A potential approach to the $X(3872)$ thermal behavior

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Outline

1. Introduction
2. Theoretical framework
3. Results
4. Conclusions
There are Quarkonium-like particles that can not be explained by the simple quark-antiquark model.

Picture taken from Physics Reports 873 (2020)
Quarkonia exotics

- There are Quarkonium-like particles that can not be explained by the simple quark-antiquark model.
- Among them, we focus on the \( X(3872) \), whose internal structure is still a matter of debate.

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Among them, we focus on the $X(3872)$, whose internal structure is still a matter of debate.

There are two competing models. The tetraquark and the hadronic molecule.
Quarkonia exotics

![Diagram of hadronic objects](https://www.fz-juelich.de/en/ias/ias-4/research/exotic-hadrons/exotics_pad.jpg)

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Picture taken from Phys.Rev.Lett. 128 (2022) 3, 032001
Conventional quarkonium in heavy-ion collisions

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- Improved theoretical understanding in recent years.
- The heavy quarkonium potential has both a real and an imaginary part.
- The origin of the imaginary part is the collision of quarkonium with medium particles.
- In some limits, it is a good approximation to model quarkonium using a Schrödinger equation with a complex potential.

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Due to this, our aim is to obtain qualitative results. We use as insights results from perturbative computations, lattice QCD and the large $N_c$ limit.
1 Introduction

2 Theoretical framework

3 Results

4 Conclusions
The Born-Oppenheimer approximation

- We assume that heavy quarks move non-relativistically around the center-of-mass, with velocity $v$. 

$\Lambda_{\text{QCD}} \gg E \sim m_Q v^2$. From the point of view of the heavy quarks, the light particles move very fast.

The effect of light particles and gluons can be encoded in a potential computed assuming that the heavy quarks are frozen and separated a given distance $r$. 

Two step-approximation:

▶ Compute the potential taking the heavy quarks as static color sources.
▶ Solve the Schrödinger equation.
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The $T = 0$ potential

This potential is well fitted by the formula

$$V(r, 0) = \frac{A_{-1}}{r} + A_0 + A_2 r^2.$$ 

Lattice data is not sensitive to large $r$ behavior. But, using Effective String Theory results, we know that at very large $r$ it only grows linearly.
The finite $T$ potential

The real part

We use the following assumption

$$V(p) = \frac{V_{\text{vac}}(p)}{\epsilon(p, m_D)},$$

where $\epsilon$ is the medium permittivity in the HTL approximation and $m_D$ is the Debye mass.

$$\Re[V(r, m_D)] = A_1 \left( m_D + \frac{e^{-m_D r}}{r} \right) + A_0 + A_2 \left[ \frac{6}{m_D^2} (1 - e^{-m_D r}) - \left( 2r^2 + \frac{6r}{m_D} \right) e^{-m_D r} \right]$$

Rationale

This model was able to describe lattice quarkonium potential at finite $T$ using $m_D$ as a fitting parameter (Phys. Rev. D 101(5), 056010 (2020)).
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\[
V(\text{GeV}) \quad m_D = 1.2 \text{ GeV} \\
\text{solid line} \\
V(\text{GeV}) \quad m_D = 0.8 \text{ GeV} \\
\text{dashed line} \\
V(\text{GeV}) \quad m_D = 0.4 \text{ GeV} \\
\text{dotted line} \\
\text{vacuum (} m_D = 0 \text{)} \\
\text{dashed-dotted line}
\]

\[ r \text{ (fm)} \]

0.0 0.2 0.4 0.6 0.8 1.0

0.4
0.6
0.8
1.0

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The finite $T$ potential

The imaginary part

The imaginary part of the potential of conventional quarkonium has the following properties:

At short distances it goes like $r^2$ because the medium sees quarkonium as a small dipole. At long distances, the heavy quarks are not correlated. Therefore, the imaginary part of the potential is equal to $-i$ times the decay width of a single heavy quark. Between these two limits it is a smoothly increasing function.
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The imaginary part

For example, in the HTL approximation

$$\Im V(r) = -\alpha_s C_F T \phi(m_D r).$$
The finite T potential

The imaginary part

In a tetraquark state treated in the BO approximation, the heavy quarks are in an octet state.

- When $r \to 0$ the medium sees the heavy quark pair as a non-relativistic heavy gluon. The imaginary part of the potential will be $-i/2$ times the decay width of a heavy gluon.
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- At intermediate distances we expect that the imaginary part of the potential is a smooth function that interpolates between the two regimes.

In the large $N_c$ limit the decay width of a heavy gluon is equal to that of two heavy quarks. Therefore, we can take the imaginary part of the potential to be a constant.
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The Decay Width

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- It is a function of the same constants that appear in the real part of the potential.
- Dimensional analysis.
- It is a educated guess. However, note that our aim is to get a qualitative understanding.
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The dissociation temperature

- Obtained by solving the Schrödinger equation using the complex potential.

Since the imaginary part is a constant, it factors out. The dissociation temperature is the one in which we can no longer find bound state solutions. In our case, we obtain $T_d \sim 250$ MeV.
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Mean radius vs Debye mass

\[ m_D \text{ (GeV)} \]

\[ \text{MSR (fm)} \]

\[ m_D \]

\[ 1/m_D \]

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Survival probability

We consider:

\[ S(t) = \exp\left\{ -\int_{t_0}^{t} \Gamma(T(\tau), \tau) \, d\tau \right\} \]
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**Survival probability**

$$S(t) = \exp\left[- \int_{t_0}^{t} d\tau \Gamma(T(\tau), \tau)\right],$$
Note that:

The initial temperature depends on the collision centrality and the point in which the bound state is produced. If $T \gtrsim 250$ MeV, the state melts.
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- We have developed a qualitative model for the potential of the $X(3872)$.
- Our results indicate that it melts around $250 \text{ MeV}$. The effect of the decay width is mild in heavy-ion collisions.