Department of Physics, The Ohio State University

Quarkonia and Molecules from QCD Potentials

Mesons with String Breaking and Mass Splittings

Roberto Bruschini
bruschini.1@osu.edu

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Accessing and Understanding the QCD Spectra
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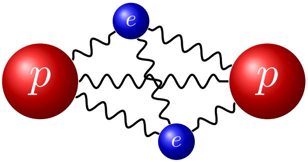
Outline

1. Born-Oppenheimer Approximation
2. String Breaking
3. Diabatic Approach
4. Practical Applications

BORN-OPPENHEIMER APPROXIMATION

BO Approximation in QED

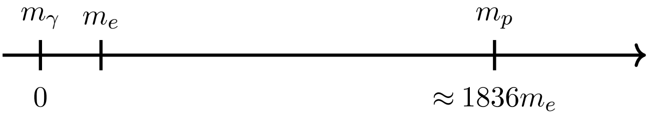


Heavy degrees of freedom

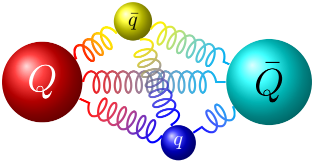
- nuclei

Light fields

- photons
- electrons



BO Approximation in QCD

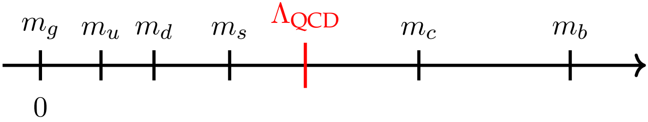


Heavy degrees of freedom

- 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.

The presence of two static quarks breaks the symmetries of QCD:

- rotations;
- parity;
- charge-conjugation parity;

down to:

- cylindrical symmetry;
- combined CP symmetry.

The quantum numbers are not

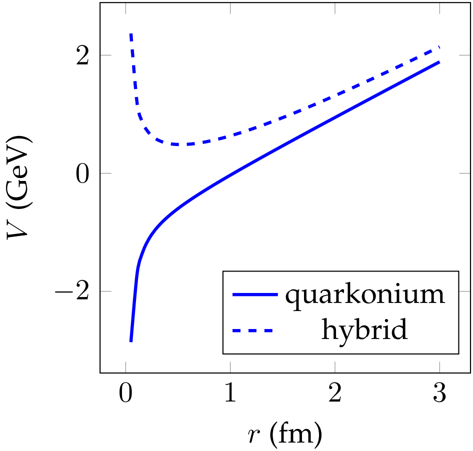
- J total angular momentum;
- P parity;
- C charge-conjugation;

but rather

- λ angular momentum projection on the $Q\bar{Q}$ axis;
- η g or u for positive or negative CP, respectively.

Heavy-Quark Spin Symmetry

The potentials are independent of the spin of the static quarks.



Juge, Kuti, and Morningstar 1999; Bali 2001

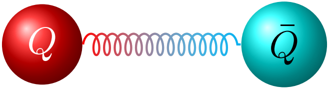
Excited states

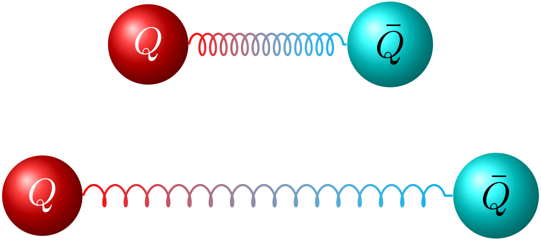
Hybrid potentials

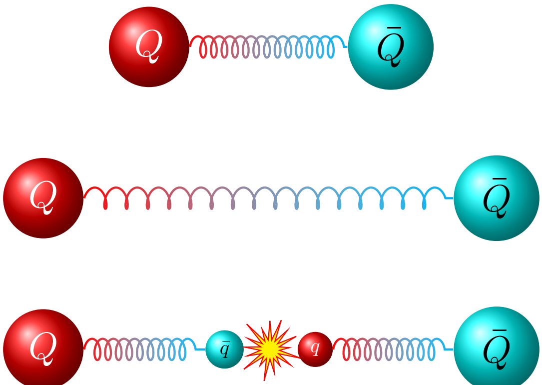
Ground state

Quarkonium potential

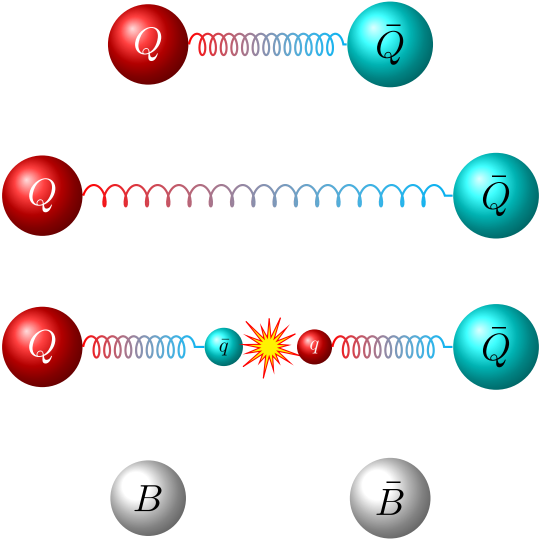
STRING BREAKING

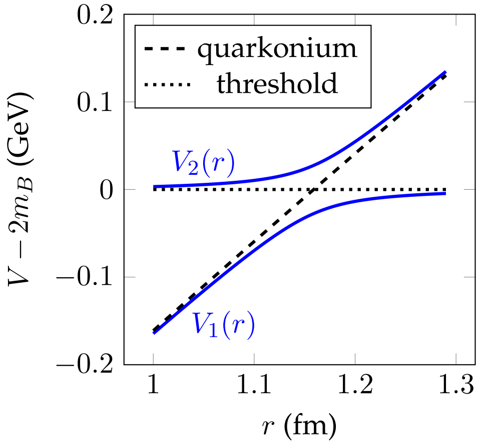

Q
$\bar{Q}$


Q
$\bar{Q}$
Q
$\bar{Q}$



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

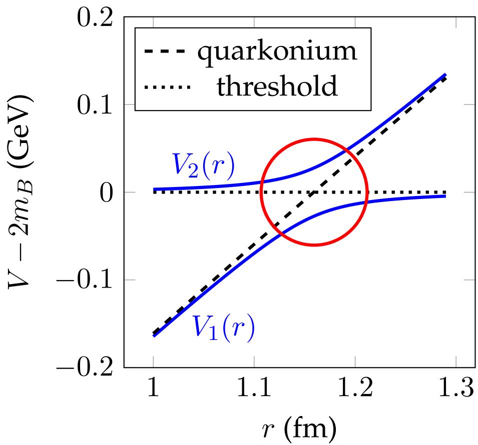

Q
$\bar{Q}$
Q
$\bar{Q}$
Q
$\bar{q}$
q
$\bar{Q}$
B
$\bar{B}$



Bali et al. 2005; Bulava et al. 2019

Open-flavor threshold

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



Bali et al. 2005; Bulava et al. 2019

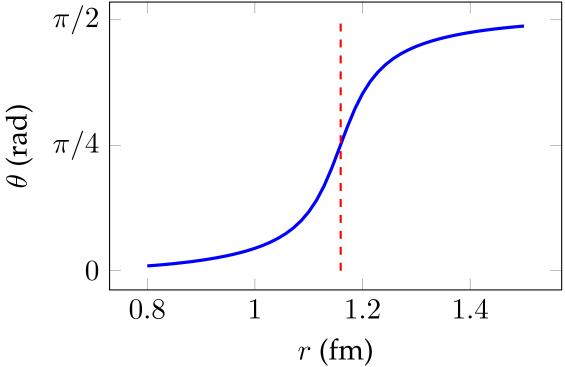
Open-flavor threshold

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

Avoided crossing

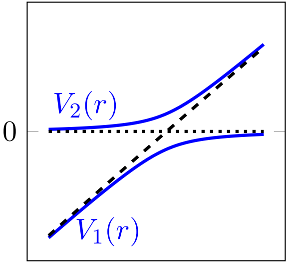
$Q\bar{Q}$ and $B\bar{B}$ mix through string breaking.

$$|\zeta_1(r)\rangle = \cos\theta(r)\,|Q\bar{Q}\rangle + \sin\theta(r)\,|B\bar{B}\rangle$$
$$|\zeta_2(r)\rangle = -\sin\theta(r)\,|Q\bar{Q}\rangle + \cos\theta(r)\,|B\bar{B}\rangle$$



Bali et al. 2005

Static potentials of mixed $Q\bar{Q}$-$B\bar{B}$ channels can be seen as eigenvalues of an interaction matrix between pure $Q\bar{Q}$ and $B\bar{B}$.



$$\longleftrightarrow \begin{pmatrix} V_{\mathcal{Q}}(r) & g(r) \\ g(r) & 0 \end{pmatrix} = \mathbf{G}(r)$$

$V_{\mathcal{Q}}(r)$ is the quarkonium potential;

$g(r)$ is the string-breaking rate from lattice QCD;

0 is the static-meson pair threshold (by definition).

Why?

The physical mass difference Δ between B and B^* mesons breaks heavy-quark spin symmetry. This effect is particularly important for molecular states.

Correcting the static potentials

1. The string-breaking rate $g(r)$ splits into different transition rates for the $B\bar{B}$, $B\bar{B}^* \pm B^*\bar{B}$, and $B^*\bar{B}^*$ channels with coefficients determined by Dirac algebra.
2. A factor of Δ or 2Δ is added to the threshold energies of the $B\bar{B}^* \pm B^*\bar{B}$ or $B^*\bar{B}^*$ channels.

The interaction matrix depends on the $Q\bar{Q}$ spin state

Q and $\bar{Q}$ have two spin states each, so there are four different interaction matrices $\mathbf{G}^{\eta,\lambda}(r)$ in total:

3 $\eta = g$ ($CP = +$, $Q\bar{Q}$ spin $s = 1$) and projection $\lambda = -1, 0, +1$;

1 $\eta = u$ ($CP = -$, $Q\bar{Q}$ spin $s = 0$) and projection $\lambda = 0$.

Interaction matrix with $\eta = u$ and $\lambda = 0$

$$\mathbf{G}^{u,0}(r) = \begin{pmatrix} V_Q(r) & \frac{1}{\sqrt{2}}g(r) & \frac{1}{\sqrt{2}}g(r) \\ \frac{1}{\sqrt{2}}g(r) & \Delta & 0 \\ \frac{1}{\sqrt{2}}g(r) & 0 & 2\Delta \end{pmatrix}$$

DIABATIC APPROACH

Why not use the interaction matrices as potentials?

The interaction matrices $\mathbf{G}^{\eta,\lambda}(r)$ are not the multichannel BO potentials. The precise relation between them depends on the particular representation of BO.

Coupled channels in BO can be treated in two representations:

Adiabatic

- mixed $Q\bar{Q}$ and di-meson channels
- derivative couplings

Diabatic

- pure $Q\bar{Q}$ and di-meson channels
- no derivative couplings

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

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

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

In the static limit, the total angular momentum is

$$\vec{J}_{\text{static}} = \vec{S} + \vec{J}_{\text{light}}$$

with:

$\vec{S}$ the total spin of the static sources;

$\vec{J}_{\text{light}}$ the total angular momentum of the light fields.

Static sources separated by $\vec{r}$ break rotational symmetry

J^2_{static} is not conserved. Only the projection $\vec{J}_{\text{static}} \cdot \hat{r}$ is.

For quarkonium mixing with di-meson configurations

$$\vec{J}_{\text{light}} = 0, \qquad \text{so} \qquad \vec{J}_{\text{static}} = \vec{S}$$

When the orbital angular momentum $\vec{L}$ is introduced, the total angular momentum is

$$\vec{J} = \vec{L} + \vec{S}$$

The eigenvalues l of L^2 and s of S^2 may be different for each channel, but it can be checked that J^2 and $\vec{J} \cdot \hat{z}$ are the same.

Reintroducing the motion restores rotational symmetry

With the introduction of orbital angular momentum, one can use angular momentum algebra to derive exact total angular momentum conservation from the diabatic potential matrix.

The spectrum consists of states with definite J^{PC}.

PRACTICAL APPLICATIONS

In practice, for any given J^{PC} configuration, the spectrum is calculated from a radial potential matrix with elements

$$\mathrm{V}_{i,i',l,l'}^{J^{PC}}(r) = \delta_{i,i'}\delta_{l,l'}\frac{l(l+1)}{2\mu_i r^2} + \mathrm{V}_{i,i',l,l'}^{\eta,J}(r).$$

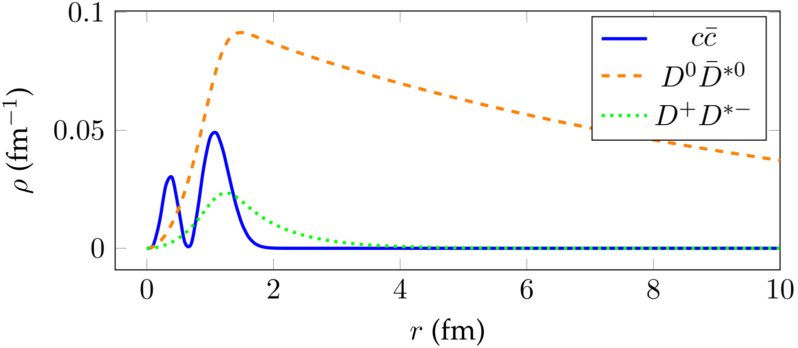
Potential matrix for $J^{PC} = 0^{-+}$

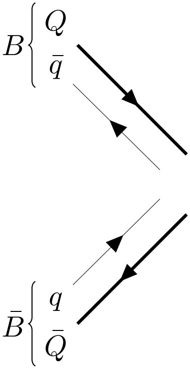
$$\mathbf{V}^{0^{-+}}(r) = \begin{pmatrix} V_{\mathcal{Q}}(r) & -\frac{1}{\sqrt{2}}g(r) & -\frac{1}{\sqrt{2}}g(r) \\ -\frac{1}{\sqrt{2}}g(r) & \frac{1}{\mu_{B\bar{B}^*}r^2}+\Delta & 0 \\ -\frac{1}{\sqrt{2}}g(r) & 0 & \frac{1}{\mu_{B^*\bar{B}^*}r^2}+2\Delta \end{pmatrix}$$

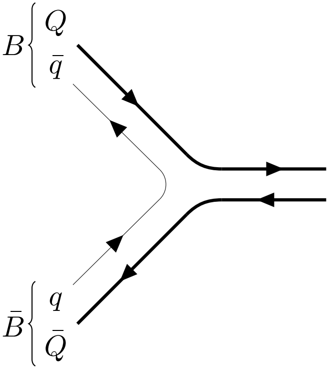
Phenomenological study of $X(3872)$

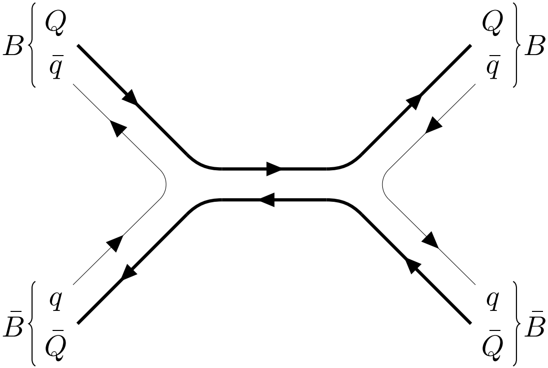
The potential matrix for $J^{PC} = 1^{++}$ can be fine tuned so there is a bound state just below the $D^0 \bar{D}^{*0}$ threshold.

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




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


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


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

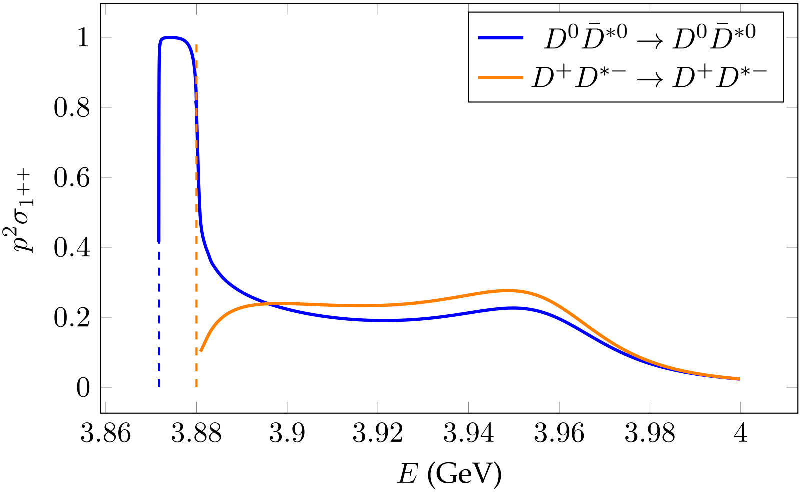
SUMMARY

Conclusion

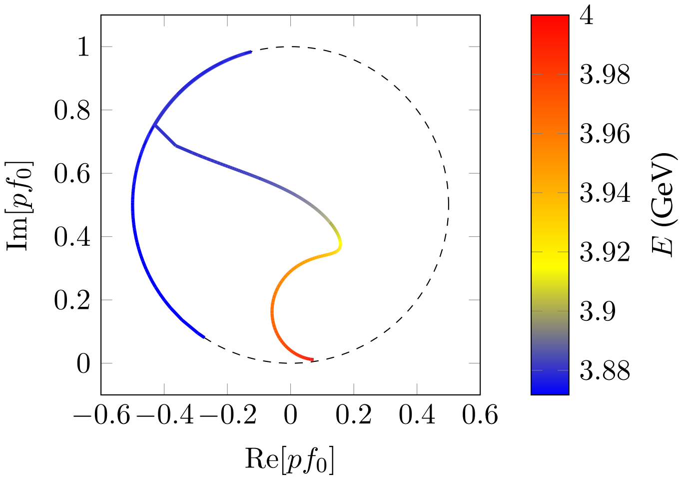
The spectrum of quarkonia and molecules can be studied *ab initio* using QCD potentials with string breaking.

- The potentials can be directly calculated in lattice QCD with static quark-antiquark and di-meson sources.
- Heavy-quark spin symmetry breaking from meson mass splittings can be consistently taken into account in lattice-QCD potentials.
- Adding orbital angular momentum within the diabatic BO framework ensures exact conservation of total angular momentum.

APPENDIX


$D^0\bar{D}^{*0} \to D^0\bar{D}^{*0}$
$D^+D^{*-} \to D^+D^{*-}$
$p^2\sigma_{1^{++}}$
1
0.8
0.6
0.4
0.2
0
3.86
3.88
3.9
3.92
3.94
3.96
3.98
4
E (GeV)

S-Wave $D^0\bar{D}^{*0} \to D^0\bar{D}^{*0}$ Argand Diagram



G. S. Bali (2001). "QCD forces and heavy quark bound states." In: *Phys. Rep.* 343.1, pp. 1–136. ISSN: 0370-1573.

G. S. Bali et al. (2005). "Observation of string breaking in QCD." In: *Phys. Rev. D* 71 (11), p. 114513.

R. Bruschini and P. González (2020). "Diabatic description of charmoniumlike mesons." In: *Phys. Rev. D* 102 (7), p. 074002.

— (2021). "Coupled-channel meson-meson scattering in the diabatic framework." In: *Phys. Rev. D* 104 (7), p. 074025.

— (2022). "Is $\chi_{c1}(3872)$ generated from string breaking?" In: *Phys. Rev. D* 105 (5), p. 054028.

— (2023). "$\chi_{c1}(2p)$: an overshadowed charmoniumlike resonance." In: *JHEP* 02, p. 216.

J. Bulava et al. (2019). "String breaking by light and strange quarks in QCD." In: *Phys. Lett. B* 793, pp. 493–498. ISSN: 0370-2693.

K. J. Juge, J. Kuti, and C. J. Morningstar (1999). "Ab Initio Study of Hybrid $\bar{b}gb$ Mesons." In: *Phys. Rev. Lett.* 82 (22), pp. 4400–4403.