Decays of Exotic Hidden-Heavy Hadrons into Pairs of Heavy Hadrons

(arXiv:2403.12868)

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EXOHAD
EXOTIC HADRONS TOPICAL COLLABORATION

Outline

The Dilemma of Exotic Hadrons

- For a long time, it was believed that every hadron is either:
  - a quark-antiquark meson;
  - a 3-quark baryon.

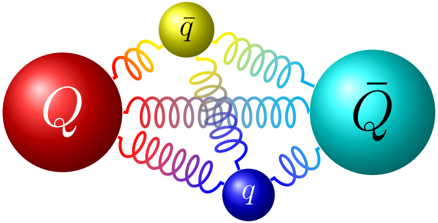
- Dozens of exotic hadrons with additional constituents have been discovered in the last 20 years.

- Among them are several hidden-heavy tetraquarks:
  - 44 $c\bar{c}$ tetraquarks;
  - 5 $b\bar{b}$ tetraquarks.

- No theoretical scheme has yet unveiled their general pattern.

The Born-Oppenheimer Approximation for QCD

Juge, Kuti & Morningstar (hep-ph/9902336)

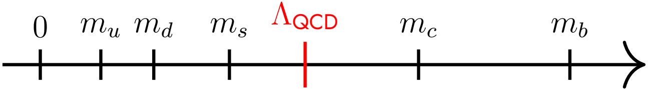


Light-QCD fields

Adjust instantaneously to the motion of the heavy (anti)quarks.

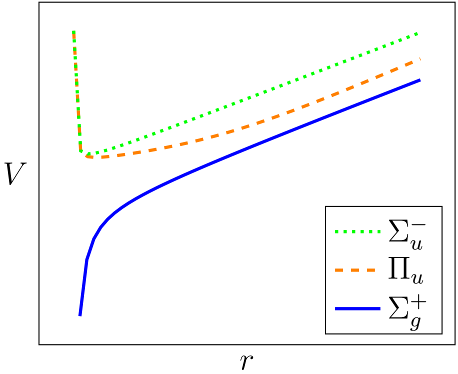
Heavy quark and antiquark

Move in potentials given by QCD with static color sources.



Born-Oppenheimer Potentials for Hidden-Heavy Hadrons

Juge, Kuti & Morningstar (hep-lat/0207004)
Capitani, Philipsen, Reisinger, Riehl & Wagner (1811.11046); Schlosser & Wagner (2111.00741)
Bicudo, Cardoso & Sharifian (2105.12159); Sharifian, Cardoso & Bicudo (2303.15152)



Π_u, Σ_u^-: hybrid potentials

- $r \to 0$: 1^{+-} gluelump
- $r \to \infty$: $N = 1, 3$ string

Σ_g^+: quarkonium potential

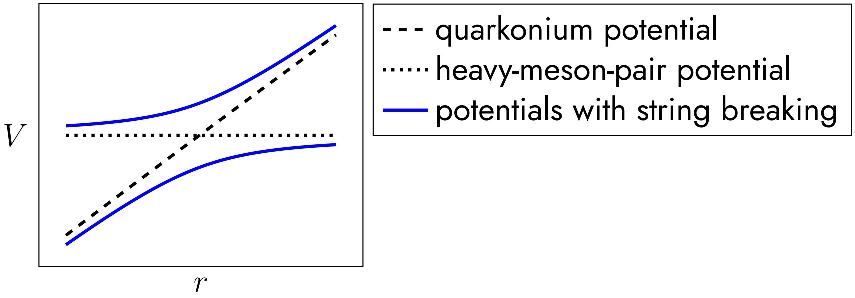
- $r \to 0$: 0^{++} vacuum
- $r \to \infty$: $N = 0$ string

Hadron-Pair Potentials and Mixing

Bali, Neff, Düssel, Lippert & Schilling (hep-lat/0505012)
Bulava, Hörz, Knechtli, Koch, Moir, Morningstar & Peardon (1902.04006)

Born-Oppenheimer potentials for heavy-hadron pairs

- constant at large distances (threshold)
- mix with potentials for hidden-heavy hadrons $\rightarrow$ decays!



Decays and Selection Rules

$g_{\lambda,\eta}$ transition rates between Born-Oppenheimer potentials

$G_{L,\eta}$ mixing potentials used to calculate decays through a Schrödinger equation

$$G_{L,\eta}\big(j^\pi, L_Q \to (j_1^{\pi_1}, j_2^{\pi_2})j', L_Q'\big) = (-1)^{L_Q+L_Q'} \times \sum_\lambda \left\langle \begin{matrix} j & L \\ \lambda & -\lambda \end{matrix} \middle| \begin{matrix} L_Q \\ 0 \end{matrix} \right\rangle \left\langle \begin{matrix} j' & L \\ \lambda & -\lambda \end{matrix} \middle| \begin{matrix} L_Q' \\ 0 \end{matrix} \right\rangle g_{\lambda,\eta}\big(j^\pi \to (j_1^{\pi_1}, j_2^{\pi_2})j'\big)$$

Model-independent selection rules

- conservation of Born-Oppenheimer quantum numbers λ and η
- conservation of angular-momentum vector $\vec{L} = \vec{J}_{\text{light}} + \vec{L}_Q$

Heavy Spins and Relative Partial Decay Rates

$G_{L,\eta}$ mixing potentials without heavy spins

$V^J_{S_Q,L,\eta}$ mixing potentials including heavy spins

$$V^J_{S_Q,L,\eta}\Big(j^\pi, L_Q \to \big[\big(\tfrac{1}{2}^+, j_1^{\pi_1}\big)J_1, \big(\tfrac{1}{2}^-, j_2^{\pi_2}\big)J_2\big]S, L'_Q\Big) =$$

$$N(-1)^{2j_1+S_Q+L'_Q+J}\sqrt{\tilde{J}_1\tilde{J}_2\tilde{S}\tilde{S}_Q\tilde{L}}$$

$$\times \sum_{j'}(-1)^{j'}\sqrt{\tilde{j}'}\begin{Bmatrix} S_Q & j' & S \\ L'_Q & J & L \end{Bmatrix}\begin{Bmatrix} \frac{1}{2} & \frac{1}{2} & S_Q \\ j_1 & j_2 & j' \\ J_1 & J_2 & S \end{Bmatrix}$$

$$\times G_{L,\eta}\big(j^\pi, L_Q \to (j_1^{\pi_1}, j_2^{\pi_2})j', L'_Q\big)$$

- ratios of mixing potentials $\to$ relative partial decay rates

Conventional vs. Exotic: Selection Rules

Quarkonium decays into $B\bar{B}$, $B^*\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$

- only 1 Born-Oppenheimer potential Σ_g^+
- allowed
- agreement with constituent models

Hybrid decays into $B\bar{B}$, $B^*\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$

- 2 different Born-Oppenheimer potentials Π_u and Σ_u^-
- forbidden for states in the Π_u potential
- allowed for states in the Σ_u^- potential and in coupled Π_u/Σ_u^- potentials
- disagreement with constituent models

Conventional vs. Exotic: Branching Ratios

Quarkonia with $J^{PC} = 1^{--}$

- $B\bar{B} : B^*\bar{B} : B\bar{B}^* : B^*\bar{B}^* = 1 : 2 : 2 : 7$
- agreement with constituent models

Hybrids with $J^{PC} = 1^{--}$

- $B\bar{B} : B^*\bar{B} : B\bar{B}^* : B^*\bar{B}^* = 1 : 0 : 0 : 3$
- disagreement with constituent models

Summary

- The pattern of hidden-heavy exotic hadrons has remained a mystery for the last 20 years!
- The Born-Oppenheimer approximation gives model-independent results for:
  - selection rules for decays into heavy-hadron pairs;
  - relative partial decay rates into heavy-hadron pairs.
- For quarkonia, these results agree with constituent models (in simple cases).
- For hybrids, these results disagree with constituent models!