Charmonium Potential at Non-Zero Temperature

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Introduction

To learn more about the early universe and structure of super-dense stars, the physics of matter at extremely high temperature and density must be understood. The strong interaction is dominant under these conditions. Hence the phase diagram of Quantum Chromodynamics (QCD) is investigated.

Quark Gluon Plasma

At extremely high temperature and density hadrons dissolve into a deconfined system of quarks and gluons, called a quark-gluon plasma (QGP).

Exponentially, QGP is investigated by orchestrating heavy ion collisions in particle accelerators. Theoretically, a major tool for its study is lattice QCD (LQCD).

Lattice QCD

- QCD formulated on a Euclidean space-time lattice.
- Ambiguous infinite-dimensional functional integral that defines QCD becomes finite and well defined.
- Evaluate integral using Monte Carlo techniques.

Due to the sign problem, the study of non-zero density LQCD is hampered. This makes non-zero temperature LQCD a more accessible means by which to study the QGP. The charmonium potential is of particular interest because J/ψ suppression is believed to be a signature of QGP [1], its calculation from first principles would also contribute to a better understanding of the melting of meson states.

Method of Calculation

Assume charm quarks are heavy enough to be treated non-relativistically.

Solve Schrödinger equation to compute the potential.

\[
V_C(r) = \frac{1}{2m_0} \nabla^2 \psi_C(r) + \rho(r) \psi_C(r)
\]

To obtain the reduced mass, \( m_0 \), energy, \( E \), and wavefunction, \( \psi_C(r) \), of the c+c system analyse split-split correlation functions via methods i) and ii).

SPECTROSCOPY

From analogy with statistical mechanics lattice spacing, \( a \), and state, \( N \), in temporal direction are related to temperature by:

\[
a_0 N = \frac{1}{T}
\]

Calculate \( V_C(r) \) for different \( N \) to investigate non-zero temperature behaviour.

i) Conventional LQCD Hadron Spectroscopy

Express the correlation function of two-operators as the sum over the eigensates of the Hamiltonian operator labelled by \( n \).

\[
C(r,t) = \langle \phi(0) | \psi(r,0) \psi(0,t) \rangle = \sum_n \langle \phi(0) | \psi(r,0) \psi(0,t) \rangle e^{-E_n t}
\]

Define an effective mass,

\[
m_{\text{eff}} = \frac{E_n}{E_n - E_0}
\]

Perform a two parameter fit of \( C(r,t) \) in time interval where \( m_{\text{eff}} \) plateaus, here \( C(r,t) = 2E_0^2 - E_0^2 \), since the ground state dominates.

\[
\psi_C(r) = \sum C_i(r) \phi_i(r) = \sum C_i(r) \phi_i(r)
\]

Computing potential obtained for \( N = 16 \) and \( N = 80 \), see evidence that potential flattens for higher temperature in agreement with deconfinement.

However, data points for greater \( T \) have larger errors - as expected from noiseier correlation functions. This makes temperature dependence of potential difficult to discern when results for all \( N \) are plotted.

Lattice Simulation Details

A Symanzik-improved, two plaquette action [2] generated two-flavour, dynamical, anisotropic gauge configurations for this study [3].

\[
\alpha_s^{-1} = 7.35 \pm 0.03 \text{ GeV}
\]

\[
\alpha_s = 0.162 \text{ fm}
\]

\[
E_0/\alpha_s = 6
\]

\[
\mathcal{M}_{1/2}/\alpha_s = 0.54 \text{ [4]}
\]

Chroma [5] is used to apply an anisotropic clover fermion action [6] to obtain the correlation functions of several different operators:

\[
\langle \bar{\psi} \gamma_\mu \psi \rangle \langle \bar{\psi} \gamma_\nu \psi \rangle
\]

\[
\langle \bar{\psi} \gamma_\mu \psi \rangle \langle \bar{\psi} \gamma_\lambda \gamma_\nu \psi \rangle
\]

\[
\langle \bar{\psi} \gamma_\mu \gamma_\nu \gamma_5 \psi \rangle \langle \bar{\psi} \gamma_\sigma \gamma_\tau \gamma_5 \psi \rangle
\]

Spectral Functions:

The \( N = 32 \) s-channel spectral function for \( r = \text{in} \).

Observe a temperature dependence of the charmonium potential in agreement with deconfinement but need to increase reliability of this claim.

Will increase statistics on 12x80 lattice and move to 32x32 lattices to achieve this.

Preliminary Results

Spectroscopy:

The \( N = 80 \) s-channel correlation functions,

\[
C(r,t) = \frac{1}{2m_0} \nabla^2 \psi_C(r) + \rho(r) \psi_C(r)
\]

\[
\psi_C(r) = \sum C_i(r) \phi_i(r)
\]

\[
\psi_C(r) \text{ can be successfully extracted.}
\]

\[
\text{For } N = 16 \text{ and } N = 80,
\]

\[
\text{spectral point } r = 0.5 \text{ where peak could not be resolved. Once this problem is overcome will proceed to calculate potential.}
\]

Summary

Charmonium wavefunction using method i) and ii) and potential using method i) can be successfully extracted. Potential using method ii) will follow after more analysis.

Observe a temperature dependence of the charmonium potential in agreement with deconfinement but need to increase reliability of this claim.

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References


