Diabatic Approach

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Quarkoniumlike Mesons in the Diabatic Approach

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1 Introduction

- Motivation
- Born-Oppenheimer Approximation
- Energy Levels in Lattice QCD
- 2 Diabatic Approach
 - Diabatic Formalism
 - String Breaking

3 Results

- Bottomoniumlike Mesons
- Charmoniumlike Mesons
- Summary and References

Outline o Motivation Introduction

Diabatic Approach

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Unconventional Charmoniumlike Mesons





Threshold effects?

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Unconventional mesons are often found near open-flavor thresholds.

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Introduction

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Results

Born-Oppenheimer Approximation

Description in Heavy and Light Fields



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Outline	Introduction	Diabatic Approach	Results
0		00000	0000000
Born-Oppenheimer Approximat	ion		

Integrating the Light Fields

1 Separate kinetic energy of the heavy quarks

$$H \ket{\psi} = E \ket{\psi}, \qquad H = K_{\mathsf{heavy}} + H_{\mathsf{light}}^{(\mathsf{heavy})}.$$

2 Solve the light-field Hamiltonian for static heavy quarks

 $H^{(ext{heavy})}_{ ext{light}} o H_{ ext{static}}(r), \qquad H_{ ext{static}}(r) \ket{\zeta_i(r)} = V_i(r) \ket{\zeta_i(r)}.$

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Static energy levels

The static energies $V_i(r)$ can be calculated *ab initio* in Lattice QCD.

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Diabatic Approach

Results

Born-Oppenheimer Approximation

Adiabatic Wave Function

Adiabatic expansion

$$|\psi\rangle = \sum_{i} \int \mathrm{d}r \, \psi_{i}(r) \left| r \right\rangle \left| \zeta_{i}(r) \right\rangle$$

- Light field states calculated at the same position of the heavy quarks
- One wave function for each light-field energy

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Image: A math a math

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Born-Oppenheimer Approximation

Adiabatic Schrödinger Equation

$$\sum_{j} \left[-\frac{\hbar^2}{2\mu} (\delta_{ij} \nabla + \tau_{ij}(r))^2 + \delta_{ij} (V_i(r) - E) \right] \psi_j(r) = 0$$

Non-adiabatic coupling terms

The kinetic energy term mixes different channels through the non-adiabatic couplings $\tau_{ij}(r) = \langle \zeta_i(r) | \nabla \zeta_j(r) \rangle$.

Adiabatic potentials

The potentials $V_i(r)$ in the Schrödinger equation are the energy levels calculated in Lattice QCD.

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Diabatic Approach

Results

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Energy Levels in Lattice QCD

Adiabatic Potentials in Quenched Lattice QCD



Quenched Lattice QCD

Gluons only, without light quarks

- Ground state: quarkonium potential
- Excited states: hybrid potentials

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Energy Levels in Lattice QCD

Adiabatic Potentials in Unquenched Lattice QCD



Unquenched Lattice QCD

Gluons and light quarks

String breaking

Channel mixing significant near the avoided crossing

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Introductior 0000000 Diabatic Approach

From Adiabatic to Diabatic

Diabatic expansion

$$\left|\psi\right\rangle = \sum_{i} \int \mathrm{d}r \, \widetilde{\psi}_{i}(r, r_{0}) \left|r\right\rangle \left|\zeta_{i}(r_{0})\right\rangle$$

Diabatic channels

$$\widetilde{\psi}_i(r, r_0) \rightarrow \psi_{Q\overline{Q}}(r), \, \psi_{M\overline{M}}(r)$$

- Light field states are calculated at a fixed position r₀.
- For r₀ far from the avoided crossing, they correspond to quark-antiquark and meson-meson.

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Outline o Diabatic Formalism Introduction

Diabatic Approach

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The Diabatic Schrödinger Equation

$$\begin{bmatrix} \begin{pmatrix} -\frac{\nabla^2}{2\mu_{Q\overline{Q}}} & 0\\ 0 & -\frac{\nabla^2}{2\mu_{M\overline{M}}} \end{pmatrix} + \begin{pmatrix} V_{Q\overline{Q}}(r) & V_{\text{mix}}(r)\\ V_{\text{mix}}(r) & T_{M\overline{M}} \end{pmatrix} - E \end{bmatrix} \begin{pmatrix} \psi_{Q\overline{Q}}(r)\\ \psi_{M\overline{M}}(r) \end{pmatrix} = 0$$

Diabatic potential matrix

The potential couples quark-antiquark and meson-meson.

Adiabatic-to-diabatic transformation

The eigenvalues of the diabatic potential matrix are the adiabatic potentials calculated in Lattice QCD.



Outline	
String Breaki	ng

Introductior

Diabatic Approach

Results

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Adiabatic Potentials in Unquenched Lattice QCD



Unquenched Lattice QCD

Gluons and light quarks

String breaking

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Outline o String Breaking

Introductior

Diabatic Approach

Results

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The Quark-Antiquark–Meson-Meson Mixing Potential



Gaussian parametrization

$$|V_{\mathsf{mix}}(r)| = \frac{\Delta}{2} e^{-\frac{(V_{Q\overline{Q}}(r) - T_{M\overline{M}})^2}{2\Lambda^2}}$$

Δ: mixing strength
Λ: mixing width

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Mixing Effects on the Quarkoniumlike Spectrum

Above threshold

- Meson states acquire decay width.
- Quarkonium masses are shifted.

Below threshold

- Meson states acquire molecular components.
- Unconventional mesons may appear near threshold.

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Unified description above and below threshold

Appearance of unconventional mesons and resonance decays are described by the same mixing potential.

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Bottomoniumlike Mesons

Bottomoniumlike Spectrum





From Lattice QCD $\Delta \approx 50$ MeV

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 Relatively small threshold effects

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Bottomoniumlike Mesons

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Strong Decay Widths of Bottomoniumlike States

J ^{PC}	М	$\Gamma_{B\overline{B}}$	$\Gamma_{B\overline{B}^*}$	$\Gamma_{B^*\overline{B}^*}$	$\Gamma_{B_s\overline{B}_s}$	Γ^{Theor}_{total}	Γ_{total}^{Expt}
0++	10785.8	1.6		5.3	0.7	7.6	
1^{++}	10778.9		0.2	1.7		1.9	
2++	10588.4	4.3				4.3	
2++	10782.3	5.4	1.5	21.0	10.4	38.3	
$1^{}$	10599.8	21.9				21.9	20.5 ± 2.5
$1^{}$	10697.0	2.0	1.0	38.0		41.0	

Masses and widths in MeV units

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Outline	
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Introduction

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Charmoniumlike Spectrum





- Fitting χ_{c1}(3872)
 Δ ≈ 130 MeV
- More prominent threshold effects

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Strong Decay Widths of Charmoniumlike States

J ^{PC}	М	$\Gamma_{D\overline{D}}$	$\Gamma_{D\overline{D}^*}$	$\Gamma_{D_s\overline{D}_s}$	Γ^{Theor}_{total}	Γ_{total}^{Expt}
0++	3920.9	0.6			0.6	
2++	3881.1	49.5	0.4		49.9	$\textbf{35.3} \pm \textbf{2.8}$
2++	4003.9	4.8	6.3	3.5	14.5	
$1^{}$	3771.7	20.2			20.2	27.2 ± 1.0

Masses and widths in MeV units

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Outline o Charmoniumlike Mesons

Introduction

Diabatic Approach

Results ○○○○●○○

Diabatic Wave Function of $\chi_{c1}(3872)$



about 3% of $c\overline{c}$ about 97% of $D\overline{D}^*$ $\sqrt{\langle r^2 \rangle} \approx 11 \text{ fm}$

Diabatic $\chi_{c1}(3872)$

It can be described as a $D\overline{D}^*$ molecule created by the mixing between $D\overline{D}^*$ and $c\overline{c}$.

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Outline 0	Introduction 0000000	Diabatic Approach 00000	Results ○○○○●○
Summary and References			

Summary

- The Born-Oppenheimer approximation gives a description of quarkonium firmly based on Lattice QCD.
- The diabatic framework allows to include open-flavor mesons and string breaking into this description nonperturbatively.
- The diabatic potential matrix, calculable from Lattice QCD, can give account of the spectrum as well as strong decays of quarkoniumlike mesons.

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Outline	Introduction	Diabatic Approach	Results
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Summary and References			

For Further Reading

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