In-Medium Charmonium Production in Proton-Nucleus Collisions

Xiaojian Du, Ralf Rapp
Cyclotron Institute
Department of Physics and Astronomy
Texas A&M University

RHIC & AGS Annual Users’ Meeting
Brookhaven National Laboratory, Upton, NY
2019.06.04
Outline

• Introduction
• Quarkonium Transport Approach
  • Rate Equation
  • Success of the Approach in AA Collisions
• p/dA Collisions with Data: $R_{pA}$ and $v_2$
  • Nuclear Modification Factor $R_{pA}$
  • Elliptic Flow $v_2$
• Summary

X. Du, R. Rapp, JHEP03(2019)015
Why p/d-A Collisions? Why Quarkonium?

Questions in p/d-A collisions:

- Medium Effects (in such small system)?
- Anisotropies (different from A+A collisions)?

Heavy Quarkonium, J/ψ, ψ(2S), ϒ(1S), ϒ(2S), ....as a probe:

1. Survive in QGP (E_{BINDING}>T_c), 2. Small velocity (potential picture works),
3. Large masses (baseline from hard production)
4. Various species (bound/melt at different parts of potential), …

→Ideal for probing strong force / Q̅Q potential in medium
Transport Approach

Kinetic Rate Equation

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

Transport Coefficients

- Reaction Rates
  \[ \Gamma_\psi (T(\tau)) \]
  NLO Quasi-Free

- Equilibrium Limits
  \[ N_{eq}^\psi (T(\tau)) \]
  From Heavy quark conservation

Key Parameters

- Coupling \( \alpha_s \)
  Affects Reaction Rates
  Fixed from Previous Calculations compared with data

- Thermal Relaxation Time
  Modifies Equilibrium Limit
  Extracted from Heavy Quark Diffusion Simulations

Key Inputs

- In-Medium \( Q\bar{Q} \) Potential/Binding Energy
- Heavy Quark/-onium pp Cross Section \( \gamma_c \)
  \( \gamma_c \) -> fugacity factor
- Initial State Effects (nPDF)
- Fireball Evolution
From Potential to Observables

In-Medium $q\bar{q}$ Potential

Quarkonium Binding Energies

Transport → Observables

Reacton Rates

• Hierarchy:
  → Different Melting temperatures for $J/\psi$, $\psi(2S)$, …
  Sequential Suppression …
  Sequential Regeneration …

• Probing In-Medium Potential
Elliptic Fireball Evolution

1. Need temperature evolution to solve the rate equation (medium effects)

Entropy conserved: \( S_{\text{tot}} = s(T)V_{\text{FB}}(\tau) \rightarrow \text{Temperature } T(\tau) \)

2. Provide elliptic geometry of background medium (anisotropies)

Elliptic medium expansion: \( V_{\text{FB}} = (z_0 + v_z\tau) \pi R_x(\tau) R_y(\tau) \)

Key Fireball Parameters:

→ Guided from light hadron spectra and \( v_2 \)

Temperature Evolution

[Graph showing temperature evolution over time for different collision centralities]
**Success of Transport Approach in AA**

**Charmonium**

Simultaneous description of ground and excited states:
→ Sequential suppression

Momentum spectra:
→ Demonstrate regeneration
→ Degree of heavy quark Thermalization

Charm/Bottom-onium difference:
Charmonium:
→ Large regeneration
→ Close to thermal

Bottomonium:
→ Small regeneration
→ Far from thermal

Has predictive power

**Bottomonium**

See also: ALI-PREL-126572

ALICE, PLB785 (2018) 419

X. Du, M. He, R. Rapp, PRC96 (2017), no.5, 054901
Success of Transport Approach in AA

J/ψ Excitation Function:

→ Further demonstration of regeneration

J/ψ and Y(2S):

→ Due to Large regeneration for J/ψ

similar binding energies

BUT
different excitation functions

R. Rapp, X. Du, NPA967 (2017) 216
Centrality Dependent $R_{dA}/R_{pA}$ at RHIC/LHC

Nuclear modification factor

$$R_{pA} = \frac{N_{pA}}{N_{coll}N_{pp}}$$

- $J/\Psi$ very little suppressed
- $\Psi(2S)$ more suppressed
- Pb-going larger $J/\Psi$, $\Psi(2S)$ gap than p-going
- Small regeneration contribution

Medium effect

RHIC & AGS Annual Users’ Meeting & Workshop 2019
Dependent $R_{pA}$ at the LHC

- Small regeneration contribution:
  
  Verified by moderate $p_T$ dependence

  $\rightarrow$ Thermalized and regenerated charmonium accumulates at low-$p_T$
Elliptic Flow ($v_2$) at the LHC

Elliptic flow ($v_2$):

- Anisotropy in A-A: non-central collision
- Anisotropy in p-A: fluctuation

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

- $v_2$ in primordial: leakage effect (geometry)
- $v_2$ in regeneration: flow effect

- $v_2$ compare to experimental data: Puzzle?
  
  Data suggests large $J/\psi$ $v_2$ but small $J/\psi$ suppression
  
  Large $v_2$ not from hot medium effect alone, from initial state effect?
Summary

• There is hot medium effect in pA collisions
  → $J/\psi$ and $\psi(2S) R_{pA}$ “gap” ($\psi(2S) R_{pA} < J/\psi R_{pA}$)
  → $R_{pA}$ “gap” larger at Pb-going, smaller at p-going

• $J/\psi$ regeneration is small in pA collisions
  → $J/\psi R_{pA}(p_T)$ has no peak at low $p_T$

• Initial state effect might be important for a simultaneous description of $R_{pA}$ and $v_2$ in pA collisions
  → Small $J/\psi$ suppression but large $J/\psi v_2$

Thank you!