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Transport Theory of Heavy Flavor in Relativistic Nuclear Collisions

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Abstract

A short overview is presented for the recent progress in the theory of heavy flavor transport in ultra-relativistic nuclear collisions, including a summary of different transport models, their phenomenological results of heavy meson quenching and flow at RHIC and LHC, a possible solution to the R_{AA} vs. v_2 puzzle and predictions for heavy flavor observables beyond the current measurements.

Keywords: relativistic nuclear collisions, heavy flavor, transport theory

1. Introduction

Heavy quarks serve as valuable probes of the transport properties of the quark-gluon plasma (QGP) matter created in relativistic heavy-ion collisions at the Relativistic Heavy-Ion Collider (RHIC) and the Large Hadron Collider (LHC). Because of their large mass, most heavy quarks are produced at the primordial stage of collisions via hard scatterings and then they travel through and interact with the medium with their flavors conserved, and thus observe the full evolution history of the QGP fireballs. Over the past decade, experimental observations at both RHIC and LHC have revealed a great many interesting data of heavy flavor hadrons and their decay leptons, among which the most surprising ones are their small values of the nuclear modification factor R_{AA} and large values of the elliptic flow coefficient v_2, which are almost comparable to those of light hadrons [1, 2, 3]. This seems contradictory to one's earlier expectation of the mass hierarchy of parton energy loss inside the QGP and is known as the "heavy flavor puzzle". Therefore, it still remains a great challenge to fully understand the heavy flavor dynamics in heavy-ion collisions. This includes not only parton energy loss inside the QGP, but also heavy flavor initial production, hadronization and hadronic interaction.

In this talk, a brief overview will be provided for the frequently utilized heavy quark transport models. Then their phenomenological results will be presented and compared with experimental data. After that, recent theoretical developments will be discussed, including predictions for the two-particle correlation functions of heavy flavor and medium modification of heavy mesons in proton-nucleus collisions.

2. Transport Models of Heavy Flavor in Heavy-Ion Collisions

2.1. Collisional Energy Loss of Heavy Quarks

In the most general form, the heavy quark evolution can be described using the Boltzmann equation:

$$\left[\frac{\partial}{\partial t}+\frac{p_i}{E_{\vec{p}}}\frac{\partial}{\partial x_i}+F_i\frac{\partial}{\partial p_i}\right]f_Q(t,\vec{x},\vec{p})=C\left[f_Q\right], \qquad (1)$$

in which the left hand side is the total time derivative of the heavy quark distribution function and the right hand side represents the collision term. Usually two assumptions are applied: first, one may neglect the drift term (the third term), or the mean free force from the QGP medium exerted on heavy quarks; and second, one can integrate or average over the position space of the distribution function and only concentrate on the evolution of the momentum space without considering the second term. With theses two assumptions, only the partial time derivative (the first term) remains on the left hand side.

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The collision term can be expressed as a subtraction of the loss term from the gain term:

$$C[f_Q] = \int d^3k \left[w(\vec{p}+\vec{k},\vec{k}) f_Q(\vec{p}+\vec{k}) - w(\vec{p},\vec{k}) f_Q(\vec{p}) \right],$$

where $w(p,k)$ represents the transition rate of a heavy quark from momentum p to $p-k$ and can be directly calculated from the microscopic scattering cross sections.

One may simplify the transport equation with further assumptions. For example, in the quasi-elastic scattering process, we can assume the momentum change of heavy quark during its each scattering with a light parton is small ($|\vec{k}| \ll |\vec{p}|$). Then we have

$$C[f_Q] \approx \int d^3k \left(k_i \frac{\partial}{\partial p_i} + \frac{1}{2} k_i k_j \frac{\partial^2}{\partial p_i \partial p_j} \right) w(\vec{p},\vec{k}) f_Q(\vec{p}),$$

and the Boltzmann equation is reduced to the Fokker-Planck equation of the distribution function $f_Q(t,\vec{p})$:

$$\frac{\partial}{\partial t} f_Q = \frac{\partial}{\partial p_i} \left\{ A_i(\vec{p}) f_Q + \frac{\partial}{\partial p_j} \left[B_{ij}(\vec{p}) f_Q \right] \right\}. \quad (2)$$

In addition, we may also assume every heavy quark is scattered multiple times during its evolution inside the medium, then the Fokker-Planck equation can be stochastically realized by the Langevin equation:

$$dx_i = \frac{p_i}{E_{\vec{p}}} dt, \quad (3)$$

$$dp_i = -\eta_D(\vec{p}) p_i dt + \xi_i dt. \quad (4)$$

In Eq. (4), the first term is known as the drag term and the second term is related to the thermal random force. One may refer to Ref. [4] for calculations of the transport coefficients above – A_i, B_{ij}, η_D and ξ_i. It is worth noticing that these two simplifications from the Boltzmann equation to the Fokker-Planck equation and then to the Langevin equation are only valid for the collisional energy loss, or the $2 \to 2$ scattering of heavy quarks inside the QGP, but not for their radiative energy loss because the gluon radiation process usually does not satisfy these two assumptions.

Various transport models have been constructed to study the heavy quark diffusion inside the dense nuclear matter, such as the parton cascade model based on the Boltzmann equation [5, 6, 7, 8], the linearized Boltzmann approach coupled to a hydrodynamic background [9, 10] and the Langevin-based transport models [11, 12, 13, 14]. In the Boltzmann models, the most important ingredient is evaluating the collision term. For most current studies, only the leading order (LO) diagrams for heavy quark scatterings with light quarks and gluons are considered. The dominant contribution is from the t-channel matrices of the $Qg \to Qg$ and $Qq \to Qq$ processes whose infrared singularity is usually regulated by introducing the Debye screening mass into the gluon propagator [15, 7, 16]. For the Langevin equation, all the interactions are encoded in the transport coefficients. One can use perturbative QCD (pQCD) to calculate these coefficients [11], but can also go beyond that. For instance, in Refs. [17, 18, 12], a non-perturbative resonance scattering method has been proposed to calculate the transport coefficients: one may assume heavy-light quark interaction with certain potential and solve the T-matrix using the Lippmann-Schwinger equation from which diffusion coefficients can be extracted. Due to the existence of the resonant states, the energy loss is enhanced compared to the pQCD calculation. One can also use the lattice QCD [19, 20, 21] to calculate the transport coefficients. However, the current uncertainties of lattice calculations are still large and no reliable inputs for transport models are available. There are other treatments of the collisional energy loss of heavy quark such as the parton-hadron-string dynamics model introduced by Ref. [22].

2.2. Radiative Energy Loss of Heavy Quarks

While collisional energy loss alone is successful in describing heavy flavor observables in the low transverse momentum p_T region where the phase space for the medium-induced gluon radiation is restricted by the large mass of heavy quarks [23, 24], it has been shown insufficient [25, 26] at high p_T.

To incorporate gluon radiation into the Boltzmann transport model, one need to evaluate the pQCD diagrams for the $2 \to 3$ processes for the collision term. Although a full evaluation is available [27], the result is tedious and hard to efficiently implement in numerical calculations. For this reason, the Gunion-Bertsch approximation is adopted by Refs. [9, 28] that is derived at high energy limit and reproduce the exact calculation of the matrix elements over a wide rapidity range. The LO pQCD calculation does not include the LPM effect due to the coherent scatterings. To mimic this effect in the numerical simulation, Ref. [29] requires that the heavy quark mean free path is larger than the formation time of radiated gluons times an X factor.

The radiative energy loss has also been implemented in the Langevin framework [25, 26]:

$$d\vec{p}/dt = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g. \quad (5)$$

The classical Langevin equation is modified such that apart from the drag force and thermal random force, a