1.) Heavy Quarks and in-Medium QCD Force

Quarkonia

Heavy-Quark Diffusion

How do heavy-flavor spectral + transport properties emerge from in-medium QCD force?

- $E_B(T)$, $G_Y(p,T)$
Outline

1.) Introduction
2.) Heavy-Quark Diffusion
3.) Hadronization
4.) Quarkonium Transport
5.) High-\(p_T\) Suppression
6.) Small Systems
7.) Conclusions
2.1 Heavy-Flavor Transport in URHICs

- HQ diffusion intrinsically non-perturbative
  → strong coupling → remnants of confining force → resonances
  ⇒ no principle difference between diffusion and hadronization int.’s
- initial cond. (nPDFs, …), pre-equil. fields
- $c$-quark diffusion in QGP liquid
- $c$-quark hadronization
- $D$-meson diffusion in hadron liquid

[S. Cao]
2.2 Extraction of Diffusion Coefficient

- Bayesian extraction using Langevin/Boltzmann \([W. \text{ Ke}]\)
  - Emphasized the importance of “realistic” model input to statistical analysis

- AdS/CFT Approach \([R. \text{ Hambrock}]\)
  - \(D_s (2\pi T) = 4/\sqrt{\lambda} = 1.2-1.7\)
  - \(\gamma = D/TE \sim 1/E\) favored (as in QCD-based models)

[EMMI RRTF ‘18]
2.3 Diffusion and Bulk Evolution

- **Update of Nantes Approach** [P.B. Gossiaux]
  - update of bulk evolution (EPOS2 → EPOS3)
  - requires moderate changes in HQ diffusion/hadronization
  ⇒ slightly larger $D_s$ than before

- **Broader Theory Efforts** [EMMI RRTF, HQ-jet]
  - Individual bulk+hadroniz. models + common HQ int.
    “pQCDx5”, $D_s(2\pi T) \approx 6$

- **Pre-equilibrium phase** - Possibly significant [S. Mrowczynski]
2.4 Upshot of Charm Diffusion Coefficient

\[ D_s = \frac{T}{\langle m_Q \gamma_Q(p=0) \rangle} \]

- suggests minimum of \( D_s(2\pi T) \sim 2-4 \) near \( T_{pc} \)
- scatt. rate: \( \Gamma_{coll} \sim \frac{3}{D_s} \sim 1 \text{ GeV} \) — no light quasi-particles!
- \( T \)- and \( p \)-dependence reflect core property of QCD

\[ \text{AdS/CFT} \]

[EMMI RRTF ‘18]
3.) Hadronization: Statistical vs. Coalescence

Charm Chemistry from pp to PbPb

- No surprises; SHM
- Strangeness enhanced!
- Flow push?!
- Coalescence … > 5x SHM?

- Control over wave-function effects, equilibrium limit?
- Chemical vs. kinetic equilibrium? (recall: recombination ↔ interaction)
4.) Quarkonia Transport: Equilibrium Limits Matter

\[
\frac{dN_\psi}{d\tau} = - \Gamma_\psi \left[ N_\psi - N_\psi^{eq} \right]
\]

- **ϒ(1S,2S)** Boltzmann transport with b-quark diffusion

- \( \Upsilon \) yields relax to equilibrium:
  \[ \mathcal{R} \sim [1 - \exp(-\tau/\tau_b)] \text{ with } \tau_b \sim 7 \text{ fm/c} \]
  -- consistent with [Du et al ’17]
  -- implies \( D_s(2\pi T) \sim 4 \)
- QQ pot. \( V_s(r) = -C_F \alpha_s/r \), \( T_{diss}(2S) = 210 \text{MeV} \)
- Significant regeneration (~20% for \( \Upsilon(1S) \))
4.2 Quarkonia Transport II

• **AdS/CFT Approach**
  - Coulomb potential
  - Large dissociation width
  [W. Horowitz]

  ![Graph showing \( \Gamma(Y(1S)) \)]

  - Rate Equation Approach
    - In-medium Cornell potential
    - Relatively large widths
    - Formation time effects
  [G. Wolschin]

  ![Graph showing \( R_{AA} \) vs. \( N_{\text{part}} \)]

  - over-predicts suppression

• **Quantum Evolution Approaches**
  ![Equation: \( \partial_t f_s = -i(H_{s,\text{eff}} f_s - f_s H_{s,\text{eff}}^\dagger) + \mathcal{F}(f_0) \)]

  - Significance of quantum effects?
  - Can it be mapped into a rate equation?
  [M.A Escobedo]
4.3 Quarkonium Upshot

$T_d(\psi') < T_0^{SPS} (~240) < T_d(J/\psi, \Upsilon') \leq T_0^{RHIC} (~350) < T_d(\Upsilon) \leq T_0^{LHC} (~550)$

- Summary of lattice-QCD results

$T_d(\chi_c) \simeq 185 \text{ MeV} < T_d(J/\psi) \simeq 240 \text{ MeV}$

$T_d(\Upsilon) > 407 \text{ MeV}$

[P. Petreczky, MIAPP ’18]
5. **High-$p_T$ Heavy Quarks**

- **Path length dependence:**

  \[ \Delta E / E \sim T^a L^b \]

  \[ R_{L}^{XePb} \equiv \frac{1 - R_{XeXe}}{1 - R_{PbPb}} \approx \left( \frac{A_{Xe}}{A_{Pb}} \right)^{b/3} \]

  [M. Djordjevic]

- Close-to-linear behavior predicted

- **Formation time effects**

  [A. Majumder]

- **Formation time effects**

  - $b$-quarks on shell faster than $c$-quarks
  \[ \Rightarrow \] earlier quenching

\[ \hat{q} / T^2 = 5.03 \]

\[ [D_1(2\pi T) = 5.00] \]

Pb-Pb @ 5.2 TeV (m.b.)
6.) Charm in pA Collisions:

- **$R_{pA}$** data consistent with shadowing
  - But: large $v_2$

- Collectivity?
  - small $c$-quark $v_2$
  - very similar for charmonia
7.) **Summary**

- Continued progress on extracting diffusion coefficient (+ $p$-dependence): 
  
  \[(2\pi T) D_s = 3 \pm 2\]; implies melting of soft QGP quasi-particles

- Problem of charm chemistry for $\Lambda_c$

- Strengthened connections between: hidden $\leftrightarrow$ open heavy HF; 
  lattice QCD $\leftrightarrow$ quarkonium transport (melting + regeneration) 
  $\rightarrow$ Quantify transport parameters (in-med. potential?); quantum transport

- New views on high-$p_T$ heavy quarks

- “Collectivity problem” of heavy quark/onium in small systems
3.6 QGP Equation of State + Spectral Functions

Thermodynamic Potential

Selfconsistent SFs

\[ \Omega = \frac{-1}{\beta} \sum_n \text{Tr}\{\ln(-G^{-1}) + (G_0^{-1} - G^{-1})G\} \pm \Phi \]

\[ G = G_0 + G_0 \Sigma G \quad \Sigma = GT \quad T = V + VGGT \]

- Near \( T_c \), light partons melt + broad hadronic resonances emerge

[S.Liu+RR ’16]

- Quark spectral functions
- "Meson" T-matrix

\[ T = 194 \text{MeV} \quad T = 400 \text{MeV} \]
4.4 Transport Coefficients

Viscosity and Heavy-Quark Diffusion

- Strongly coupled: \((2\pi T) D_s \sim (4\pi) \eta/s\)
- Perturbative: \((2\pi T) D_s \sim 5/2 (4\pi) \eta/s\)
- Transition as \(T\) increases


2.1 Quarkonium Transport in URHICs

\[ \tau [fm/c] \]

- production + evolution of \( \bar{c}c \) wave pack.
- \( \tau_{\text{form}} \approx 1 \text{fm/c} \)
- c-quark diffusion in QGP
- \( \tau_{\text{c eq}} \approx 5 \text{fm/c} \)
- QGP kinetics
- \( c+\bar{c} \leftrightarrow \psi \)
- \( \tau_{\psi \text{ eq}} \approx 1/\Gamma_{\psi} \)
- hadronic kinetics
- \( \sim T_{\text{pc}} : c \ and \ \bar{c} \) hadronize

2.3 Quarkonium Width Comparisons

- Fair agreement for $\Upsilon$ states
- Larger spread for $\Upsilon$ states
- Binding energies differ