Quarkonia dynamics in the QGP with open quantum systems

Stéphane Delorme

A virtual tribute to Quark Confinement and the Hadron Spectrum 2021

Collaborators:

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- Roland Katz (Post-doc)
Quarkonium in heavy-ion collisions

Static screening

\[ T \neq 0 \rightarrow \text{Suppression of color attraction} \]

Melting of pairs at high \( T \)

\[ \Rightarrow \text{Suppression} \]

Dynamical processes

Collisions with medium partons

\[ \rightarrow \text{Pair dissociation} \]

\[ \Rightarrow \text{Suppression} \]

Often described by an imaginary potential

Lafferty, A. Rothkopf
Quarkonium in heavy-ion collisions

Recombination

Initially uncorrelated heavy quarks form a quarkonium

Essential to have a formalism that can treat this effect

Need to treat in-medium real time quarkonium dynamics

→ Open quantum systems
Open quantum systems

System + environment
\[ \rho(t = 0) = \rho_{Q\bar{Q}} \otimes \rho_{QGP} \]

Evolution of the total system
\[ \rho(t) = U(t, 0) [\rho_{Q\bar{Q}} \otimes \rho_{QGP}] U(t, 0)^\dagger \]

Trace out environment degrees of freedom

System (Q\bar{Q} pair)
\[ \rho_{Q\bar{Q}}(t = 0) \]

Evolution of the system
\[ \rho_{Q\bar{Q}}(t) = \text{Tr}_{QGP} [U(t, 0)\rho(t = 0)U(t, 0)^\dagger] \]
3D Quantum Master Equation

\[
\frac{d}{dt} \left( \frac{\mathcal{D}_s}{\mathcal{D}_o} \right) = \mathcal{L} \left( \mathcal{D}_s(s, s', t), \mathcal{D}_o(s, s', t) \right)
\]

\[
\mathcal{L} = \begin{pmatrix}
\mathcal{L}_{ss} & \mathcal{L}_{so} \\
\mathcal{L}_{os} & \mathcal{L}_{oo}
\end{pmatrix}
\]

- Weak coupling between heavy quarks and plasma particles
- Valid in the quantum brownian regime (high temperature)
- Resolved through a semi-classical approximation
- Pioneering work to be explored

3D Quantum Master Equation

\[ \mathcal{L} = \mathcal{L}_0 + \mathcal{L}_1 + \mathcal{L}_2 + \mathcal{L}_3 \]

- **\( \mathcal{L}_0 \):** Kinetic terms
- **\( \mathcal{L}_1 \):** Static screening (V)
- **\( \mathcal{L}_2 \):** Fluctuations (W)
- **\( \mathcal{L}_3 \):** Dissipation (\( W'/W'' \))

**Transition between color states and dissipation effects**

**Our work:**

- Extension of the equations to preserve positivity
  \( \Rightarrow \) new \( \mathcal{L}'_3 \) and \( \mathcal{L}_4 \)
- Direct resolution in 1D
- New potential better suited for 1D studies
  R. Katz, S. Delorme, P.B. Gossiaux
  (in preparation)
- For now: focus on charmonia
Optimized 1D potential

Based on 3d lattice data
D. Lafferty, A. Rothkopf

1d parametrization to reproduce 3d decay widths and temperature-dependant mass spectra

Different parametrizations for charmonia and bottomonia
1D equations resolution: State probabilities

- Higher suppression at larger temperatures for S-like states
- Transient phase up to $\sim 5$ fm/c: re-equilibration
- Same late-time evolution for S-like states at 300 and 400 MeV
- Interplay between binding, diffusion and transitions between states
1D equations resolution: State probabilities

- 1S-like and 1P/2S-like states closer at larger temperature
- Statistical distribution (although not detailed balance)
1D equations resolution: Singlet density operator

$D_s \quad T = 300 \text{ MeV}$

Dissociated component

Bound core to be studied

Quantum coherences?
More realistic initial state

- P-like octet initial state

- Same late-time evolution as the 1S-like singlet initial state

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Evolving medium

- Initial P-like octet state with initial temperature 400 MeV

- $T(t) = T_0 \left( \frac{1}{1+t} \right)^{1/3}$

- After $\approx 8$ fm/c, temperature too low
  → Outside of potential validity range
Conclusion & Perspectives

- We have a fully functional tool to explore the 1D dynamics
- We developed a new potential based on 3d Lattice QCD, tailored for 1d studies
- Work on the feasibility of a semi-classical treatment under way

- Further study the validity of semi-classical approximations
- Application of a semi-classical treatment if possible and comparison with full quantum dynamics
- Study the bottomonium system
- Go to more realistic background: 3d dynamics, hydro...