Quarkonium Production in Heavy Ion Collisions: from Open Quantum System to Transport Equation

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Quarkonium Production in Heavy Ion Collisions

- Heavy quarkonium as probe of QGP:
  
  - **Static screening**: suppression of color attraction $\rightarrow$ melting at high $T$ states of different sizes have different melting $T$ $\rightarrow$ thermometer
  
  - **Dynamical screening**: dissociation induced by in-medium scattering, can happen even below melting $T$, imaginary potential
  
  - **Recombination**: unbound heavy quark pair forms quarkonium, can happen below melting $T$, crucial for phenomenology and theory consistency
  
- Cold nuclear matter effect, feed-down contributions

A. Mocsy, arXiv:0811.0337
Plasma Screening Effects from Thermal Loops

- Static and dynamical screening effects in **same theoretical framework**

- **Propagator of color singlet** (J/ψ, Y(1S) ...)

- **Real part of correction** —> decrease in real part potential, static screening

- **Imaginary part** —> dissociation rate from optical theorem, provide theoretical guidance on dissociation term $C^(-)$ in transport equation

\[
(\partial_t + \mathbf{v} \cdot \nabla) f(x, p, t) = -C^-(x, p, t) + C^+(x, p, t)
\]

- **Can we put screening & recombination in same framework and learn theoretical guidance on recombination term?** YES!
Open Quantum System

- Total system = system + environment:
  \[ H = H_S + H_E + H_I \]

\[ \rho(t = 0) = \rho_S \otimes \rho_E \]

System & environment
(Heavy quark pairs & QGP)

Unitary evolution
Time reversible

\[ U(t, 0)(\rho_S \otimes \rho_E)U^\dagger(t, 0) \]

System & environment

Trace out (integrate out) environment

\[ \rho_S(t = 0) \]

System (heavy quark pairs)

Non-unitary
Time irreversible

\[ \text{Tr}_E\left[U(t, 0)(\rho_S \otimes \rho_E)U^\dagger(t, 0)\right] \]
Weak coupling to 2nd order: Lindblad equation

\[
\rho_S(t) = \rho_S(0) - i \left[ tH_S + \sum_{a,b} \sigma_{ab}(t)L_{ab}, \rho_S(0) \right] + \sum_{a,b,c,d} \gamma_{ab,cd} \left( L_{ab}\rho_S(0) L^\dagger_{cd} - \frac{1}{2} \{ L^\dagger_{cd} L_{ab}, \rho_S \} \right)
\]

Markovian approximation

Wigner transform

Boltzmann transport equation

\[
\frac{\partial}{\partial t} f_{\text{nls}}(x, k, t) + \mathbf{v} \cdot \nabla_x f_{\text{nls}}(x, k, t) = C_{\text{nls}}^{(+)}(x, k, t) - C_{\text{nls}}^{(-)}(x, k, t)
\]
Weak coupling to 2nd order: Lindblad equation

\[
\rho_S(t) = \rho_S(0) - i \left[ tH_S + \sum_{a,b} \sigma_{ab}(t) L_{ab}, \rho_S(0) \right] + \sum_{a,b,c,d} \gamma_{ab,cd} \left( L_{ab} \rho_S(0) L_{cd}^\dagger - \frac{1}{2} \{ L_{cd}^\dagger L_{ab}, \rho_S \} \right)
\]

Markovian approximation

Wigner transform

Boltzmann transport equation

\[
\frac{\partial}{\partial t} f_{nls}(\mathbf{x}, \mathbf{k}, t) + \mathbf{v} \cdot \nabla f_{nls}(\mathbf{x}, \mathbf{k}, t) = C_{nls}^{(+)}(\mathbf{x}, \mathbf{k}, t) - C_{nls}^{(-)}(\mathbf{x}, \mathbf{k}, t)
\]

Static screening

Recombination

Dissociation

XY T.Mehen, arXiv:1811.07027
Screening and Recombination in Same Framework

Weak coupling to 2nd order: Lindblad equation

\[
\rho_S(t) = \rho_S(0) - i \left[ tH_S + \sum_{a,b} \sigma_{ab}(t)L_{ab}, \rho_S(0) \right] + \sum_{a,b,c,d} \gamma_{ab,cd} \left( L_{ab}\rho_S(0)L_{cd}^\dagger - \frac{1}{2} \{ L_{cd}^\dagger L_{ab}, \rho_S \} \right) + \sum_{a,b} \gamma_{ab} \rho_S(0) L_{ab} \rho_S(0) + \sum_{a,b} \gamma_{ab} \rho_S(0) \rho_S(0) L_{ab}
\]

Same diagram as for screening

New diagram in this approach gives recombination
Two Key Assumptions Justified from Scale Hierarchy

• Two key assumptions:

1. **System interacts weekly with environment?**

2. **Markovian approximation (no memory effect)?**

• Justified from separation of scales and effective field theory (potential NRQCD)

\[
M \gg Mv \gg Mv^2 \gtrsim T \gtrsim m_D
\]

1. **Dipole interaction between quarkonium and QGP**

\[
rT \sim \frac{T}{Mv} \lesssim v
\]

2. **System relaxation time >> environment correlation time (coarse graining)**

\[
(rT)^2 T \ll T
\]

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What Have We Achieved?

• Derive Boltzmann transport (rate) equation from QCD using **separation of scales**, provide validity condition of Boltzmann transport equation

\[ M \gg Mv \gg Mv^2 \gtrsim T \gtrsim m_D \]

• Static screening, dissociation and recombination in **same theoretical framework**, provide theoretical guidance on recombination term

• Recombination of quarkonium depends on **real-time** open heavy flavor distributions, which can be obtained from transport of open heavy flavors

• Detailed balance and thermalization can be demonstrated **dynamically** from coupled transport equations of open and hidden heavy flavors
Detailed Balance and Thermalization

Setup:
- QGP box w/ const $T=300$ MeV, $Y(1S)$ & b quarks, total b flavor = 50 (fixed)
- Initial momenta sampled from uniform distributions 0-5 GeV
- Turn on/off open heavy quark transport

\[ \text{Y(1S) percentage v.s. time} \]

\[ N_{b,\text{hidden}} / N_{b,\text{tot}} \]

\[ t \text{ (fm/c)} \]

\[ 10^{-5} \]

\[ 10^{-4} \]

\[ 10^{-3} \]

\[ \text{simulation w/ uniform initial momenta} \]

\[ \text{relativistic equilibrium} \]

\[ \text{non-relativistic equilibrium} \]

Dissociation-recombination interplay drives to detailed balance

Open heavy flavor transport necessary to drive kinetic equilibrium of quarkonium

XY, B.Müller arXiv:1709.03529

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Collision Event Simulation

• Initial production:
  
  **PYTHIA 8.2: NRQCD factorization**
  

  **Nuclear PDF: EPS09 (cold nuclear matter effect)**
  
  Eskola, Paukkunen, Salgado, JHEP 0904 (2009) 065

  **Trento, sample position, hydro. initial condition**
  

• Medium background: 2+1D viscous hydrodynamics (calibrated)
  

• Study bottomonium (scales are well-separated); include 1S 2S; ~26% 2S feed-down to 1S in hadronic phase (from PDG); initial production ratio 1S : 2S ~ between 3:1 to 4:1 (PYTHIA)
Fix $\alpha_s = 0.3$

Tune $T_{\text{melt}}(2S) = 210$ MeV

Tune $V_s = -C_F \frac{0.42}{r}$

Use same set of parameters

Our results also consistent with ATLAS data presented by Songkyo Lee (Tu 14:00)
Use same set of parameters
Cold nuclear matter effect $\sim 0.72$
(use p-Au data of STAR)

In our calculation, direct $1S$ (non-feed-down) is suppressed in central collisions by $\sim 15\%$
Upsilon Azimuthal Anisotropy in 5020 GeV PbPb

\[ E \frac{d^3 N}{d p^3} = \frac{1}{2\pi} \frac{d^2 N}{p_T dp_T dy} (1 + 2v_2 \cos(2\phi) + \cdots) \]

Y(1S)

Y(2S) in 10-60%, |y| < 2.4:
\[ v_2 = 0.0299 \pm 0.0025 \]

Consistent with CMS data on Y(1S) and Y(2S)

ALICE results, see talk by Xiaozhi Bai (Tu 14:20)

CMS results, see talk by Jaebeom Park (Tu 16:20)

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Conclusions

• Open quantum system + separation of scales $\rightarrow$ Boltzmann transport equation in theoretically controlled way
  \[ M \gg Mv \gg Mv^2 \gtrsim T \gtrsim m_D \]

• Screening and recombination in same framework, approach detailed balance dynamically

• Phenomenological results on Upsilon at RHIC and LHC, suppression and azimuthal anisotropy

• Precision era, theory and experiment comparison (machine learning)

• If $T \gg Mv^2$ $\rightarrow$ open quantum system in limit of quantum Brownian motion
  Y.Akamatsu, M.Asakawa, A.Rothkopf
  N.Brambilla, M.A.Escobedo, A.Vairo, P.Vander Griend