Microscopic Charmonium Production from a Boltzmann+Langevin Approach

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Abstract

We calculate charmonium production in Ultrarelativistic Heavy-Ion Collisions (URHICs) within a semiclassical Boltzmann transport approach for the dissociation and regeneration of charmonium where open charm diffusion is explicitly accounted for. The diffusion of charm quarks is simulated using Langevin dynamics yielding time-dependent quark spectra which serve as input into the regeneration processes of charmonia. The dissociation/regeneration rates for charmonia and relaxation rate for charm quarks are calculated from the same charm-medium interaction. Relative to perturbative rates, a large K-factor (representing nonperturbative interaction strength) is required to account for the phenomenology of open charm observables, which we implement for both the heavy-quark relaxation rate in the Langevin simulation and for the charmonium reaction rates in Boltzmann simulation. Our approach thus establishes a consistent transport framework for the simultaneous evolution of open and hidden heavy flavor with microscopically calculated transport coefficients in both sectors. First results of phenomenological applications are presented.

Charmonium Transport

We employ a Boltzmann equation for describing both dissociation and regeneration of charmonia in the QGP medium [1][2]

$$\frac{\partial f_\Psi}{\partial t} + \vec{v}\cdot\nabla f_\Psi = -\alpha f_\Psi + \beta \,.$$

where $\alpha \equiv \alpha(\vec{p},T(t))$ and $\beta \equiv \beta(\vec{p},T(t))$ represent the dissociation and regeneration rates.

Those two inelastic rates are approximated by a quasifree assumption based on pQCD matrix amplitudes for elastic scattering of charm quarks with gluon and light quarks in the QGP medium.

$$\alpha(\vec{p},T) = \sum_i \int \mathrm{d}\Pi_\Psi d_i \overline{|M_{i\Psi\to\tilde{i}c\bar{c}}|^2}\,(1\pm f_i(\tilde{p}_i))(1-f_c(p_c))(1-f_{\bar{c}}(p_{\bar{c}}))f_i(p_i)$$

$$\beta(\vec{p},T) = \sum_i \int \mathrm{d}\Pi_\Psi d_{\tilde{i}} d_c d_{\bar{c}} \overline{|M_{\tilde{i}c\bar{c}\to i\Psi}|^2}\,(1\pm f_i(p_i))f_i(\tilde{p}_i)\gamma_c f_c(p_c)\gamma_c f_{\bar{c}}(p_{\bar{c}})$$

They are related to each other due to detailed balance. Specifically, they have a simple relation in thermal equilibrium:

$$\beta(\vec{p},T) = \gamma_c^2 d_\Psi \exp\left(-\frac{E_\Psi}{T}\right)\alpha(\vec{p},T)$$

with fugacity $\gamma_c(t)$ determined from charm number conservation via a statistical model:

$$N_{c\bar{c}} = \frac{1}{2}\gamma_c(t) n_c(T(t)) V_{\rm FB}(t)\frac{I_1(\gamma_c n_c(T(t))V_{\rm FB}(t))}{I_0(\gamma_c(t)n_c(T(t))V_{\rm FB}(t))}$$

Charm Quark Transport

The charm quark energy loss can be simulated by solving a stochastic Langevin equation [3]

$$\mathrm{d}\vec{x} = \frac{\vec{p}}{E(p)}\mathrm{d}t\,,\ \mathrm{d}\vec{p} = -A\vec{p}\,\mathrm{d}t + \sqrt{2\mathrm{d}t D}\vec{\rho}.$$

where the relaxation rate $A(\vec{p},T)$ can be calculated as:

$$A(\vec{p}_c,T) = \sum_i \int \mathrm{d}\Pi_c d_i \overline{|M_{ic\to ic}|^2}\,(1\pm f_i(\tilde{p}_i))(1-f_c(p'_c))f_i(p_i)\left(1-\frac{\vec{p}_c\cdot\vec{p}'_c}{\vec{p}_c^2}\right)$$

and it can be related to the diffusion coefficient $D(\vec{p},T(t))$ with Einstein relation:

$$A(\vec{p},T(t)) = \frac{1}{E(p)}\left(\frac{D(\vec{p},T(t))}{T} - \frac{\partial D(\vec{p},T(t))}{\partial E(p)}\right)$$

It is essential to point out that the scattering amplitude in the relaxation rate is the same as the scattering amplitude implemented in the quasifree approximation

$$\overline{|M_{i\Psi\to\tilde{i}c\bar{c}}(p_i,p_\Psi,\tilde{p}_i,p_c,p_{\bar{c}})|^2} = 2\overline{\left|M_{ic\to\tilde{i}c}\left(p_i,\frac{m_\Psi-m_c}{m_\Psi}p_\Psi,\tilde{p}_i,p_c\right)\right|^2}(2\pi)^3 2E_{\bar{c}}\delta^{(3)}\left(\vec{p}_{\bar{c}}-\frac{m_c}{m_\Psi}\vec{p}_\Psi\right)$$

This guarantees the consistency of charm quark energy loss with charmonium chemical reaction in the QGP medium.

Connection of Charm and Charmonium Simulation

The off-thermalized charm quark and anti-charm quark recombine to form the off-thermalized spectrum of charmonium in the medium.

It is suggested by quite a few heavy quark simulations that the pure pQCD rate is not large enough for a theoretical description of heavy quark production compared to experimental data. A large K-factor is suggested [4] which accounts for nonperturbative effect and describes the phenomenology of heavy quark energy loss. Since the charm quark collisional energy loss and charmonium chemical reaction share the same scattering amplitude, the same K-factor also needs to be multiplied to charmonium reaction rates.

Joint Simulation of Charm and Charmonium

A large K-factor >5 is suggested by charm simulation and phenomenology, revealing the fact that K>5 might also be favorable for charmonium. We test a few K-factors for dissociation/relaxation rates for charmonium and charm quarks, then compare the calculation to experimental data.

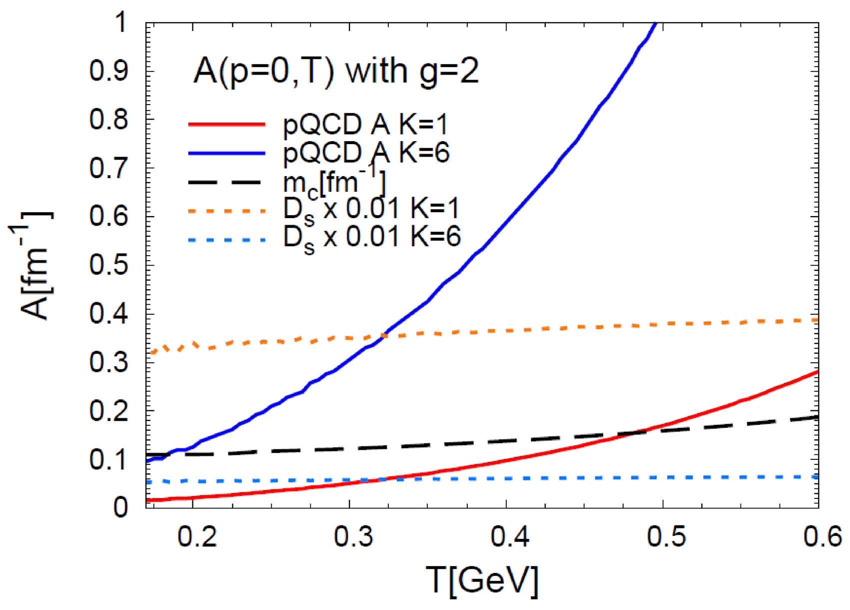

Fig.1 pQCD calculated relaxation rate for charm quark with coupling constant g=2 for K=1 (red) and K=6 (blue), as well as the charm-quark mass mc (dashed black) and the corresponding spatial diffusion coefficient $\mathcal{D}_s(2\pi T)=\frac{2\pi T^2}{m_c A(p=0)}$ for K = 1 (dotted orange) and K = 6 (dotted light blue)

In Figure.1 we show the relaxation rate and the corresponding spatial diffusion coefficient with different K-factors. The pure pQCD calculated spatial coefficient

$$\mathcal{D}_s(2\pi T)\sim 30$$

is too large for describing the low-momentum heavy flavor phenomenology.

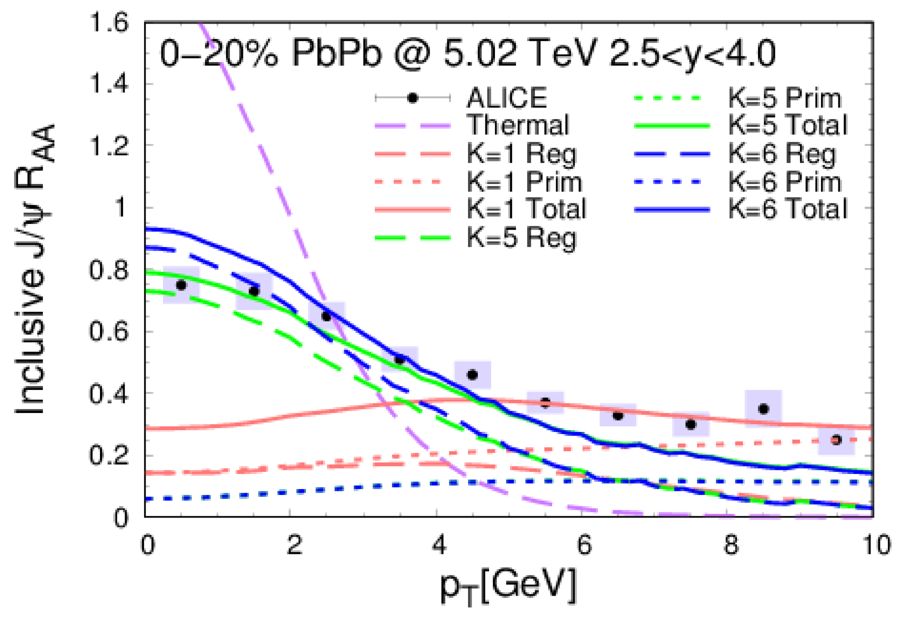

Fig.2 Inclusive J/ψ $R_{AA}(p_T)$ from Langevin-Boltzmann transport for charm/onia using the same pQCD matrix elements with different K factors of 1, 5 and 6 (red, green and blue lines) compared to ALICE data [5]. Shown are the regeneration and primordial contributions and their sum (dashed, dotted and solid lines, respectively), as well as for thermally regenerated charm-quarks (purple dashed line).

In Figure.2 we show the inclusive J/ψ $R_{AA}(p_T)$ from our Langevin-Boltzmann transport with off-thermalized charm quarks simulated from Langevin and thus off-thermalized J/ψ from the regeneration contribution.

It shows that the data for charmonium also favor a large K-factor like 5 or 6. We also notices that the high-momentum J/ψ can only be described by small K-factor like 1, this should be understandable since the QCD coupling drops at large momentum transfer, thus a realistic K-factor would favor a smooth decrease from 5 or 6 at low momentum to 1 at high momentum.

Conclusions

We developed a Boltzmann+Langevin approach employing **(A) a consistent scattering amplitude** for both charmonium and charm quark collisions in the QGP medium. In this sense, the large K-factor suggested by heavy flavor phenomenology is also implemented in charmonium reaction. Furthermore, during a joint simulation, the off-thermalized charm quark spectra simulated by Langevin provide **(B) off-thermalized charmonium spectra** through regeneration process. **(C) The first phenomenological comparison to charmonium data also favors large K-factor at low-momentum and small K-factor at high momentum which is consistent with the behavior of QCD interaction strength.**

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