Double-charm spectroscopy

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Based on recent work with J. Vijande, A. Valcarce,
E. Hiyama, M. Oka & A. Hosaka,
older work with J.P. Ader, P. Taxil, S. Zouzou, J.L. Ballot, S. Fleck,
C. Gignoux, B. Silvestre-Brac, Fl. Stancu, M. Genovese,
Cafer Ay, & Hyam Rubinstein,

Introduction

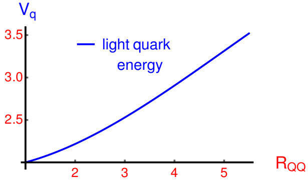
- After years of (interesting) $Q\bar{Q}$ physics
- More attention now on the $QQ\ldots$ sector
- Some milestones
  - 1970 GIM
  - 1974 October revolution
  - 1974-75 Gaillard, Lee and Rosner
  - 1977 Upsilon discovery and French's baryonium
  - 1981 $QQ\bar{q}\bar{q}$ becomes stable in the large M/m limit (ART)
  - 1988 First serious quark model of QQq
  - 2002 Double-charmonium production in e^+e^-
  - 2002-2005 Ξ_{cc} seen by SELEX in two decay modes
  - 2002 COMPASS Workshop at CERN, Cooper, Moinester, R. insist on double charm
  - 2003 $X(3872)$
  - 2017 Ξ_{cc}^{++} at LHCb
  - 2017 $QQ\bar{q}\bar{q}$ "reinvented" at Chicago and Tel-Aviv

Doubly-heavy baryons

- Obviously $r(QQ) \ll r(Qq)$ in (QQq) for large M/m
- The two heavy quarks are clustered in the ground state
- But the naive diquark model is misleading
- The diquark internal energy is modified by the third quark,
- The first excitations are within QQ
- For instance, with a linear potential, masses $M/m = 5$,
- $E_{\text{var}} = 4.940$ $E_{\text{BO}} = 4.938$ $E_{Dq} = 4.749$ (arbitrary units)

Doubly-heavy baryons

- Born-Oppenheimer is more appropriate
- As for $H_2{}^+$ in atomic physics
- Solve for q at fixed cc
- Effective cc potential, the QQ analogue of $Q\bar{Q}$



Born-Oppenheimer potential for (QQq), $M/m = 5$, $V \propto \sum_{i<j} r_{ij}$
Fleck, R., PTP 82 (1989) 760

Summary for QQq

- LHCb mass favored as compared to SELEX
- Hyperfine splitting about 120 MeV or more for ccq
- bcq has more states
- An effective QQ system
- First excitations within cc
- cc effective potential = analog of the $c\bar{c}$ effective potential of charmonium (gluon and light-quark degrees of freedom integrated out)

History

- Many candidates
- Many predictions
- Baryonium
- Z baryon (light pentaquark)
- Dibaryon H, ...
- Heavy pentaquark $\bar{c}uuds$ $\bar{c}ddus$, $\bar{c}ssud$ (Gignoux et al., Lipkin)

Volume 72B, number 1 PHYSICS LETTERS 5 December 1977

EVIDENCE FOR A NARROW WIDTH BOSON OF MASS 2.95 GeV

Bari–Bonn–CERN–Daresbury–Glasgow–Liverpool–Milano–Purdue–Vienna Collaboration

Early speculations

- Based on duality (Rosner)
- Based on chromomagnetism
  - $\sum_{i<j} A(r_{ij})\tilde{\lambda}_i.\tilde{\lambda}_j\, \boldsymbol{\sigma}_i \boldsymbol{\sigma}_j / m_i\, m_j$
  - Scalar mesons, H dibaryon (Jaffe), $\bar{Q}qqqq$ (Gignoux et al., Lipkin)
  - Also present in $QQ\bar{q}\bar{q}$ vs. $Q\bar{q} + Q\bar{q}$
- Yukawa interaction
  - Deuteron
  - $D\bar{D}^*$, $B\bar{B}^*$ (Törnqvist, ...)
  - DD^*, BB^* (Manohar, ...)

Doubly heavy tetraquarks $QQ\bar{q}\bar{q}$

- First proposed by Ader et al. in 1981

Do narrow heavy multiquark states exist?

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(Received 11 August 1981)

- And many others: Heller et al., Rosina et al., Brink et al., Lipkin, Barnea et al., Vijande et al., Oka et al., Bicudo et al., etc.
- Early papers somewhat forgotten in the recent literature!

$(QQ\bar{q}\bar{q})$

- $(QQ\bar{q}\bar{q})$ becomes stable if M/m large
- As shown 37 years ago by Ader et al.
- And many others: Heller et al., Rosina et al., Brink et al., Lipkin, Barnea et al., Vijande et al., Oka et al., Bicudo et al., etc.
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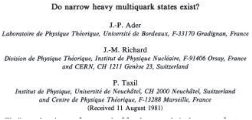

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(Received 11 August 1981)

~~Chicago 2017~~

Geneva 1981

Why $(QQ\bar{q}\bar{q})$ becomes stable?

- Even in the pure chromoelectric limit, stable for large M/m,
- Very close analogy with atomic physics

Stable multiquarks: Lessons from atomic physics
J.M. Richard (LPSC, Grenoble). 1992. 8 pp.
Published in In *Bad Honnef 1992, Quark cluster dynamics* 84-91
Prepared for Conference: C92-06-29.3, p.84-91 Proceedings

71, NUMBER 9 PHYSICAL REVIEW LETTERS 30 AUGUST 1993

Proof of Stability of the Hydrogen Molecule

J.-M. Richard
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J. Fröhlich, G.-M. Graf, and M. Seifert
Theoretical Physics, Eidgenössische Technische Hochschule Zürich-Hönggerberg, Zürich, Switzerland
(Received 24 May 1993)

We sketch two rigorous proofs of the stability of the hydrogen molecule in quantum mechanics. The first one is based on an extrapolation of variational estimates of the ground state energy of a positronium molecule to arbitrary mass ratios. The second one is an extension of Heitler-London theory to nuclei of finite mass.

$$H = \left(\frac{1}{4\,M} + \frac{1}{4\,m}\right) \sum \boldsymbol{p}_i^2 + V + \left(\frac{1}{4\,M} - \frac{1}{4\,m}\right) \left[\boldsymbol{p}_1^2 + \boldsymbol{p}_2^2 - \boldsymbol{p}_3^2 - \boldsymbol{p}_4^2\right]$$
$$= H_{\text{even}} + H_{\text{odd}}$$

- With **the same threshold** for H and H_{even}.
- C-symmetry breaking: $E(H) \leq E(H_{\text{even}})$.
- In atomic physics H_2 more stable than Ps_2
- Quark models with flavor indep.: $QQ\bar{q}\bar{q}$ becomes stable.

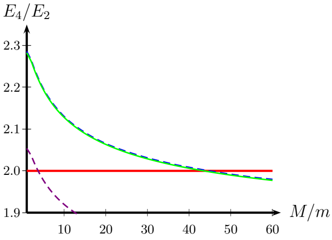
Illustration with a toy model

- Pure chromo-electric

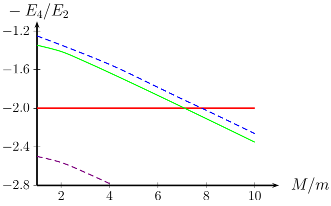
$$H = \sum_i \frac{\boldsymbol{p}_i^2}{2\,m_i} - \text{c.o.m.} - \frac{3}{16}\sum_{i<j} \tilde{\lambda}_i.\tilde{\lambda}_j\, v(r_{ij}) \ ,$$

with masses $\{m_i\} = \{M, M, m, m\}$.

- Two color wave functions (notation by Chan H-M et al. in the 70s) $T = \bar{3}3$ and $M = 6\bar{6}$
- Assume either pure T, or pure M or include color-mixing
- Stability reached and improved as $M/m \nearrow$



linear (pure T)



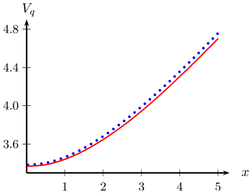
Coulomb (pure T)

Lessons from the toy model

- The critical M/m depends on the shape of the potential
- Perfect control of the 4-body dynamics $E_{\text{low}} < E < E_{\text{Variational}}$
- The diquark *approximation* fails
- Born-Oppenheimer very good, again
- Questions: spin-corrections? color mixing? 3- and 4-body forces?

Lessons from the toy model: Born-Oppenheimer approximation

- Works very well
- $V_{\text{eff}}(QQ\bar{q}\bar{q}) \simeq V_{\text{eff}}(QQq) + \mathrm{C^t}$
- with $\mathrm{C^t} = Qqq - Q\bar{q}$
- i.e., Eichten and Quigg's identity when one solves for QQ
- $(QQ\bar{q}\bar{q})_{\bar{3}3} \simeq QQq + Qqq - Q\bar{q}$



B.O. potential for $QQ\bar{q}\bar{q}$ (solid red line) and shifted QQq (dotted blue line).

Lessons from the toy model: Hall-Post lower bound

- Invented in the 50's for few-nucleon systems
- Discovered independently in studies of boson systems (Fisher-Ruelle, Dyson-Lenard, Lévy-Leblond, ...)
- And for comparing mesons and baryons (Ader et al., Nussinov, ...)
- Simple form

$$H_3(m) = \sum \left[\frac{\boldsymbol{p}_1^2}{4\,m} + \frac{\boldsymbol{p}_2^2}{4\,m} + V_{12} \right] = \sum_{i<j} H_2^{(i,j)}(2\,m)$$

- Implies (g.s.)

$$E_3(m) \geq 3\,H_2(2\,m)$$

- Many refinements to remove c.m. motion and optimize the decomposition to improve the lower bound (Basdevant, Martin, R., Wu, Zouzou, Krikeb, ...)

Application to all-heavy $QQ\bar{Q}\bar{Q}$

- Hall-Post method shows rigorously that with the T color wave function, $QQ\bar{Q}\bar{Q}$ is unbound
- Equal masses m, T color wavefunction

$$H_4(m) = \frac{1}{2}h_{12}(m) + \frac{1}{2}h_{34}(m) + \frac{1}{4}\sum_{\substack{i=1,2\\ j=3,4}} h_{ij}(m)$$

where h is the 2-body Hamiltonian, thus

$$E_4(m) \geq 2E_2(m)$$

- Removing the center-of-mass properly leads to the better

$$E_4(m) \geq E_2(m) + E_2(m/2)$$

e.g., $E_4 \geq 2.26\, E_2$ for a linear potential

- Numerical calculations show that M state is also unbound, and also the ground-state with $T - M$ mixing

$(QQ\bar{q}\bar{q})$ spin effects

The $T_{cc} = DD^*$ Molecular State

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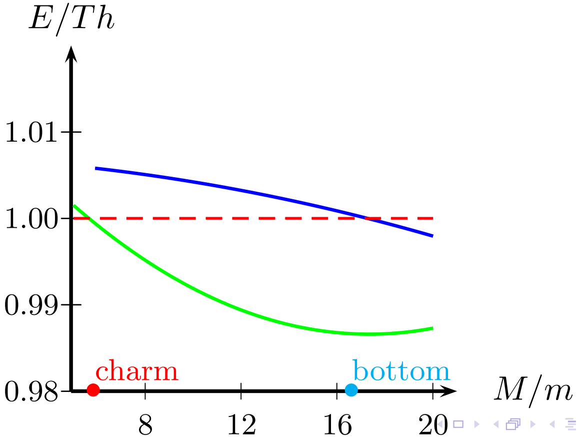
Received September 6, 2004; accepted October 11, 2004
Published online December 9, 2004;

Abstract. We show that the molecule-like configuration of DD^* enables weak binding with two realistic potential models (Bhaduri and Grenoble AL1). Three-body forces may increase the binding and strengthen the cc diquark configuration. As a signature we propose the branching ratio between radiative and pionic decay.

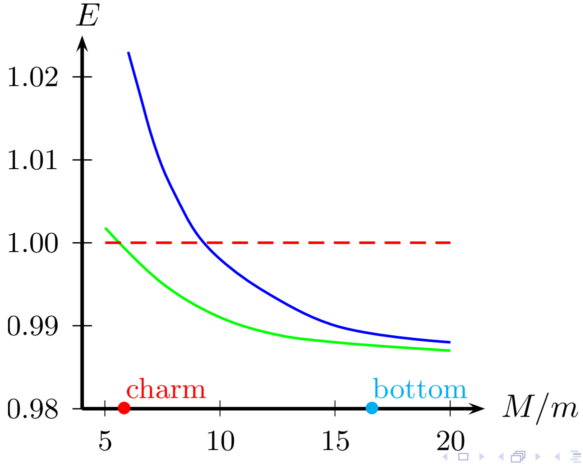
$(QQ\bar{q}\bar{q})$ spin effects

- Use an explicit model tuned to ordinary hadrons, and including an explicit short-range spin-spin term
- Chromoelectric interaction favors $(QQ\bar{q}\bar{q})$ vs. $(Q\bar{q}) + (Q\bar{q})$
- Chromomagnetic interactions also helps in some cases, e.g., 1^+



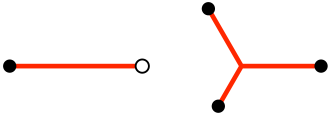
Toy model of $(QQ\bar{q}\bar{q})$ color mixing

- Chromoelectric and chromomagnetic transitions from T to M type of states
- Crucial in particular near the critical M/m ratio



Improved chromoelectric model

- Based on the string model
- Linear confinement interpreted as



- Not very visible in baryon spectroscopy as compared to

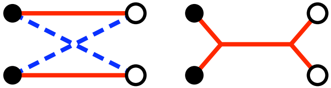
$$V_{\mathrm{conf}} = \frac{1}{2}(r_{12} + r_{23} + r_{31})$$

of the naive additive model.

String potential for $QQ\bar{Q}\bar{Q}$

- Instead of $\propto \sum \tilde{\lambda}_i.\tilde{\lambda}_j r_{ij}$, use

$$V = \min\left\{ r_{13} + r_{24}, r_{14} + r_{23}, \min_{J,K}(r_{1J} + r_{2J} + r_{JK} + r_{K3} + r_{K4})\right\} ,$$



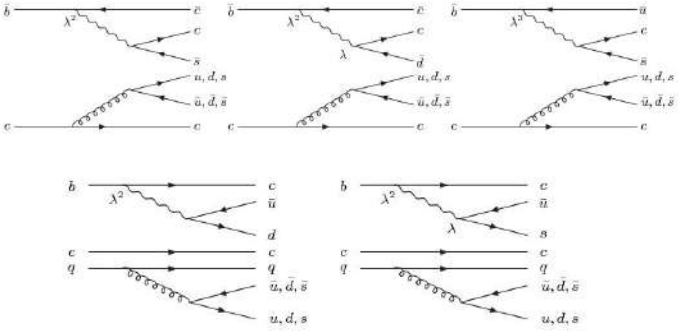
- Not so difficult (one does not need to compute the location of the junctions (Ay, R.,Rubinstein (2009), Bicudo et al.)
- gives more attraction (R., Vijande and Valcarce, 2007), and even binding for equal masses not submitted to the Pauli principle, say $(QQ'\bar{Q}\bar{Q}')$ with $M(Q) = M(Q')$ but $Q \neq Q'$.
- This restriction was forgotten in some recent papers

Summary for $QQ\bar{q}\bar{q}$

- $bb\bar{q}\bar{q}$ stable. Variety of states with various spin and isospin. Weak decay
- $cc\bar{u}\bar{d}$ with $I = 0$ and $J^{PC} = 1^{++}$ at the edge
- Thus several scenarios
  - $DD\pi$ resonance
  - Sharp $DD\gamma$
  - Stable vs. strong and EM if one can combine SR quark physics and LR Yukawa physics coherently (to be studied)
  - $bc\bar{u}\bar{d}$ and perhaps $bc\bar{q}\bar{q}$ good candidates
- Of course, SF scenario welcoem: cascade $bb\bar{u}\bar{d} \to bc\bar{u}\bar{d} + x \to cc\bar{u}\bar{d} + \cdots$ welcome

Production of double charm tetraquarks

- e^+e^- at 10 GeV (Oka et al.) around .3 fb
- In hadron colliders, two $c\bar{c}$ pairs plus rearrangement into DD^*
- B decay (e.g.„ Roma group)

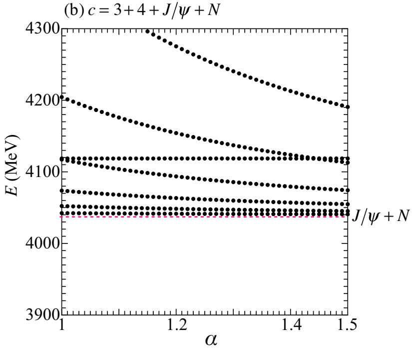


Hidden-charm pentaquark bound states

- Valcarce, Vijande, R., Phys. Lett. B774 (2017) 710-714 [arXiv:1710.08239]
- $(\bar{c}cqqq)$ with $I = 1/2$ and $J = 5/2$ below the lowest S-wave threshold $\bar{D}^*\Sigma_c^*$ (but above $N\eta_c$ in D-wave)
- For $I = 3/2$ and $J = 1/2, 3/2$ binding below S- and D-wave thresholds
- Both chromo-electric and -magnetic parts necessary for binding
- More complicated final states, perhaps, than the LHBb P_c

Hidden-charm pentaquark resonances

- Hiyama et al. (recent paper): real scaling, borrowed from electron-atom and electron-molecule scattering to separate, among the energies above the threshold, actual resonances from fictitious states produced by the variational method. Looks promising.
- Similar to Lüscher criteria for lattice, stability plateau in QCDSR



Outlook

- The three- and four-body problems are delicate, even for simple models
- Naive clustering assumptions usually do not work
- Already 37 years of study of $(QQ\bar{q}\bar{q})$
- Stable if M/m large enough
- Even for a pure chromo-electric interaction, but chromomagnetism helps for 1^{++}
- $(cc\bar{u}\bar{d})$ with 1^{+} at the edge in some specific models
- Main uncertainty: extrapolation from $Q\bar{Q}'$ and $QQ'Q''$ to multiquarks.
- Multibody forces suggested in the string model give interesting features
- Weak decay of bottom hadrons looks promising, again