurement of $\Lambda_c$ baryon production as a function of centrality and $p_T$ in Au+Au collisions is also shown. A significant enhancement of the $\Lambda_c$ production is observed in central Au+Au collisions, suggesting coalescence hadronization of charm quarks in the QGP.

Funding: This paper and the presentation at HQ2018 are funded by project LTT18002 of the Ministry of Education, Youth and Sport of the Czech Republic and by the Grant Agency of the Czech Technical University in Prague, grant No. SGS16/238/OHK4/3T/14.

Acknowledgments: I would like to thank the organizers for giving me the opportunity to present STAR results at the Hot Quarks 2018 conference.

Conflicts of Interest: The author declares no conflict of interest.

References


© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).