The effective Hamiltonian for singlet and octet evolution is defined by

\[ H = \ldots \]

Here, six collapse operators cover: singlet and light quarks and gluons as the medium.

Acknowledgements and references


Speaker and Conference Info

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Abstract

In Ref[1], using the potential non-relativistic quantum chromodynamics (pNRQCD) effective field theory, we derive a Lindblad equation for the evolution of the heavy-quarkonium reduced density matrix that is accurate to next-to-leading order (NLO) in the ratio of the binding energy of the state to the temperature of the medium. Finally, we make comparisons with our prior leading-order pNRQCD results and experimental data available from the ATLAS, ALICE, and CMS collaborations.

1. Heavy quarkonium as an Open Quantum System

In Open Quantum System (OQS) approach, we consider heavy quarkonium as an open quantum system/probe and light quarks and gluons as the medium.

\[ \hat{H}^{\text{NRQCD}} \]

Here, we consider the following relevant scales: temperature \( T \), bound state mass \( m \gg T \), bound state size \( r \sim 1/\sqrt{m} \sim 1/(\text{Bohr radius}) \). Dives mass \( m_B \), binding energy \( E \sim m_B^2 \), medium relaxation time scale \( t_M \). probe time scale \( t_p \sim \sqrt{E/T} \), probe relaxation time scale \( \tau_M \sim 1/\Delta_n \).

OQS + pNRQCD treatment gives the following Lindblad equation

\[ \frac{d\rho_{\text{probe}}}{dt} = -i[H_{\text{probe}}, \rho_{\text{probe}}] + \sum_{n} \left( C_n^{*} \rho_{\text{probe}} C_n - \frac{1}{2} \{ C_n^{*} C_n, \rho_{\text{probe}} \} \right) \]  (1)

where, \( H_{\text{probe}} \) is Hamiltonian and \( C_n \) are the collapse/jump operators.

If we define a non-Hermitian effective Hamiltonian

\[ H_{\text{eff}} = H_{\text{probe}} + \frac{\Delta}{2} \]  (2)

with \( \Delta = C \) and \( \Gamma = \sum_n \Gamma_n \), then Eq. (1) becomes

\[ \frac{d\rho_{\text{probe}}}{dt} = -i[H_{\text{eff}}, \rho_{\text{probe}}] + \sum_{n} \left( C_n^{*} \rho_{\text{probe}} C_n \right) \]

2. Lindblad equation to NLO in E/T

\[ \frac{d\rho}{dt} = -i[H, \rho(t)] + \sum_{\ell=1}^{6} \left( C^2_{\ell} \rho(t) C^\dagger_{\ell} - \frac{1}{2} \{ C^*_{\ell} C_{\ell}, \rho(t) \} \right), \quad H = \left( h + \text{Im} \Sigma_s \right) C_{\ell} \]  (3)

where,

\[ \text{Im} \Sigma_s = \begin{pmatrix} \frac{\Delta^2}{2} & \frac{\Delta}{2} & \frac{\Delta}{2} \\ \frac{\Delta}{2} & \frac{\Delta}{2} & \frac{\Delta}{2} \\ \frac{\Delta}{2} & \frac{\Delta}{2} & \frac{\Delta}{2} \end{pmatrix} \]

\[ C_{\ell} = \begin{pmatrix} 0 \\ \frac{\Delta}{2} \\ \frac{\Delta}{2} \end{pmatrix} \]

\[ \kappa = \sum_{\ell=1}^{6} \int_0^\infty du \left( \left\langle L_\ell(0,0) L_\ell^\dagger(0,0) \right\rangle \right) \]

Here, six collapse operators cover: singlet = octet, octet = singlet, octet = octet.

The effective Hamiltonian for singlet and octet evolution is defined by

\[ H_{\text{eff}}^s = h_0 + \text{Im} \Sigma_s + H_{s}(s/a)^2 \]

with \( \Gamma_s = \sum_{\ell}(1,1) \Gamma_{s,\ell} \) and \( \Gamma_o = \sum_{\ell}(1,1) \Gamma_{o,\ell} \) with \( \Gamma_s = \sum_{\ell}(1,1) \Gamma_{s,\ell} \) and \( \Gamma_o = \sum_{\ell}(1,1) \Gamma_{o,\ell} \).

3. Numerical Solution

We solve the form of the Lindblad equation given in Eq. (2) using Quantum Trajectories Method. For details see Ref[2].

4. NLO Results

5. Conclusions

- We have gone beyond prior studies [2,3] by deriving and numerically solving a Lindblad-type evolution equation that is accurate to NLO in \( E/T \).
- We used quantum trajectories method successfully to solve the NLO Lindblad equation.
- We have shown that when going from LO to NLO there is a sizable correction to the singlet decay width for \( T(5S) \) and smaller corrections for the \( T(2S) \) and \( T(3S) \) states.
- The inclusion of NLO corrections has allowed us to extend the pNRQCD+OQS treatment down to temperatures in the vicinity of the QCD phase transition; in practice, we have lowered the decoupling temperature from \( T_d = \sim 180 \text{MeV} \) at \( T = \sim 180 \text{MeV} \) at NLO.