Doubly heavy dibaryons

available at *http://www.ipnl.in2p3.fr/perso/richard/SemConf/Talks.html*

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Motivation

- Several mechanisms have been identified to produce exotic hadrons
  - Hadron-hadron bound states
  - Chromo-electric forces
  - Chromo-magnetic forces, ...
- The latter can be seen in simple toy models (NRQM) which can be used as guidance in more elaborate calculations
- Pure chromo-magnetic effects already studied ($H = (uuddss)$, heavy pentaquark P=($\bar{Q}qqqq$), ...)
- Pure chromo-electric effects: ($QQ\bar{q}\bar{q}$) stable for large M/m, but not yet investigated experimentally
- A combination of chromoelectric and chromomagnetic helps for binding ($QQ\bar{q}\bar{q}$) with finite M
- This could also be effective for $(QQqqqq)$
- As well as a near degeneracy of the thresholds, $(QQq) + (qqq) \simeq (Qqq) + (Qqq)$

Few-charge systems: Sub-critical binding

- (Z, e^-, e^-) obvious for $Z > 1$, as (Z, e^-) attracts e^-
- $Z = 1$ and even $Z \lesssim 1$ more interesting
- Detailed studies in the so-called $1/Z$ expansion of

$$H = -\Delta_1 - \Delta_2 - \frac{1}{r_1} - \frac{1}{r_2} + \frac{1}{Z}\,\frac{1}{r_{12}}$$

demonstrates binding down to to $Z \gtrsim 0.9107$.

Few-charge systems: Mass dependence-1

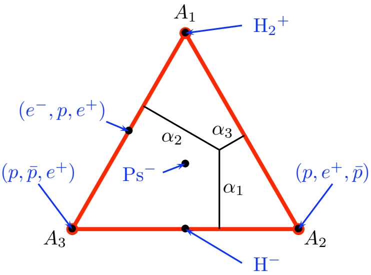
- (e^-, p, p) stable, as well as (e^+, e^-, e^-) and (p, e^-, e^-)
- but, except near the hydrogen-molecular ion, departure from $m_2 = m_3$ quickly spoils binding
- any $(M^\pm, m^\mp, m^\mp)$ stable for $M < m$, $M = m$ and $M > m$ (Hill)
- (a^+, b^-, c^-) understood as

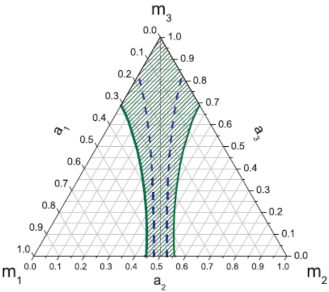
$$\psi = \gamma\,(a^+, b^-)\,c^- + \beta\,(a^+, c^-)\,b^-$$

benefits from better constructive interferences if the two thresholds are degenerate or nearly degenerate.

Mass dependence-2

- "Dalitz" plot of stability as a function of $\alpha_i = 1/m_i$
- rescaled to $\sum_i \alpha_i = 1$





King et al. J. Chem. Phys. 141 (2014) 044120
Martin, R., Wu, Phys. Rev. A46, 3697

Mass dependence-4-body

- Interesting mass dependence for $(m_1^+, m_2^+, m_3^-, m_4^-)$
- (e^+, e^+, e^-, e^-) weakly bound
- (p, p, e^-, e^-) comfortably bound
- $(p, e^+, \bar{p}, e^-)$ above $(p, \bar{p}) + (e^+, e^-)$ though some metastability near the $\mathrm{H\bar{H}}$ threshold cannot be excluded
- any system with $m_3 = m_4$ is stable, and, again, this corresponds to two degenerate thresholds $(m_1^+, m_3^-) + (m_2^+, m_4^-)$ and $(m_1^+, m_4^-) + (m_2^+, m_3^-)$ (Varga et al.)

Stability with additive chromo-electric forces

- $$\sum_{i<j} \frac{q_i\, q_j}{r_{ij}} \to -\frac{3}{16} \sum_{i<j} \tilde{\lambda}_i.\tilde{\lambda}_j\, v(r_{ij}) \equiv \alpha_{ij}\, v(r_{ij})$$

  where $v(r)$ is the quarkonium potential
- baryon potential ("1/2" rule) $\frac{1}{2} \sum v(r_{ij})$
- It shares many features with the potential of atomic physics
  - independent of the masses (flavour-independence)
  - in the positronium molecule, $\sum q_i q_j = -2$, the same as for two separated (e^+, e^-) ions
  - Here $\sum \alpha_{ij}\, v(r_{ij})$ with $\sum \alpha_{ij} = +2$ for both $(qq\bar{q}\bar{q})$ and a set of two mesons
  - this means that binding, if any, does not result from an obvious excess of attraction
  - but from astute correlations and anti-correlations in the wave function, that the 4-body calculation has to include properly.

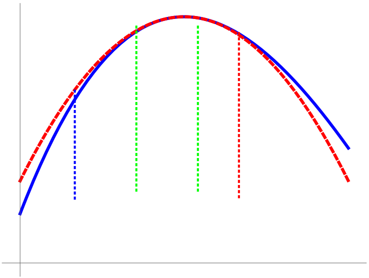
Comparison Abelian and non-Abelian cases

Why $(q, q, \bar{q}, \bar{q})$ differs from Ps_2

- Consider

$$H = \sum_{i=1}^{4} \frac{\boldsymbol{p}_i^2}{2\,m} + \sum_{i<j} g_{ij}\, v(r_{ij}) \quad \text{with} \quad \sum g_{ij} = 2$$

- Ground state energy is maximal for $g_{ij} = 1/3 \quad \forall i,\ j$
- If $H = H_0 + \lambda\,[2(v_{12} + v_{34}) - (v_{13} + v_{14} + v_{23} + v_{24})]$, then $E_0(\lambda)$ maximal at $\lambda = 0$ and decreases if $|\lambda| \nearrow$



- Atom-atom $\lambda = 1/3$
- Ps_2 $\lambda = -2/3$
- meson-meson $\lambda = 1/3$
- $(\bar{3} - 3)$ tetraquark $\lambda = 1/12$
- $(6 - \bar{6})$ tetraquark $\lambda = -7/24$

Stability with additive chromo-electric forces-2

Symmetry breaking

- particle identity
  - in atomic physics, (m^+, m^+, m^-, m^-) bound, but (M^+, m^+, M^-, m^-) unbound for $(2.2)^{-1} \lesssim M/m \lesssim 2.2$
  - in the additive chromo-electric model,$(q, q, \bar{q}, \bar{q})$ unbound and $(Q, q, \bar{Q}, \bar{q})$ even farther from binding below the lowest threshold $(Q\bar{Q}) + (q\bar{q})$ if the mass ratio increases starting form 1.
- charge conjugation
  - In atomic physics, there is a favourable symmetry breaking $(e^+, e^+, e^-, e^-) \to (p, p, e^-, e^-)$, and indeed, the H_2 molecule is more deeply bound than Ps_2, and has more stable excitations.
  - In the additive chromo-electric model, $(q, q, \bar{q}, \bar{q})$ is not bound, but $(Q, Q, \bar{q}, \bar{q})$ becomes stable for some $M/m > (M/m)_0$

Chromomagnetic binding-1

- Chromomagnetism was anticipated in early studies on the quark model (Dalitz, Sakharov, Lipkin, . . .)
- More formally proposed by DGG, the MIT group, . . . , as the analogue of the Breit–Fermi interaction, to explain the hyperfine splittings among hadrons
- The simplest version reads

$$V_{ss} = -\frac{3}{16}\, C_{ss} \sum_{i<j} \tilde{\lambda}_i.\tilde{\lambda}_j\, \boldsymbol{\sigma}_i.\boldsymbol{\sigma}_j\, \frac{\delta^{(3)}(\boldsymbol{r}_{ij})}{m_i\, m_j}$$

  and successfully explains splittings like $J/\psi - \eta_c$, $\Delta - N$, $\Sigma^* - \Sigma$, $\Sigma - \Lambda$, . . .
- either in perturbation, to estimate $\langle\delta^{(3)}(\boldsymbol{r}_{ij})\rangle$, or in regularised versions.

Chromomagnetic binding-2

- 1977: coherences in

$$\mathcal{O}_{\mathrm{CM}} = \sum_{i<j} \tilde{\lambda}_i.\tilde{\lambda}_j \, \boldsymbol{\sigma}_i.\boldsymbol{\sigma}_j$$

  if $A = B \cup C$ denotes a multiquark A with $B + C$ as threshold

$$\langle \mathcal{O}_{\mathrm{CM}} \rangle_A > \langle \mathcal{O}_{\mathrm{CM}} \rangle_B + \langle \mathcal{O}_{\mathrm{CM}} \rangle_C$$

- First estimate: assuming SU(3) flavour symmetry ($m_s = m_u$)
- And $\langle \delta^{(3)}(\boldsymbol{r}_{ij}) \rangle$ the same in $H = (u, u, d, d, s, s)$ and in $\Lambda = (u, d, s)$, Jaffe found H 150 MeV below $\Lambda\Lambda$
- Proliferation of works based on this idea
- However, when revisited (Oka-Yazaki, Rosner, Karl et al., . . .)
  - SU(3) breaking not favourable
  - $\langle \delta^{(3)}(\boldsymbol{r}_{ij}) \rangle$ much smaller in H than in Λ.

Chromomagnetic binding-3

- The H has not been found in spite of many experiments
- Some recent lattice calculation do not exclude the H
- $X(3872)$ seen at Belle, Babar, Fermilab, CERN
- Hidden charm, but does not fit $(c\bar{c})$ spectroscopy too well
- Molecular model $D\bar{D}^* + D\bar{D}$ rather popular
- but difficulties, e.g., with radiative decays
- Diquark model $(cq) - (\bar{c}\bar{q})$ a little *ad-hoc*
- Simple chromomagnetic model, $X = (c, \bar{c}, q, \bar{q})$ $\quad (q = u, d)$

$$H = \sum_{i<j} a_{ij}\, \tilde{\lambda}_i.\tilde{\lambda}_j\, \boldsymbol{\sigma}_i.\boldsymbol{\sigma}_j$$

- reproduce the $X(3872)$ at the right mass with $J^{PC} = 1^{++}$, as almost a pure colour-octet-octet in $(c\bar{c}) - (q\bar{q})$
- This refraining from fall-apart decay

Combining chromo-magnetism and chromo-electricity

- In the case of H, somewhat a conflict between confining interaction and spin-spin forces
- There are a few favourable cases
- Doubly-flavoured tetraquarks ($QQ\bar{q}\bar{q}$)
  - In the early papers, one insisted on chromo-electric properties, and the analogy with H_2 (heavy-heavy interaction absent in the threshold $(Q\bar{q}) + (Q\bar{q})$)
  - Rosina et al., Hyodo et al., ... also stressed the favourable chromo-magnetic properties (light-light interaction absent in the threshold)
- Doubly flavoured dibaryons ($QQqqqq$)
  - Favourable chromo-magnetism *à la H* for some quantum numbers
  - Favourable chromo-electricity due to QQ interaction
  - Two thresholds $(QQq) + (qqq)$ and $(Qqq) + (Qqq)$ nearly degenerate (one has better CE, the second better CM). This might induce a good mixing of configurations

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Ongoing study

- - Paul Sorba (Annecy), J-M R. (Lyon)
  - Alfredo Valcarce (Salamanca), Javier Vijande (Valencia)
  - Emiko Hiyama (RIKEN)
- either $(qqqqbc)$ with spin $J = 0$ or $(qqqqcc)$ (or bb) with $J = 1$
- 5 colour states
- 5 spin states for $J = 0$, more for $J = 1$
- Thus a 25×25 coupled-channel problem, with little simplification due to symmetries.
  Presumably, one cannot neglect the internal orbital excitations.
- Toy model

$$H = \sum_i \frac{\boldsymbol{p}_i^2}{2\,m_i} - \frac{16}{3} \sum_{i<j} \tilde{\lambda}_i.\lambda_j \left[\beta\, r_{ij} - \frac{\alpha}{r_{ij}} + \gamma\, \frac{\boldsymbol{\sigma}_i.\boldsymbol{\sigma}_j}{m_i\, m_j}\, \tilde{\delta}^{(3)}(\boldsymbol{r}_{ij}, \mu) \right]$$

where $\tilde{\delta}$ is a short-range form of the spin-spin interaction, with regularizing parameter μ (or μ_{ij})

Ongoing study-2

- The normalization of this toy model is such that

$$\beta\, \boldsymbol{r} - \frac{\alpha}{r} + \gamma\, \frac{\boldsymbol{\sigma}_i . \boldsymbol{\sigma}_j}{m_1\, m_2}\, \tilde{\delta}^{(3)}(\boldsymbol{r}, \mu)$$

  is the charmonium potential for J/ψ or η_c and their radial excitations
- The non-perturbative treatment of the spin-spin forces is crucial, presumably, to have a fair and consistent estimate of 2-body correlations in baryons and in hexaquarks (unlike early papers on H)

Ongoing study-3

- The algebra of colour and spin-colour operators is done one way, and under checking by another method
- Already, the limit of H is recovered, namely for $(uuddss)$ with $J = 0$ and unbroken $\mathrm{SU}(3)_\mathrm{f}$

$$E_\mathrm{CM}(H) = -\frac{9}{2}\,\frac{\gamma}{m^2}\langle\tilde{\delta}\rangle_H\,, \qquad E_\mathrm{CM}(\Lambda) = -\frac{3}{2}\,\frac{\gamma}{m^2}\langle\tilde{\delta}\rangle_\Lambda$$

- The limit of the 1987-vintage pentaquark of Lipkin and Gignoux et al. is also recovered

$$E_\mathrm{CM}(qqqq) = -\frac{6}{2}\,\frac{\gamma}{m^2}\langle\tilde{\delta}\rangle_{qqqq}\,,$$

if $(qqqq)$ has spin 0, colour $\bar{3}$ and is a triplet of $\mathrm{SU}(3)_\mathrm{f}$ ($(uuds)$, $(ddsu)$ or $(ssud)$)

Ongoing study-4

- Estimate of the threshold
- If chromomagnetism dominates $(Qqq) + (Qqq) < (QQq) + (qqq)$
- In a pure chromoelectric model (See Lieb, Nussinov, Martin, Taxil and R.) $(QQq) + (qqq) < (Qqq) + (Qqq)$
- With current fits of ordinary baryons, the extrapolation leads to

$$(Qqq) + (Qqq) \simeq (QQq) + (qqq)$$

- This suggests binding of $(QQqqqq)$ with
  - $J = 1$ for $(ccqqqq)$ where $qqqq$ has $J_q = 0$ and is $\mathrm{SU(3)_f}$ triplet such as $uuds$
  - $J = 0$ for $(bcqqqq)$
  - Note According to LHCb, $(bc\ldots)$ easier to detect than $(cc\ldots)$!
- Results to come soon.

Alternative approaches to heavy dibaryons

Already an abundant literature

9. **Possible H-like dibaryon states with heavy quarks**
Hongxia Huang, Jialun Ping (Nanjing Normal U.), Fan Wang (Nanjing U.). Nov 19, 2013. 5 pp.
Published in **Phys.Rev. C89 (2014) 3, 035201**
DOI: 10.1103/PhysRevC.89.035201
e-Print: arXiv:1311.4732 **[hep-ph]** | PDF

1. **Dibaryons with Two Heavy Quarks**
S.M. Gerasyuta, E.E. Matskevich (St. Petersburg State U.). Sep 2011. 10 pp.
Published in **Int.J.Mod.Phys. E21 (2012) 1250058**
DOI: 10.1142/S0218301312500589
e-Print: arXiv:1109.2338 **[hep-ph]** | PDF

Possible Deuteron-like Molecular States Composed of Heavy Baryons
Ning Lee, Zhi-Gang Luo, Xiao-Lin Chen, Shi-Lin Zhu (Peking U.). Apr 2011. 17 pp.
Published in **Phys.Rev. D84 (2011) 014031**
DOI: 10.1103/PhysRevD.84.014031
e-Print: arXiv:1104.4257 **[hep-ph]** | PDF

etc., etc.

Alternative approaches to heavy dibaryons

- Yukawa interaction between charmed baryons
- This is already well developed in the strange sector: hypernuclear physics
- ΛN or $\Lambda\Lambda$ probably unbound, but hypertriton and heavy hypernuclei have been observed
- And also double-strangeness hypernuclei
- Recently, speculations about (n, n, Λ, Λ) (R., Wang, Zhao)
- Charmed hypernuclei sketched by Dover et al. in the late 70s.
- New wave of studies after the X(3872)
- For instance Oka et al. $\Lambda_c\Lambda_c$
- Riska et al.: $\Xi_{cc}\Xi_{cc}$ and periodic table where $N \to \Xi_{cc}$
- Perhaps in the future: combination of LR and SR forces

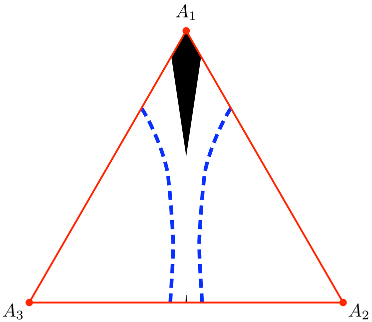
Conclusions. Multiquarks:

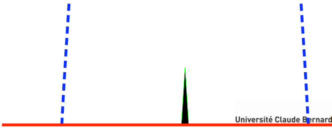
- Interesting analogies with atomic physics
- Combinations of heavy and light quarks favoured
- Subtle interplay of central and spin-spin forces required to get stable configurations
- More experiments needed beyond hidden-charm and hidden-beauty X, Y, Z
- Simultaneous search for doubly-heavy baryons, doubly-heavy tetraquarks suggested
- $(bcuuds)$ (and $(bcddus)$ and $(bcssdu)$) might be the next goal of multiquark spectroscopy

Extra slides

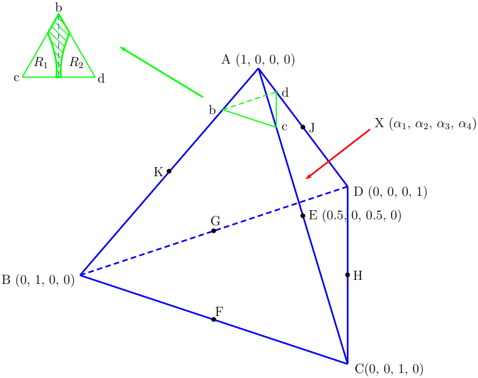
Mass dependence-3

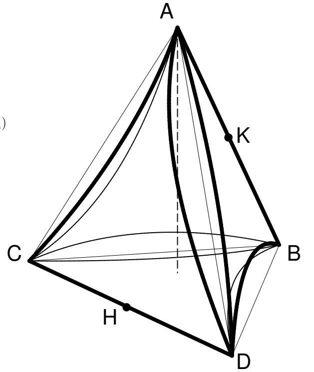
- Critical mass dependence also for excited states
- For instance unnatural parity excitation of H^-
- Threshold $\mathrm{H}(2p) + e^-$ (before radiative corrections)
- Very weakly bound for $((M=\infty)^\pm, m^\mp, m^\mp)$
- Quickly disappears for $((M=\infty)^\pm, m^\mp, m^\mp) \to (M^\pm, m^\mp, m'^\mp)$ with $M<\infty$ and/or $m \neq m'$.





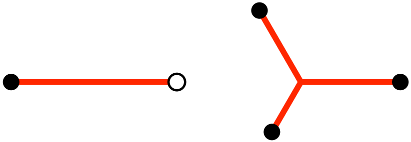
Mass dependence-4-body





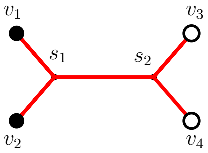
Steiner tree-1

Improving the pairwise ansatz for baryons

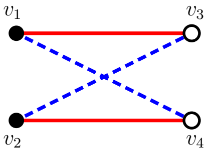
- The colour-additive model $V \propto \sum \tilde{\lambda}_i^{(c)}.\tilde{\lambda}_j^{(c)}\, v(r_{ij})$
  - used for mesons vs. baryons (Stanley and Robson, Lipkin, . . .)
  - exact in the quark–diquark limit
- now routinely replaced by the *Y*-shape ansatz
- 
- as anticipated by Artru, Dosch, Merkuriev, Fabre de la Ripelle, Kogut, Kuti, . . . , and now supported by lattice QCD,
- But the change in baryon spectroscopy not very significant, as compared to the additive model.

Steiner tree-2

- *Y* shape ext. to tetraquarks as



- But the dynamics is dominated by

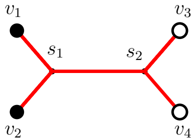


- *V* taken as the minimum at each point

- Picture now supported by lattice QCD and even ADS/QCD, but anticipated (Lenz et al., Carlson et al.)
- More recent: dramatic changes in tetraquark spectroscopy (Vijande et al.)
- If alone, binds most configurations.
- Hence promising future for exp. tetraquark search, especially in the heavy quark sector.

Steiner tree-3

- Computing the connected diagram not completely obvious: techniques of computational geometry used in the cartoon industry!



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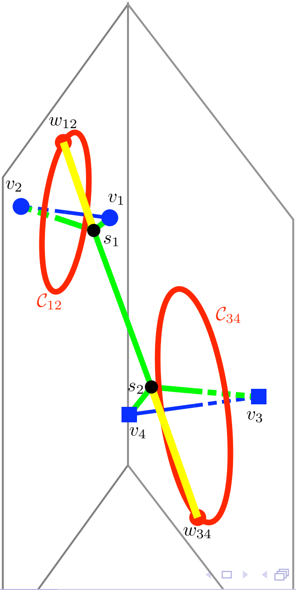
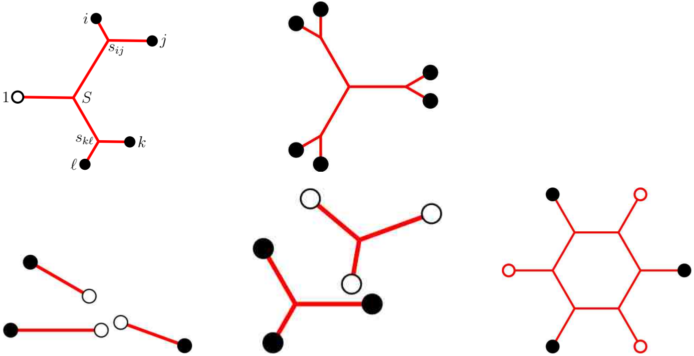


Steiner tree-4

Can be extended to 5 or 6-body, or higher states. The dynamics is dominated by flip-flop diagrams, though the connected diagrams are the most scenic



Steiner tree-5

- Comments:
- In absence of antisymmetrization, the Steiner-tree model is an interesting improvement of the adiabatic potential (minimised over rotations in colour space)
- Should be improved to account for the colour degree of freedom in case of identical quarks
- see, e.g., Vijande et al., Phys.Rev. D87 (2013) 034040