Spin-Dependent Interactions and Heavy-Quark Transport in the QGP

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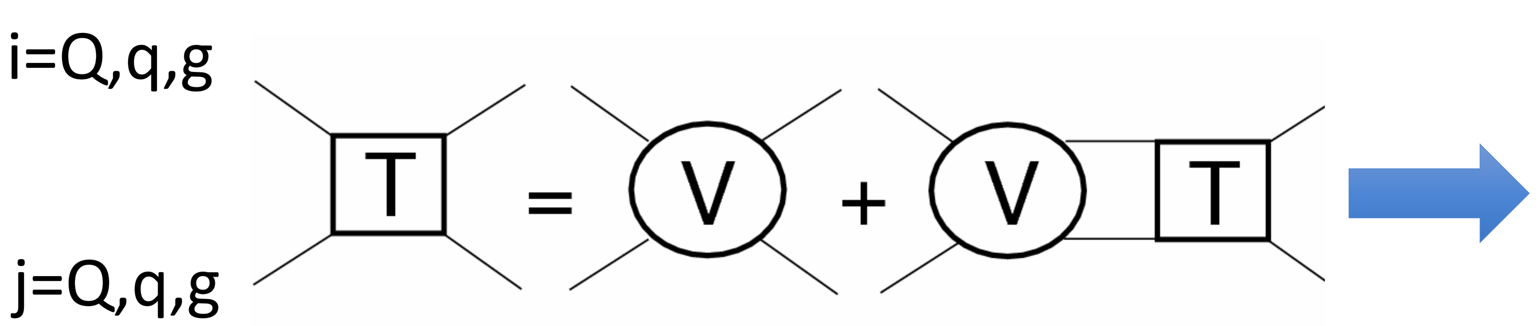
We advance a previously constructed thermodynamic T-matrix approach for heavy-quark (HQ) transport in the quark-gluon plasma (QGP) to include the effects of spin-dependent interactions between partons, which is part of a general effort to include 1/M corrections. We first study the experimental values of the mass splittings in vacuum quarkonium spectroscopy and find that the confining potential that is a mixture of vector and scalar potentials rather than a purely scalar one improves the description. We then study the in-medium charm-quark transport coefficients at different temperatures; the temperature corrections to the in-medium potential are constrained by results from thermal lattice-QCD for the HQ free energy and equation of state. It turns out that the mixing effect for confining potential enhances the friction coefficient, A(p), for charm quarks in the QGP over previous calculations with a purely scalar potential. Our results suggest that the microscopic description of HQ transport improves the current phenomenology of open heavy-flavor observables at RHIC and the LHC.

METHODS

T-matrix Approach

Thermodynamic T-matrix [1,2] is a quantum many-body approach to QGP, it resums infinite scattering ladder diagrams as the diagram and equation below:

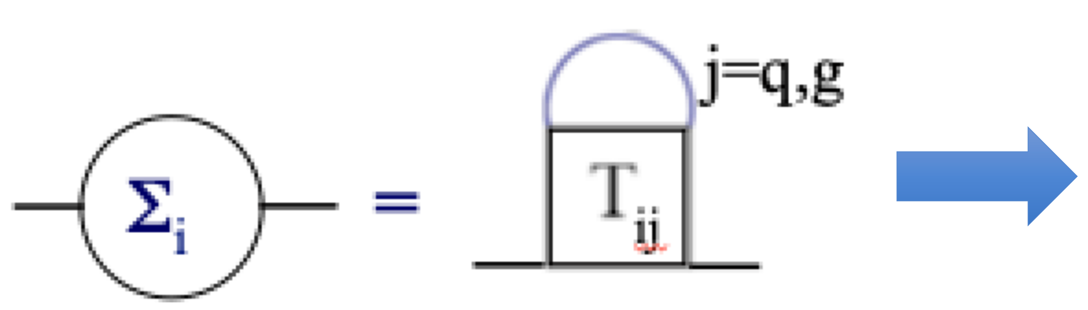


$$T_{ij} = V_{ij} + \int V_{ij} G_i G_j T_{ij}$$

In-medium potential (input): V_{ij}

In-medium 1-body propagator: $G_i = 1/[E - \omega_k - \Sigma_i(E,k)]$

Self-energy:



$$\Sigma_i = \int G_j T_{ij}$$

The functional equation $\Sigma = T(\Sigma)G(\Sigma)$ can be solved self-consistently.

The series $1 + \alpha + \alpha^2 \cdots = 1/(1-\alpha)$ can be resummed for strong coupling, which makes T-matrix a useful tool to study non-perturbative QCD. This equation is therefore well suited to study the strongly coupled QGP near the critical temperature T_c where both bound and scattering states are expected to be important.

Interactions in T-matrix Equation

- static (Cornell) potential: $V = -\frac{4}{3}\alpha_s \frac{1}{r} + \sigma r$
  - Coulomb (V_C) confining(V_S)
- relativistic corrections:
  - leading order: $V = RV^{vec} + V^{sca}$
    - relativistic correction due to vector interaction

    with $R = \sqrt{\frac{\varepsilon_i(p)\varepsilon_j(p)}{M_i M_j}} \sqrt{1 + \frac{p^2}{\varepsilon_i(p)\varepsilon_j(p)}} \sqrt{\frac{\varepsilon_i(p')\varepsilon_j(p')}{M_i M_j}} \sqrt{1 + \frac{p'^2}{\varepsilon_i(p')\varepsilon_j(p')}}$

    common assumption: $V^{vec} = V_C$, $V^{sca} = V_S$

    our assumption [3,4]: $V^{vec} = V_C + (1-\chi)V_S$, $V^{sca} = \chi V_S$

    mixing coefficient (proportion of scalar component in V_S)
  - higher order in 1/M: $V = RV^{vec} + V^{sca} + V^{LS} + V^{SS} + V^T$

    spin-orbit: $V^{LS} = \frac{3}{2M^2 r}\langle \boldsymbol{L}\cdot\boldsymbol{S}\rangle \left(\frac{d}{dr}V^{vec} - \frac{d}{dr}V^{sca}\right)$

    spin-spin: $V^{SS} = \frac{3}{3M^2}\langle \boldsymbol{S_1}\cdot\boldsymbol{S_2}\rangle \Delta V^{sca}$

    tensor: $V^T = \frac{3}{12M^2} S_{12} \left(\frac{1}{r}\frac{d}{dr}V^{vec} - \frac{d^2}{dr^2}V^{sca}\right)$

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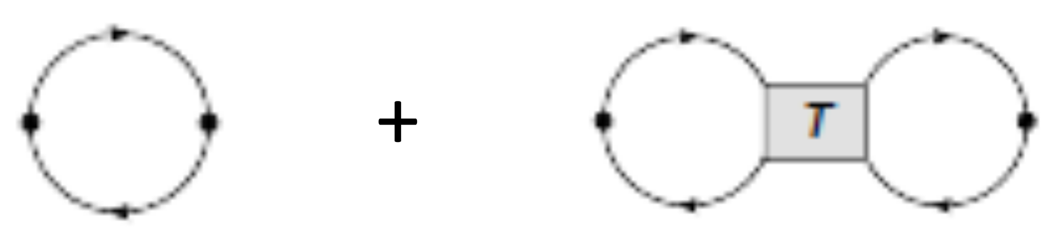
RESULTS

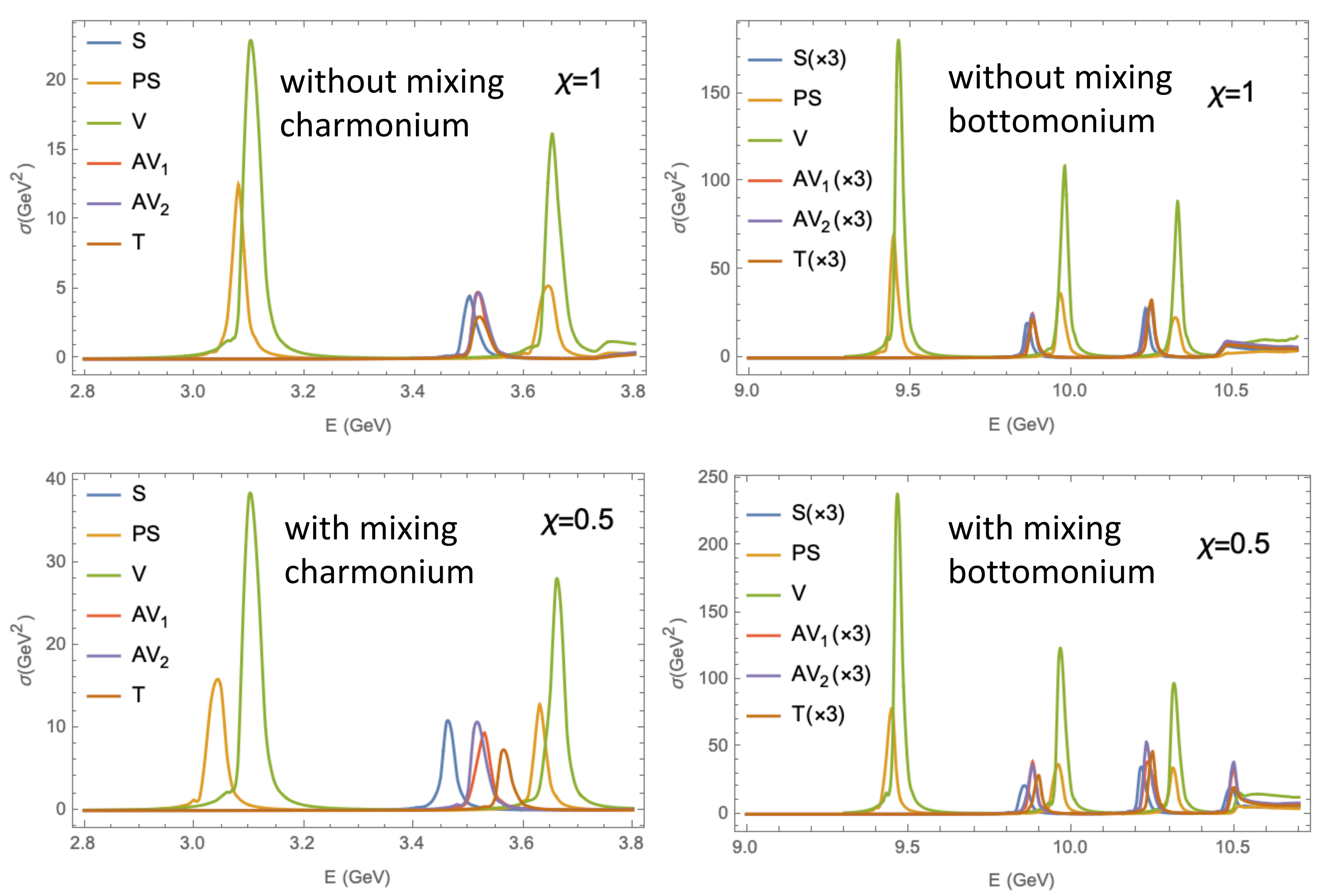
Charmonium & Bottomonium Spectroscopy in Vacuum

correlation functions:



$$G_0(E) \sim \int d^3p\; G^0_{Q\bar{Q}}(E,p) \qquad G_{\rm int}(E) \sim \int d^3p\; G^0_{Q\bar{Q}}(E,p) \times \int d^3p'\; G^0_{Q\bar{Q}}(E,p')T_{Q\bar{Q}}(E,p,p')$$

spectral function: $\sigma(E) = \frac{1}{\pi}\mathrm{Im}[G_0(E) + G_{\rm int}(E)]$

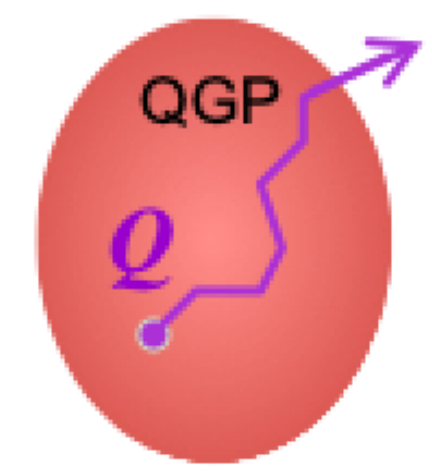


The vacuum spectral functions for charmonium and bottomonium in scalar (S), pseudoscalar (PS), vector (V), axial-vector (AV) and tensor (T) channels.

The results with mixing effect (χ=0.5) significantly improve the agreement with experimental data over the results without mixing (χ=1), especially in the mass splittings for charmonia.

In-medium Charm-Quark Transport Coefficients

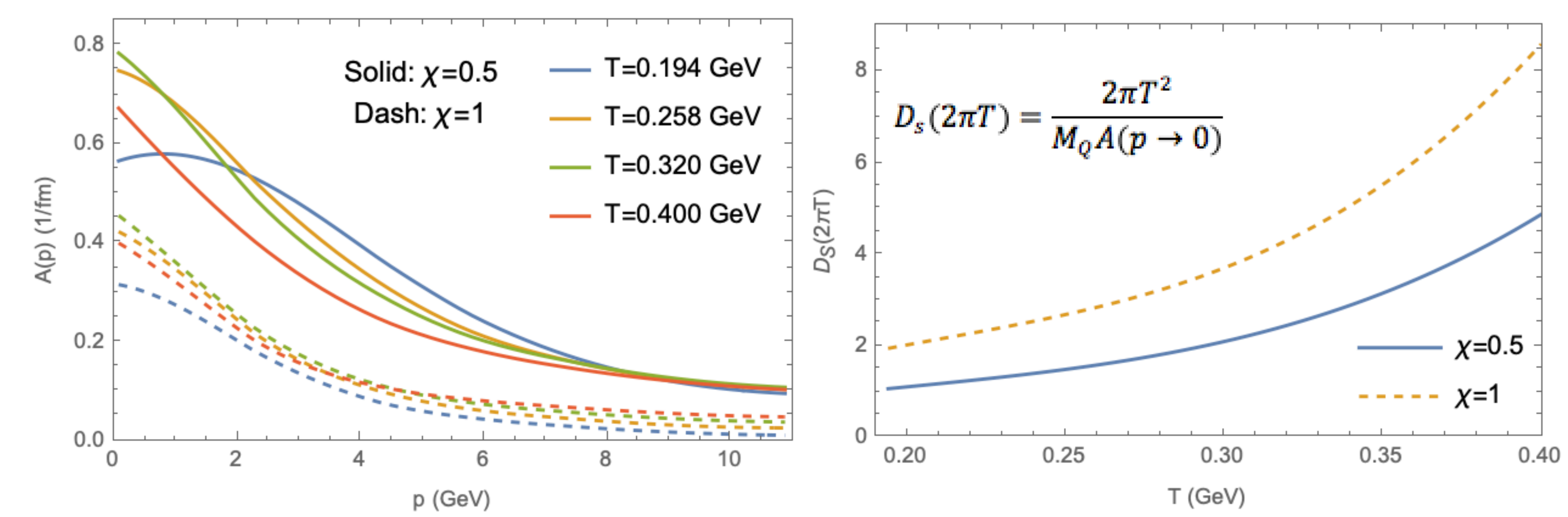
Fokker-Planck equation: $\frac{\partial}{\partial t} f(p,t) = \frac{\partial}{\partial p_i}\left\{A(p)p_i f(p,t) + \frac{\partial}{\partial p_j}[B_{ij}(p) f(p,t)]\right\}$



friction coefficient: $A(p) \sim \sum_i \int d^4p'\, d^4q\, d^4q' |T_{Qi}|^2 \left(1 - \frac{\mathbf{p}\cdot\mathbf{p}'}{\mathbf{p}^2}\right)$

spatial diffusion coefficient: $D_s = \frac{T}{M_Q A(p\to 0)}$

heavy-light T-matrix



The A(p) for χ = 1 without mixing are significantly enhanced by introducing the mixing effect with χ = 0.5, especially at high momenta; as a consequence, the diffusion coefficient is reduced by the mixing effect, especially at high temperature.

CONCLUSION

The introduction of vector component in confining interaction significantly improves the vacuum charmonium and bottomonium spectroscopy. When implementing the modified potential in the calculation of heavy-quark friction coefficients, a substantial enhancement due to the vector interaction is found, which is likely to improve the current phenomenology of open heavy-flavor observables.

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