Department of Physics, The Ohio State University

Exotic Heavy Mesons and Lattice QCD Potentials

Roberto Bruschini
bruschini.1@osu.edu

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Outline

1. Why QCD Phenomenology?
2. Born-Oppenheimer Approximation
3. Practical Applications

WHY QCD PHENOMENOLOGY?

QCD at low energies is extremely complicated

- Perturbation theory cannot calculate the hadron spectrum.
- Color confinement is poorly understood (analytically).

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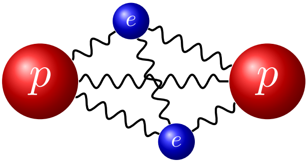
Lattice QCD

One can study numerical simulations of QCD on a lattice.

BORN-OPPENHEIMER APPROXIMATION

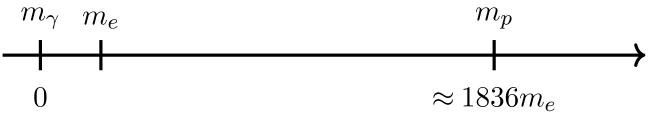


Heavy degrees of freedom

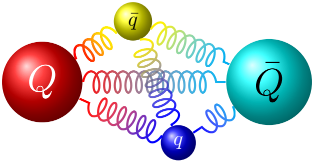
- nuclei

Light fields

- photons
- electrons



Born-Oppenheimer Approx. for QCD

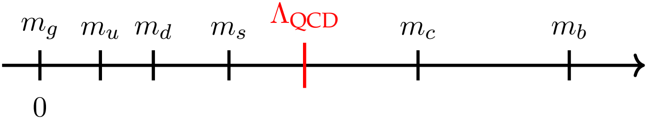


Heavy degrees of freedom

- heavy quarks

Light fields

- gluons
- light quarks

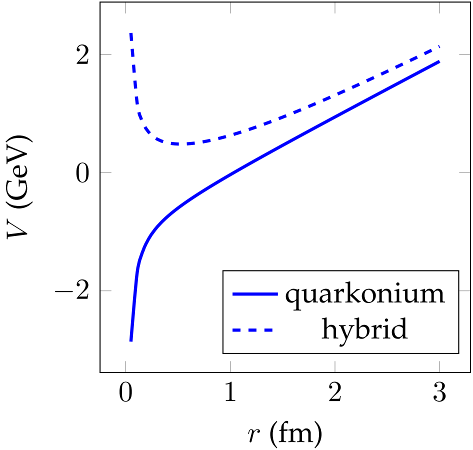


The sharp difference between the energy scales involved allows to separately solve the physics of the heavy and light fields:

1. The energy levels for the light fields with static quarks at distance r, $V_i(r)$, are calculated in lattice QCD.
2. The motion of the heavy quarks is calculated from a Schrödinger equation with $V_i(r)$ as potential.

Watch out for avoided crossings!

If some energy levels show mixing, one has to include also coupling terms between the corresponding channels.



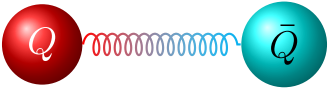
Juge, Kuti, and Morningstar 1999; Bali 2001

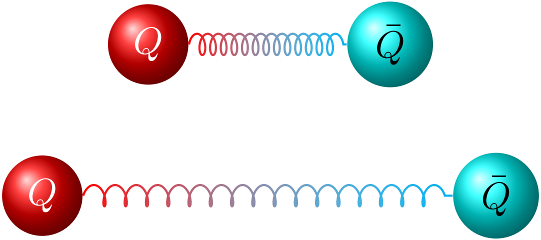
Excited states

Hybrid potentials

Ground state

Quarkonium potential


Q
$\bar{Q}$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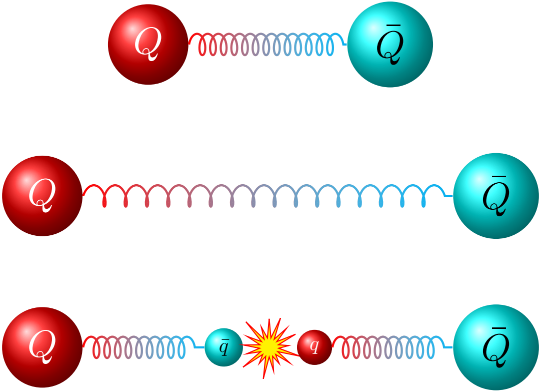
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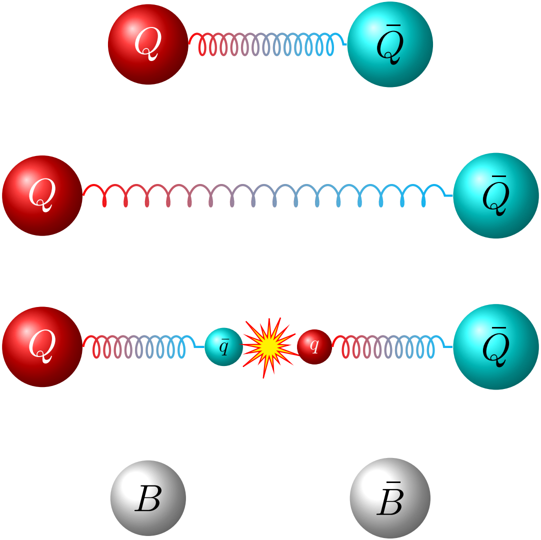
Q
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Q
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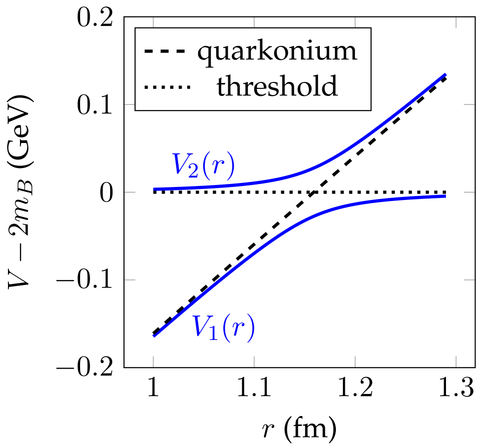
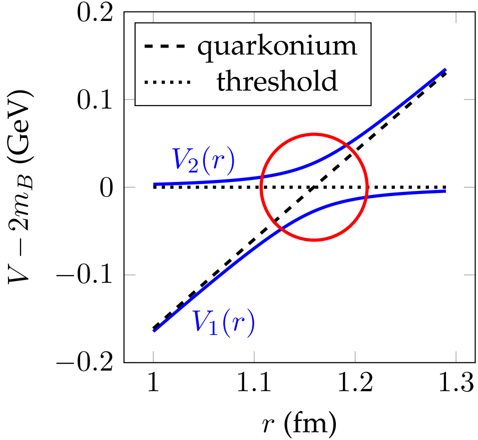
q
$\bar{Q}$
B
$\bar{B}$



Bali et al. 2005; Bulava et al. 2019

Open-flavor threshold

Minimum energy for the production of an open-flavor meson pair



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Open-flavor threshold

Minimum energy for the production of an open-flavor meson pair

Avoided crossing

$Q\bar{Q}$ and $B\bar{B}$ mix through string breaking.

$$\sum_{i',\sigma'}\left(-\delta_{i,i'}\delta_{\sigma,\sigma'}\frac{\nabla^2}{m_Q}+\mathrm{V}_{i,i'}^{\eta,\sigma,\sigma'}(\vec{r})\right)\Psi_{i'}^{\eta,\sigma'}(\vec{r})=E\Psi_{i}^{\eta,\sigma}(\vec{r})$$

Diabatic channels with total spin s and projection σ

$$\Psi_i^{\eta,\sigma}(\vec{r})\rightarrow\Psi_{Q\bar{Q}(s)}^{\eta,\sigma}(\vec{r}),\Psi_{B\bar{B}(s)}^{\eta,\sigma}(\vec{r})$$

Diabatic potential matrix

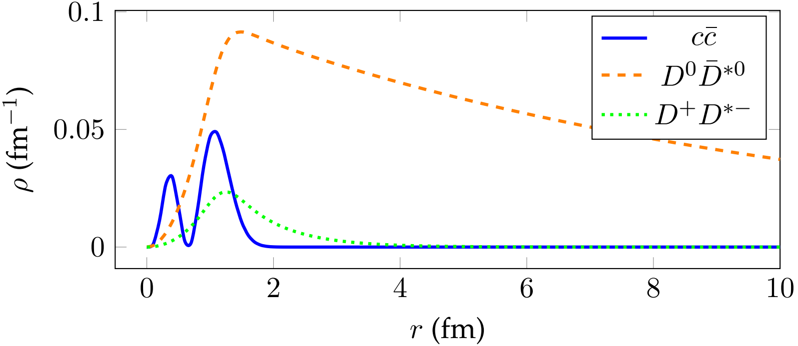
$$\mathrm{V}_{i,i'}^{\eta,\sigma,\sigma'}(\vec{r})=\sum_{\lambda}D_{\sigma,\lambda}^{s_i}(\varphi,\theta,\psi)D_{\sigma',\lambda}^{s_{i'}}(\varphi,\theta,\psi)^{*}\mathrm{G}_{i,i'}^{\eta,\lambda}(r)$$

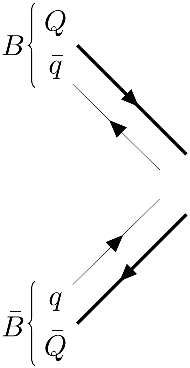
PRACTICAL APPLICATIONS

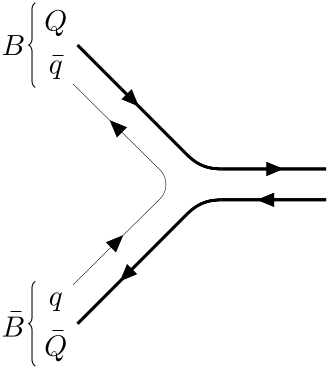
Phenomenological study of exotic heavy mesons

The potential matrix for $J^{PC} = 1^{++}$ can be fine tuned so there is a bound state just below the $D^0 \bar{D}^{*0}$ threshold.

Calculated radial probability density $\rho(r)$ for $X(3872)$:




B
Q
$\bar{q}$
$\bar{B}$
q
$\bar{Q}$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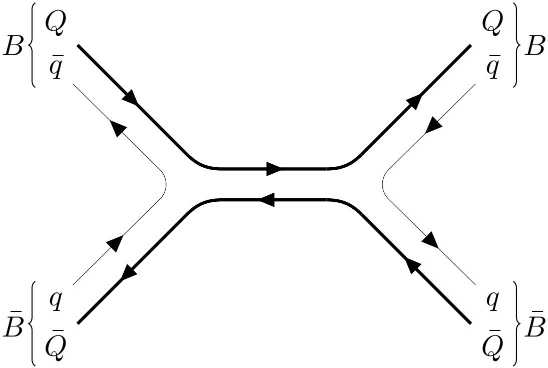
$\bar{Q}$


B
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q
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q
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SUMMARY

Summary

- QCD is an extremely complicated theory with a rich and fascinating phenomenology.
- Some experimentally observed particles challenge even our most basic understanding of strong interactions.
- The spectrum of exotic heavy mesons can be studied using potentials calculated in lattice simulations of QCD.

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