Double-charm baryons and tetraquarks and other exotics

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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, including QQq
  - 1977 Upsilon discovery
  - 1981 $QQ\bar{q}\bar{q}$ becomes stable in the large M/m limit (ART)
  - 1985, ... Leon Heller (Los Alamos), Tjon, Carlson, same conclusion
  - 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
  - 2016-17 $QQ\bar{q}\bar{q}$ “reinvented”

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
- Or, say, spontaneous diquark formation in QQq as $M/m \nearrow$
- But the naive diquark model not very accurate if taken as an approximation
- The diquark internal energy is modified by the third quark,
- The first excitations are within QQ
- So you need a new diquark for each excitation

Doubly-heavy baryons

- Born-Oppenheimer is very appropriate for (M, M, m) (invented in 1927)
- As for $\mathrm{H_2}^+$ in atomic physics
- Solve for q at fixed cc
- Effective cc potential, the QQ analog of $Q\bar{Q}$ pot. in charmonium
- LHCb mass favored as compared to SELEX
- Hyperfine splitting about 120 MeV or more for ccq
- bcq has more states

Early speculations on exotics

- 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 at work 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, ...)
- Many “candidates”, too many, that were not confirmed, e.g.,

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EVIDENCE FOR A NARROW WIDTH BOSON OF MASS 2.95 GeV

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

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

- $(QQ\bar{q}\bar{q})$ 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., C. Michael et al., Bicudo et al., Regensburg group, Maltmann et al., Ali et al., S-L. Zhu et al., Rosner et al., Quigg et al., M. Nielsen et al., etc.
- Early papers somewhat forgotten in the recent literature!
  - Perhaps an illustration of the Matthew effect (sociologist Robert K. Merton in 1968)
  - Matthew 25:29:

For to every one who has will more be given,
and he will have abundance;
but from him who has not,
even what he has will be taken away.

Do narrow heavy multiquark states exist?

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(Received 11 August 1981)

Four-body problem in QM

- In principle rather straightforward
- Sometimes delicate
- For example in nuclear physics
  - (p, p, n, n) is easy
  - (n, n, n, n) debated, as well as (Λ, Λ, n, n) (Zhao, Wang, R.)
- In atomic physics, (M^+, m^+, M^-, m^-) near $M/m = 2$
  - at first unstable, as all 3-body subsystems, $(M^+, M^-, m^\pm)$ and $(m^+, m^-, M^\pm)$ are unbound
  - actually stable (Bressanini; Varga; R.)
- $(Q, Q, \bar{q}, \bar{q}) <$ or $\geq 2\,(Q\bar{q})$???
  not obvious even in a simplistic quark model.

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

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Proof of Stability of the Hydrogen Molecule

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(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.

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

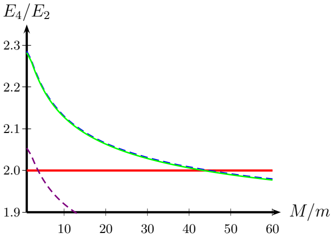
- With **the same threshold** for H and H_{even}.
- C-symmetry breaking: $E(H) \leq E(H_{\text{even}})$.
- In atomic physics H_2 more stable than Ps_2
- Quark models with flavor indep.: $QQ\bar{q}\bar{q}$ becomes stable.

Illustration with a simple quark model

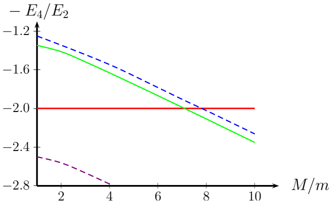
- Pure chromo-electric

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

  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)



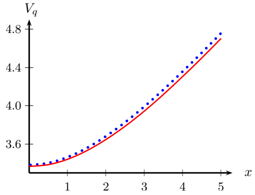
Coulomb (pure T)

Lessons from the simple quark 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* tends to overbind
- Born-Oppenheimer very good, again
- Questions: spin-corrections? color mixing? 3- and 4-body forces?

Lessons from the simple quark model: Born-Oppenheimer approximation

- Works very well
- $V_{\rm eff}(QQ\bar{q}\bar{q}) \simeq V_{\rm eff}(QQq) + \mathrm{C}^{\rm t}$
- with $\mathrm{C}^{\rm t} = Qqq - Q\bar{q}$
- 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).

Hall-Post lower bound for the quark model

- Invented in the 50's for few-nucleon systems
- Discovered independently in studying of boson systems (Fisher-Ruelle, Dyson-Lenard, Lévy-Leblond, ...)
- And 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

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

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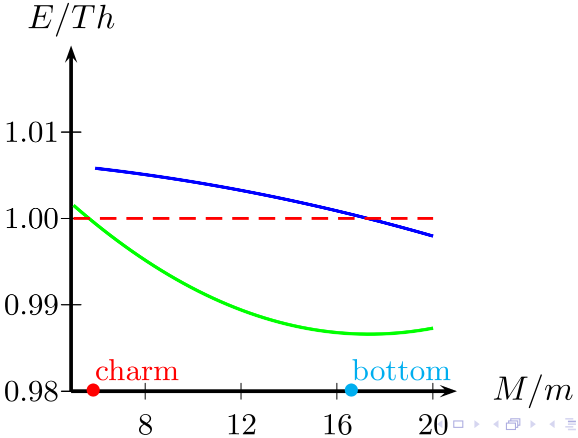
Abstract. We show that the molecule-like configuration of DD^* enables weak binding with two realistic potential models (Bhaduri and Grenoble AL1). Three-body forces may increase the binding and strengthen the *cc* diquark configuration. As a signature we propose the branching ratio between radiative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

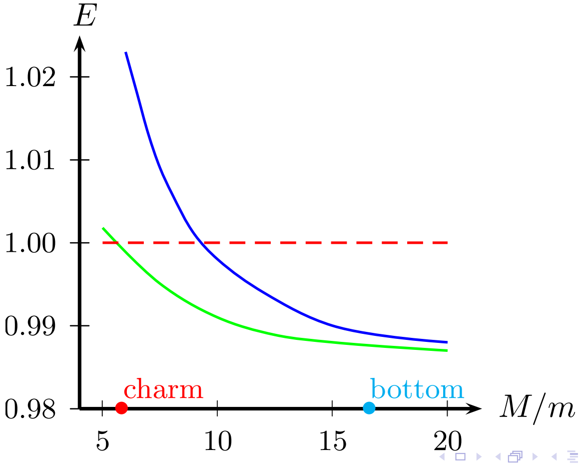
$(QQ\bar{q}\bar{q})$ spin effects

- 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^+



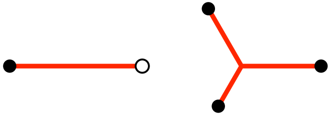
Quark model of $(QQ\bar{q}\bar{q})$ color mixing

- 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

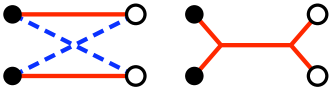
$$V_{\text{conf}} = \frac{1}{2}(r_{12} + r_{23} + r_{31})$$

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 (no need to compute the location of the junctions, Ay, R., Rubinstein (2009), Bicudo et al.)
  Use Melzak algorithm for Steiner trees, instead
- 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 $Q \neq Q'$.

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

- $bb\bar{q}\bar{q}$ stable. Variety of states with various spin and isospin. Weak decay
- $bc\bar{q}\bar{q}$ should be OK
- $cc\bar{u}\bar{d}$ with $I = 0$ and $J^{PC} = 1^{++}$ at the edge
- Thus several scenarios
  - $DD\pi$ resonance
  - Sharp $DD\gamma$
  - Stable vs. strong and EM?? requires add. attraction beyond quark model, e.g., LR meson-exchange
  - $bc\bar{u}\bar{d}$ and perhaps other $bc\bar{q}\bar{q}$ good candidates
- SF scenario welcome: cascade
  $bb\bar{u}\bar{d} \to bc\bar{u}\bar{d} + x \to cc\bar{u}\bar{d} + \cdots$ Welcome but unlikely

Anticharmed pentaquarks

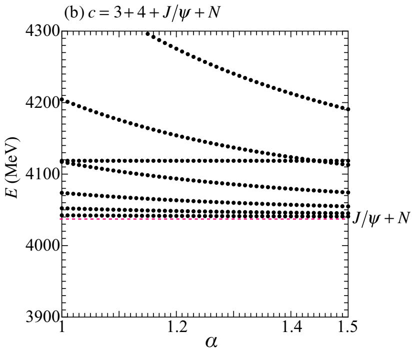
- $\bar{Q}uuds$, $\bar{Q}ddus$ and $\bar{Q}ddus$ stable (Gignoux et al; Lipkin, 1987)
  - Limit $m_Q \to \infty$
  - SU(3)$_F$
  - same short-range correlation $\langle \delta^{(3)}(\boldsymbol{r}_{ij}) \rangle$ as in ordinary baryons
- Similar to $H(uuddss)$ (Jaffe, 1977)
- Searched for by E791 at Fermilab
  (Ashery et al., PRL 81 (1998) 44, PLB 448 (1999) 303)
- Non-strange version searched for at HERA
- Revisited recently (Valcarce, Vijande, R.)
- No binding within conventional quark models

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. (arXiv:1803.11369, PRC in press): 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