$\bar{b}\bar{b}ud$ four-quark systems in the Born-Oppenheimer approximation: prospects and challenges

Antje Peters[1] Pedro Bicudo[2] Marc Wagner[1]

[1]Goethe-Universität Frankfurt am Main, Institut für Theoretische Physik, Max-von-Laue-Straße 1, D-60438 Frankfurt am Main, Germany
[2]CFTP, Dep. Física, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

peters@th.physik.uni-frankfurt.de

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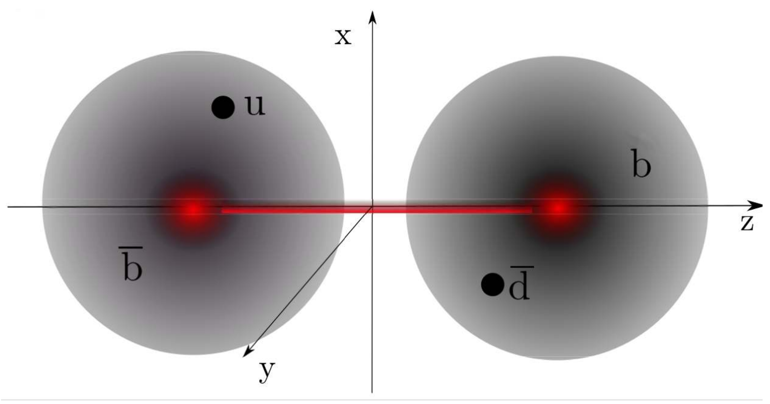
Motivation

A number of mesons observed in experiment, e.g. at the LHCb or at Belle, lack a satisfactory theoretical description. Examples are the charged states $Z_b(10610)$ and $Z_b(10650)$. They are bottomonium-like, which can be concluded from their masses and decay products. However, they also carry electric charge, which means they must include additional quarks. It is most likely that these additional quarks are a light quark-antiquark pair. So the quark content of the Z_b states is assumed to be $b\bar{b}u\bar{d}/b\bar{b}d\bar{u}$.

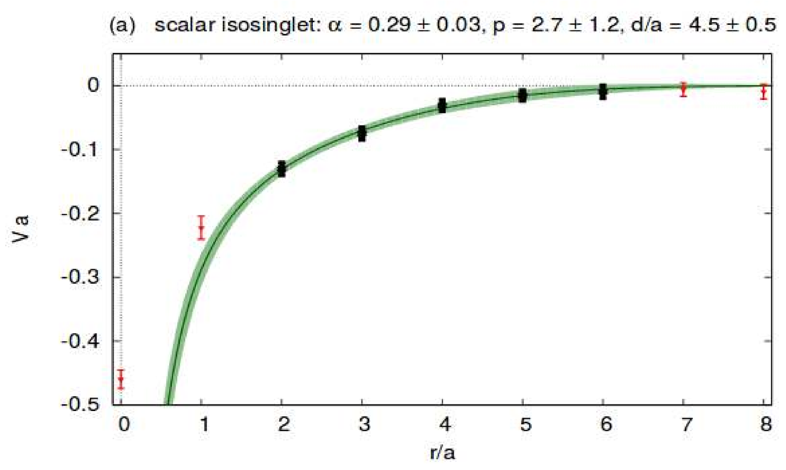
Four-quark states in the static-light approximation

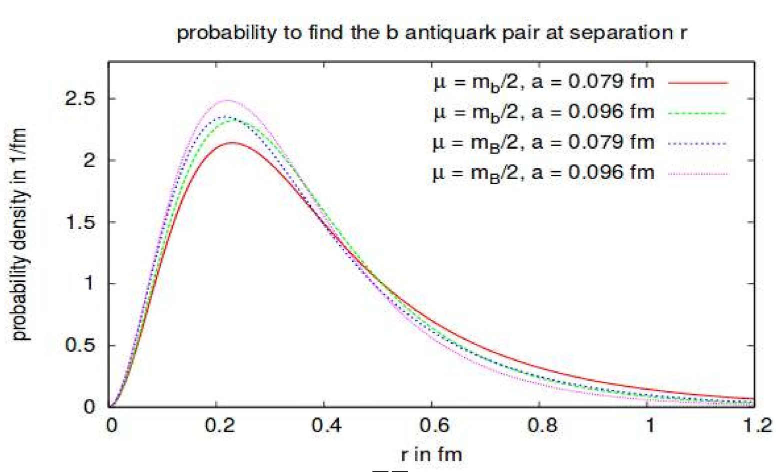


To investigate binding of a four-quark state, we work in the Born-Oppenheimer approximation:

- b quarks static $\Rightarrow$ heavy quark spin decouples from system
- u/d quarks fully dynamic
- Compute potentials of the b quarks in the presence of the u, d quarks; many different parity/angular momentum channels.
- For large separations between b quarks: BB potentials resp. $B\bar{B}$ potentials.
- Insert potential into Schrödinger equation and check for bound state or resonance.

$\bar{b}\bar{b}ud$ (BB) systems in the static-light approximation





The investigation of four-quark systems with two static antiquarks $\bar{b}\bar{b}$ and light quarks ud predicts two tetraquark states that have not yet been measured experimentally:

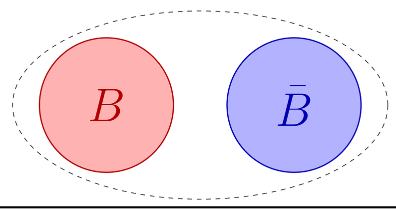
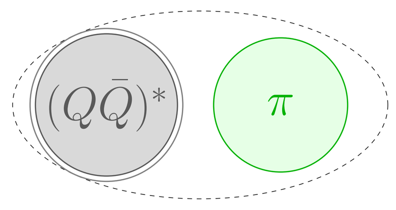
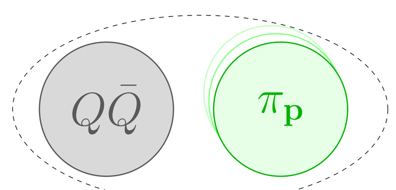
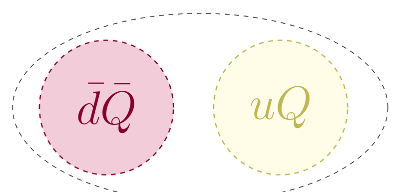
- $\bar{b}\bar{b}ud$ bound state in the $I(J^P) = 0(1^+)$ channel with binding energy $E_B = -90^{+43}_{-36}$ MeV*, taking into account heavy quark spin effects: $E_B = -59^{+30}_{-38}$ MeV*
- resonance in the $I(J^P) = 0(1^-)$ channel: $E_R = 17^{+4}_{-4}$ MeV**, $\Gamma = 112^{+90}_{-103}$ MeV

For more details, cf. talk by Pedro Bicudo, June 23 at 17:10.

* with respect to the $m_B + m_{B^*}$ threshold

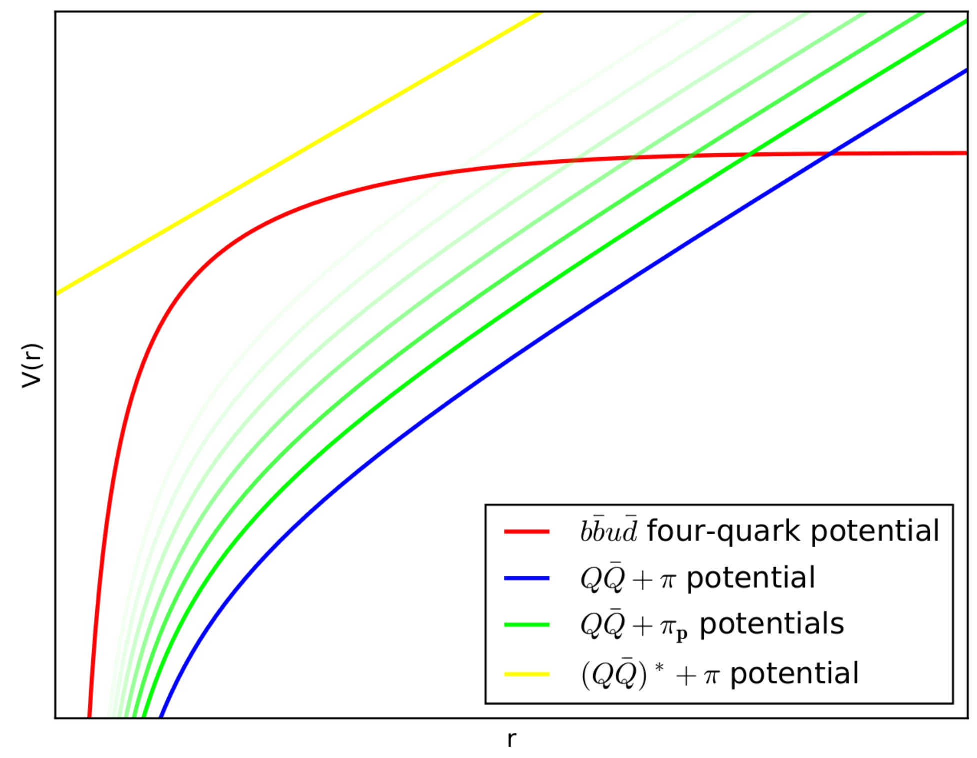
** with respect to the $2m_B$ threshold

Possible structures of a $\bar{b}\bar{b}ud$ state

label	description	sketch
$B\bar{B}$ four-quark or two-particle state	A bound four-quark state made of a loosely bound $B\bar{B}$ meson pair (a so-called mesonic molecule) or two far separated and essentially non interacting B mesons.	
$(Q\bar{Q})^*\pi$ four-quark or two-particle state	A bound four-quark state made of an excited bottomonium state and a loosely bound pion π^+ with zero momentum or two far separated and essentially non-interacting mesons.	
$Q\bar{Q}\pi_\mathbf{p}$ four-quark or two-particle state	A bound four-quark state made of a bottomonium state and a loosely bound pion π^+ with momentum $\mathbf{p}$ or two far separated and essentially non-interacting mesons.	
four-quark state	A bound four-quark state made of a diquark (color antitriplett) and an anti-diquark (color triplett).	

If the $\bar{b}\bar{b}ud$ system turns out to be a bound four-quark $\bar{b}\bar{b}ud$ state, an exotic hadron, a so-called tetraquark, is confirmed.

$b\bar{b}u\bar{d}$ spectrum: Possible scenario



Cartoon-like illustration of the $b\bar{b}u\bar{d}$ spectrum. blue: Potential of the bottomonium ground state and a pion at rest, $Q\bar{Q} + \pi$. green: Green curves indicate $Q\bar{Q} + \pi_\mathbf{p}$ potentials for different momenta $\mathbf{p}$. red: $b\bar{b}u\bar{d}$ four-quark potential. yellow: Potential of the excited bottomonium state and a pion at rest, $(Q\bar{Q})^* + \pi$.

First step: investigate $b\bar{b}u\bar{d}$ ground state and first excited state in the $I(J^P) = 1(1^+)$ channel

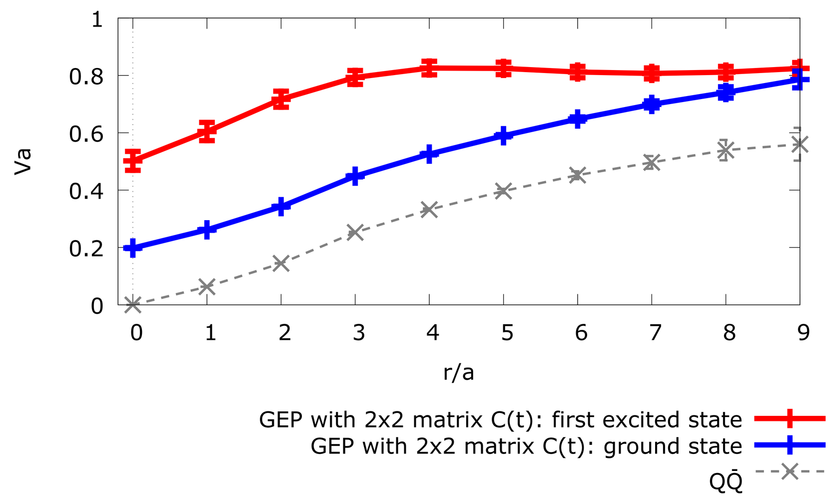
For a start we investigate the first excited $b\bar{b}u\bar{d}$ state by considering the $Q\bar{Q}+\pi$ (respectively $Q\bar{Q}\pi$) state and the $B\bar{B}$ (respectively $B+\bar{B}$) state explicitly. The aim is to check whether the $B\bar{B}$ potential is still attractive enough to host a bound state if contributions from the $Q\bar{Q}+\pi$ state have been removed.
We build the correlation matrix :

$$C_{jk}(t,r) = \langle\Omega|\, O_j^\dagger(t) O_k(0)\,|\Omega\rangle \underset{t\to\infty}{=} A^0_{jk}\exp(-V_0(r)t) + A^1_{jk}\exp(-V_1(r)t) + \ldots$$

with

$$O_1(t) = O_{B\bar{B}} = \Gamma_{AB}\tilde{\Gamma}_{CD}\bar{Q}^a_C(\mathbf{x},t)q^a_A(\mathbf{x},t)\bar{q}^b_B(\mathbf{y},t)Q^b_D(\mathbf{y},t)$$
$$O_2(t) = O_{Q\bar{Q}+\pi} = \bar{Q}^a_A(\mathbf{x},t)U^{ab}(\mathbf{x},t;\mathbf{y},t)\tilde{\Gamma}_{AB}Q^b_B(\mathbf{y})\sum_{\mathbf{z}}\bar{q}^c_C(\mathbf{z},t)\,(\gamma_5)_{CD}\,q^c_D(\mathbf{z},t)$$

- We determine first excited state potential with the GEP.
- Solving the Schrödinger equation yields a binding energy of
$$E_B = (-58 \pm 71)\text{ MeV}^*$$
- Vague indication of a tetraquark state.



Further investigation of the first excited $b\bar{b}u\bar{d}$ state

We plan to investigate the structure of the first excited state $|1\rangle$.
To this end, we compute the overlap of four-quark resp. two-particle trial states and $|1\rangle$.

$|1\rangle$ is a... / overlap with...	two-particle trial state	four-quark trial state
four-quark state	$\sim \frac{1}{\sqrt{V_s}}$	no volume dependence
two-particle state	no volume dependence	$\frac{1}{\sqrt{V_s}}$

- Volume dependence of the overlap gives evidence of the first excited $b\bar{b}u\bar{d}$ state to be a two-particle state or a four-quark state (tetraquark).
- More detailed information can be obtained by implementing further operators.

References

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