Probing the hot QCD matter by heavy quarks

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Heavy quarks (HQs) [1], mainly charm and bottom quarks, are recognized as excellent probes of the quark-gluon plasma (QGP) phase produced in high-energy nuclear collisions. This is attributed to their considerable large masses ($M_c \sim 1.5$ GeV, $M_b \sim 4.5$ GeV), leading to the early production of heavy quark-antiquark pairs in the early phases of high-energy heavy-ion collisions. As a result, heavy quarks witness the entire space-time evolution of the system and serve as an effective probe of the formed matter. Furthermore, the thermalization time of heavy quarks is delayed in comparison to the light partons in the bulk medium, by a factor approximately proportional to M/T, where M is the mass of the heavy quark and T is the temperature of the thermal bath. Therefore, heavy quarks are not projected to undergo complete thermalization, allowing them to retain a memory of their interaction history, which can serve as a gauge of their interaction strength with the surrounding bulk medium. As non-equilibrium probes, produced in the early stages, they also excel in investigating the initial phase of heavy-ion collisions, encompassing the initial electromagnetic field and the pre-thermal phase.

The conventional method for investigating the dynamics of HQs in the quark-gluon plasma involves tracking their coordinate and momentum evolution through the Fokker-Planck equation, which is stochastically solved using Langevin equations [1]. Heavy quarks drag and diffusion coefficients are inputs to solve the Langevin equation. Transport models have proven to be highly effective in explaining experimentally measured observables, such as the nuclear modification factor (R_{AA}) and elliptic flow (v_2), for D-mesons. A key objective in all phenomenological investigations [1, 2] of open heavy-flavor observables is to deduce the heavy quark spatial diffusion coefficient, denoted as D_x. This parameter serves as a measure of the interaction strength between heavy quarks and the surrounding bulk medium. Additionally, D_x is directly associated with the thermalization time of heavy quarks and can be determined through lattice QCD (lQCD) calculations. The spatial diffusion coefficient, D_x, is determined in the static limit ($p \to 0$) using the expression $D_x = T/M\Gamma$, where Γ is the drag coefficient. The conventional characterization of the spatial diffusion coefficient is expressed in relation to the dimensionless quantity $2\pi T D_x$, which remains independent of the mass of the heavy quark. Simultaneously describing the heavy quark nuclear modification factor (R_{AA}) and elliptic flow (v_2) at low momentum necessitates the inclusion of nonperturbative contributions; temperature dependence of the transport coefficients also play a crucial role for a simultaneously description of both the observables. A recent investigation has demonstrated that the memory effect [3] decelerates the evolution of heavy quark momentum in the quark-gluon plasma (QGP). This observation suggests that a larger momentum diffusion coefficient, and consequently a smaller D_x, is needed to reproduce the same nuclear modification factor (R_{AA}).

The heavy baryon to heavy meson ratios play a crucial role in comprehending the in-medium hadronization of heavy hadrons in comparison to the ratio of light-flavored baryons to mesons [4]. Both RHIC and LHC experiments have observed a large Λ_c/D ratio in nucleus-nucleus collisions. The enhancement of the Λ_c/D ratio can impact the nuclear modification factor of D mesons. These ratios serve as valuable tools for untangling different hadronization models, given their sensitiv-

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ity to hadronization mechanisms [4, 5]. The challenge lies in comprehending heavy baryon to heavy meson ratios across diverse colliding systems.

Until recently, the evolution of heavy quark momentum in the pre-equilibrium phase [6], occurring prior to the formation of the quark-gluon plasma (QGP), was typically modeled as free streaming. In this pre-equilibrium phase, characterized by a very high energy density, the early dynamics can be particularly relevant, especially for heavy quarks due to their short formation time [7]. In the framework of the color glass condensate (CGC) effective theory, the pre-equilibrium stage of high-energy collisions can be characterized by strong gluon fields, specifically referred to as the Glasma. Recent studies have revealed that these fields induce significant diffusion of charm quarks in momentum space [7]. Consequently, low p_T charm quarks are shifted towards higher p_T, resulting in a spectrum of charm quarks that is tilted towards higher momenta. Considering the charm quark momentum evolution in Glasma phase, one can describe the measured nuclear modification faction of D-meson in p-Pb collisions. Pre-equilibrium phase can ulter the R_{AA}-v_2 tension in nucleus-nucleus collisions. It is crucial to emphasize that the dynamics of the Glasma phase cannot be replicated within Langevin dynamics. This distinction arises from the fact that, during the Glasma phase, heavy quarks undergo diffusion without experiencing significant drag effects.

Heavy quarks are also regarded as excellent probes for exploring the electromagnetic fields produced and the initial tilt of the fireball formed in non-central heavy-ion collisions, as manifested through the directed flow v_1 of the D-meson [8]. The electromagnetically-induced splitting, denoted as Δv_1, in the directed flow of charm and anti-charm through D and $\overline{D}$ mesons can be indicative of the generated electromagnetic field. Recent measurements by both the STAR and ALICE collaborations [9, 10] have reported non-zero values for v_1 and Δv_1 of the D meson, providing valuable insights into the dynamics of heavy-ion collisions.

Acknowledgments

S. K. D. acknowledges the support from DAE-BRNS, India, Grant No. 57/14/02/2021-BRNS.

References

[1] R. Rapp, P. B. Gossiaux, A. Andronic, R. Averbeck, S. Masciocchi, A. Beraudo, E. Bratkovskaya, P. Braun-Munzinger, S. Cao and A. Dainese, *et al.* Nucl. Phys. A **979**, 21-86 (2018)

[2] S. K. Das, F. Scardina, S. Plumari and V. Greco, Phys. Lett. B **747**, 260-264 (2015)

[3] M. Ruggieri, Pooja, J. Prakash and S. K. Das, Phys. Rev. D **106**, no.3, 034032 (2022)

[4] S. Plumari, V. Minissale, S. K. Das, G. Coci and V. Greco, Eur. Phys. J. C **78**, no.4, 348 (2018)

[5] S. K. Das, J. M. Torres-Rincon, L. Tolos, V. Minissale, F. Scardina and V. Greco, Phys. Rev. D **94**, no.11, 114039 (2016)

[6] S. K. Das, M. Ruggieri, F. Scardina, S. Plumari and V. Greco, J. Phys. G **44**, no.9, 095102 (2017)

[7] M. Ruggieri and S. K. Das, Phys. Rev. D **98**, no.9, 094024 (2018)

[8] S. K. Das, S. Plumari, S. Chatterjee, J. Alam, F. Scardina and V. Greco, Phys. Lett. B **768**, 260-264 (2017)

[9] J. Adam *et al.* [STAR], Phys. Rev. Lett. **123** (2019) no.16, 162301

[10] S. Acharya *et al.* [ALICE], Phys. Rev. Lett. **125** (2020) no.2, 022301