Bottomonium Production in Heavy-Ion Collisions

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Outline

• Introduction
  • Heavy-Ion Collisions and Quarkonium as Probe

• Bottomonium Transport Approach
  • Boltzmann and Rate Equation
  • Transport Coefficients:
    • In-Medium Binding and Reaction Rates
    • Equilibrium Limit

• Comparison with Data: $R_{AA}$ and $v_2$
  • Centrality Dependence and $p_T$-Dependence of $R_{AA}$
  • Excitation Function (Energy dependence)

• Conclusion
Why quarkonium in HIC?

• Can survive in QGP with large binding energy
• Large mass makes nonrelativistic EFT suitable
• Not in equilibrium during medium evolution
• Quarkonia decay after medium evolution
• Various species enable fruitful phenomenology
• Help to study the in-medium heavy quark potential
Quarkonium Transport in Medium

- Initial quarkonium from hard production not in equilibrium
- Simulate quarkonium time evolution towards equilibrium limit

Need a transport model quantifying

How fast the evolution is $\rightarrow$ reaction rate

Number of quarkonium in equilibrium $\rightarrow$ equilibrium limit

Quarkonium distribution evolution: Boltzmann equation:

$$\frac{\partial f_Y(x, p, \tau)}{\partial \tau} + v \cdot \frac{\partial f_Y(x, p, \tau)}{\partial x} = -\alpha_Y(T, p)f_Y(x, p, \tau) + \beta_Y(T, p)$$

- Loss
- Primordial
- Gain
- Regeneration
Transport: Rate Equation

Total quarkonium number evolution

Kinetic Rate Equation

\[ \frac{dN_Y(\tau)}{d\tau} = -\Gamma_Y(T(\tau)) [N_Y(\tau) - N_Y^{eq}(T(\tau))] \]

Transport Coefficients

- Reaction Rates
  \[ \Gamma_Y(T) = \langle \alpha(T, p) \rangle_p \]

- Equilibrium Limits
  \[ N_Y^{eq} = Vn_Y^{eq} \approx V \int \gamma_b^2 d_Y e^{-E/T} \frac{d^3 p}{(2\pi)^3} \]
Transport Coefficient: Reaction Rates

In-medium binding energy:
In-medium potential based
T-matrix approach in strongly interacting medium (solid)

F. Riek, R. Rapp, PRC 82 (2010)

- In-medium binding energy severely enhance the reaction rates
- Excited state rates much larger than ground state because of smaller binding
Transport Coefficient: Equilibrium Limit

Heavy quark conservation

\[ N_{b\bar{b}} = \frac{1}{2} \gamma_b n_{\text{op}} V_{FB} \frac{I_1(\gamma_b n_{\text{op}} V_{FB})}{I_0(\gamma_b n_{\text{op}} V_{FB})} + \gamma_b^2 n_{\text{hid}} V_{FB} \]

- \( N_{b\bar{b}} \): Initial produced \( b\bar{b} \) pairs
- \( V_{FB} \): Relativistic expanding fireball volume
- \( \gamma_b \): Fugacity factor

Bottomonium number in equilibrium

\[ N_{Y}^{\text{eq}}(T) = V_{FB} \gamma_b^2(T) n_Y(m_Y; T) \]

- Bottomonium density
Fireball Model

Need temperature evolution to solve the rate equation...

Total entropy conserved:

\[ S_{\text{total}} = s_{QGP}(T)V_{FB}(\tau) \]

Temperature Evolution

\[ \frac{dN_Y(\tau)}{d\tau} = -\Gamma_Y(T(\tau)) [N_Y(\tau) - N_Y^{\text{eq}}(T(\tau))] \]

Lattice EOS

Constructed from measured charged hadron numbers
From Transport to Observables

Initial Production (cross sections)
Cold Nuclear Matter Effects (Shadowing, Nuclear Absorption …)

Transport Equation

Final Quarkonium Numbers $N_{Y}^{AA}(1S, 1P, 2S, \ldots)$

Direct $N_{Y}^{AA}(1S)$

Feeddowns
- $N_{Y}^{AA}(1P)$
- $N_{Y}^{AA}(2S)$
- $N_{Y}^{AA}(2P)$
- $N_{Y}^{AA}(3S)$

Inclusive $N_{Y}^{AA}(1S)$

Nuclear Modification Factor $R_{AA}$: $R_{AA} = \frac{N_{Y}^{AA}}{N_{coll}^{pp} N_{Y}^{pp}}$
Centrality-dependent $R_{AA}$ at RHIC

Sequential suppression

Excited states

Ground state

Excited states

Ground state
Centrality-dependent $R_{AA}$ at the LHC

- Sequential suppression
- Direct $\Upsilon(1S)$ suppression, small regeneration
- Regeneration significant for $\Upsilon(2S)$
Sensitivity to Binding Energy

Binding Energies → Reaction Rates → $R_{AA}$ Observables

- Significant binding energy dependence of the $\Upsilon(1S)$ $R_{AA}$
Calculation of $p_T$-Spectra

Primordial component: Boltzmann Equation

$$\frac{\partial f_Y^{\text{prim}}(x, p, \tau)}{\partial \tau} + v \cdot \frac{\partial f_Y^{\text{prim}}(x, p, \tau)}{\partial x} = -\alpha(T, p) f_Y^{\text{prim}}(x, p, \tau)$$

Regeneration component: Coalescence with off-equilibrium $b$-quark spectra

$$f_Y^{\text{coal}}(p) = \int f_b(p_1) f_{\bar{b}}(p_2) W_Y(\Delta p) d^2p_1 d^2p_2$$

Langevin simulation
M. He, R. Fries, R. Rapp, PLB 735 (2014)

Coalescence at average regeneration temperature
$p_T$-dependent $R_{AA}$ at RHIC and the LHC

- Coalescence from non-thermalized $b$-quarks induces small $p_T$-dependence for bottomonium
**v_2 at LHC**

**elliptic flow v_2:**

\[
\frac{d^2 N}{d^2 p_T} = \frac{1}{2\pi} \frac{dN(p_T)}{p_T dp_T} \left(1 + 2v_2(p_T)\cos(2\phi) + \ldots\right)
\]

Both destruction and coalescence occurs early for \(\Upsilon(1S)\), later for \(\Upsilon(2S)\).
Excitation Function

Energy dependence of $R_{AA}$:
Suppression at higher energy for bottomonium

$\Rightarrow$ Significant regeneration contribution for excited states
Enhancement at higher energy for charmonium:

$\Rightarrow$ Interplay of primordial and regeneration component
Conclusion

• Learn about in-medium heavy quark anti-quark QCD force using bottomonium in heavy-ion collision
  → Significance of in-medium binding energies

• Sequential suppression for bottomonium, regeneration essential for excited state excitation function

• More suppression for bottomonium at higher energy vs. enhancement for charmonium at higher energy (regeneration).

• $\Upsilon v_2$ as a probe of suppression/recombination temperature