Tetraquarks

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

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Les Houches, France, February 2011

ÉCOLE DE PHYSIQUE des HOUCHES

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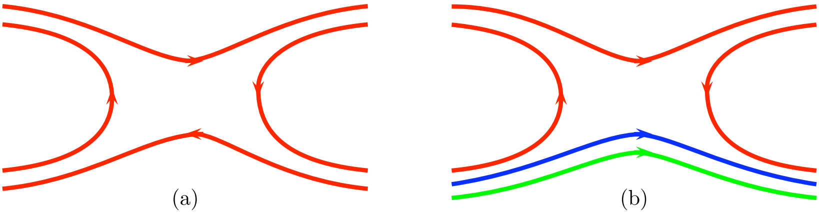
Baryonium

Duality

- Duality invented to give consistency to the description of hadronic reactions
- *s*-channel resonances, e.g., $N^\star$, Δ, etc., in the case of πN scattering
- *t*-channel resonances, e.g., ρ, ρ', etc.
- Should be equivalent with *complete* summation (Veneziano model)
- Strong *s* channel $\Rightarrow$ strong *t* channel
- Weak *t* channel $\Rightarrow$ strong *t* channel
- Can be formulated at the hadron level
- But becomes more convincing with quark diagrams

Baryonium

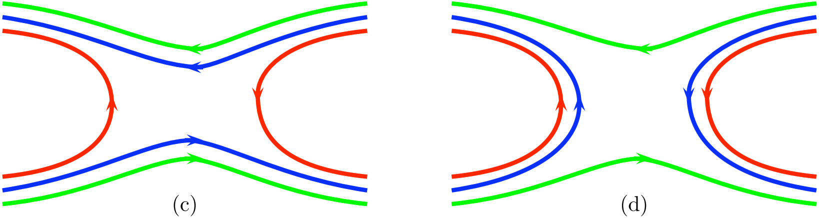
Duality diagrams -1



- $\pi - \pi$ with $I = 0$ vs. $I = 2$
- $\pi - N$

Baryonium

Duality diagrams -2

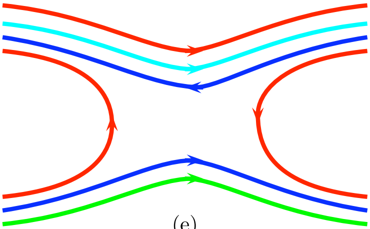


(c) (d)

- Baryon–antibaryon (Rosner)
- Prediction of baryonium, new meson preferentially coupled to baryon–antibaryon channels

Baryonium

Duality diagrams -3



(e)

- See D.P. Roy's review: baryonium–baryon scattering leads to pentaquark!
- Pandora box?

Baryonium
Experiments

- Pre-LEAR: peaks in $p\bar{p} \to \gamma + X$, bumps in $\bar{p}$ cross-section (S(1932), etc.)
- In particular, French et al., narrow peak at 2.9 GeV decaying into another peak at 2.2 or 2.0 GeV,

Volume 72B, number 1 PHYSICS LETTERS 5 December 1977

EVIDENCE FOR A NARROW WIDTH BOSON OF MASS 2.95 GeV

-
- LEAR: no confirmation
- Post-LEAR Some enhancements in baryon–antibaryon from charmonium, or B decay
- Interpretation of pre-LEAR candidates
    - Nucleon–antinucleon molecules (Shapiro, Dover, . . .)
    - $(q^2\bar{q}^2)$ states (Veneziano, Jaffe, Chan et al., . . .)

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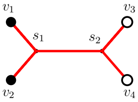
Baryonium

Quark model

- Topological structure 

With two junctions, this meson contains an underlying coupling to baryon–antibaryon.
- Explicit model: $(qq) - -(\bar{q}\bar{q})$ separated by an angular momentum barrier that suppresses the rearrangement into two mesons. By string breaking, decay into baryon antibaryon.
-

PHYSICAL REVIEW D VOLUME 17, NUMBER 5 1 MARCH 197

$Q^2\bar{Q}^2$ resonances in the baryon-antibaryon system

R. L. Jaffe
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 1 September 1977)

Two-quark–two-antiquark mesons which couple strongly to baryon-antibaryon channels are classified. The quantum numbers and masses of prominent states are predicted from the MIT bag model. The couplings of $Q^2\bar{Q}^2$ states to $B\bar{B}$ are estimated using the $^3P_0$ model and peripherality. Though most $Q^2\bar{Q}^2$ states do not couple strongly to $B\bar{B}$, many prominent resonances remain. Important $Q^2\bar{Q}^2$ resonances in the following processes are enumerated and discussed: elastic $N\bar{N}$ scattering, $N\bar{N}\to\pi^+\pi^-$, $N\bar{N}$ resonances at or below threshold, and exotic isotensor baryon-antibaryon resonances.

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Baryonium

Colour chemistry

- More speculative: mock baryonium. If the diquark has colour 6 instead of $\bar{3}$, even the baryon–antibaryon decay is suppressed, and the state might be very narrow even with high mass.

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COLOUR CHEMISTRY – A STUDY OF METASTABLE MULTIQUARK MOLECULES

CHAN Hong-Mo, M. FUKUGITA [1], T.H. HANSSON [2], H.J. HOFFMAN, K. KONISHI
Rutherford Laboratory, Chilton, Didcot, Oxon, OX11 OQX, UK

H. HØGAASEN [3]
Theory Division, CERN, 1211 Geneva 23, Switzerland

and

TSOU Sheung Tsun
Mathematical Institute, Oxford University, UK

Received 10 April 1978

-

Baryonium

Other applications

- Ideas developed for baryonium applied to other configurations (as a prediction or a warning)
- Bound states of hidden-charm baryon–antibaryon pairs
- Meso-baryons : $(q\bar{q})_8 - -(qqq)_8$
- Demon-deuteron $(qq) - (qq) - (qq)$, etc.

Constituent models of baryonium

- Sood et al.

EXACT SELECTION RULES FOR "CHROMO-HARMONIC" DIQUONIUM DECAY INTO MESONS

M.B. GAVELA, A. Le YAOUANC, L. OLIVER[1], O. PÈNE,
J.C. RAYNAL and Sudhir SOOD
Laboratoire de Physique Théorique et Hautes Energies[2], Orsay, France

Received 13 July 1978

- Using a "chromo-harmonic" interquark potential we study the stability of "diquoniums" against the decay into mesons. We find an exact selection rule which implies that "true-diquoniums" are uncoupled from open meson channels for orbital excitation greater than 1. "Mock-diquoniums" only appear for an orbital excitation greater than 8 and are coupled to mesons and to pairs of orbitally excited baryons.

- Some postulated properties might get an explanation from simple dynamics

DO WE NEED "MOCK" DIQUONIUMS TO EXPLAIN NARROW WIDTHS INTO $B\bar{B}$ CHANNELS?

J.P. ADER, B. BONNIER and Sudhir SOOD
Laboratoire de Physique Théorique[1], Bordeau, France

Received 18 April 1979

- Baryon–antibaryon widths of the "true" diquoniums are calculated using the quark-pair-creation model, otherwise very successful for the decays of ordinary baryons and mesons. The resulting widths are one order of magnitude smaller than generally believed. Combined with an earlier study of diquonium decays into mesonic channels, this would avoid the need for "mock" configurations and make it difficult to interpret structures with widths ~ 100 MeV as diquoniums.

- Similar to $(qq) - q$ structure of orbitally excited baryons.

Tetraquarks
Early attempts

- Forget baryon–antibaryon and stay in the meson sector.
  - Is there room for tetraquarks ($qq\bar{q}\bar{q}$) in the excitation spectrum?
  - Can we find stable ($qq\bar{q}\bar{q}$) states in some flavour sectors?
- Tetraquarks vs. radial excitations.

Yoichi IWASAKI

Research Institute for Fundamental Physics
Kyoto University, Kyoto

(Received January 20, 1975)

We assign $\psi(3695)$ to an exotic meson $c\bar{c}(p\bar{p}+n\bar{n})$ and $\psi(3105)$ to a vector meson $c\bar{c}$, respectively. Then we can explain naturally two facts: 1) $\psi(3695)$ decays strongly to $\psi(3105)+2\pi$ and 2) there is very little $\psi(3695)$ production compared with $\psi(3105)$ production in pN scattering at Brookhaven. In this model we expect two broad resonances at $3.7\sim4.1$

-
- Already for ψ'

Tetraquarks

Further attempts

- The same story was repeated for some higher resonances,

Hydronic molecules and the charmonium atom

M. B. Voloshin and L. B. Okun'

Institute of Theoretical and Experimental Physics
(February 16, 1976)
Pis'ma Zh. Eksp. Teor. Fiz. **23**, No. 6, 369–372 (20 March 1976)

We consider the possible existence of levels in a system consisting of a charmed particle and a charmed antiparticle; these levels result from exchange of ordinary mesons ($\omega,\rho,\epsilon,\phi$, etc.). An interpretation of the resonances in e^+e^- annihilation in the region 3.9–4.8 GeV is proposed.

-

Phys. Rev. Lett. 38, 317 - 321 (1977)

Molecular Charmonium: A New Spectroscopy?

Abstract | References | Citing Articles (72) | Page Images

Download: Page Images , PDF (873 kB), or Buy this Article (Use Article Pack) Export: BibTeX or EndNote (RIS)

A. De Rújula, Howard Georgi *, and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

Received 23 November 1976

- Recent data compel us to interpret several peaks in the cross section of e^-e^+ annihilation into hadrons as being due to the production of four-quark molecules, i.e., resonances between two charmed mesons. A rich spectroscopy of such states is predicted and may be studied in e^-e^+ annihilation.

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Tetraquarks

Alternative explanation

- Puzzling BR into $D\overline{D}$, $D^{\star}\overline{D} + c.c.$, $D^{\star}\overline{D}^{\star}$ from the node structure,

- 1) **Why Is psi-prime-prime-prime (4.414) SO Narrow?**
  A. Le Yaouanc, L. Oliver, O. Pene, J.C. Raynal, (Orsay, LPT) . LPTHE 77/35, Sep 1977. 10pp.
  Published in **Phys.Lett.B72:57,1977**.

- 2) **Strong Decays of psi-prime-prime (4.028) as a Radial Excitation of Charmonium.**
  A. Le Yaouanc, L. Oliver, O. Pene, J.-C. Raynal, (Orsay, LPT) . LPTHE 77/25, Jun 1977. 9pp.
  Published in **Phys.Lett.B71:397,1977**.

- 3) **Charmonium: Comparison with Experiment.**
  E. Eichten, K. Gottfried, T. Kinoshita, K.D. Lane, Tung-Mow Yan, (Cornell U., LNS) . CLNS-425, Jun 1979. 100pp.
  Published in **Phys.Rev.D21:203,1980**.

Tetraquarks

Same story again?

- $X(3872)$ was predicted as a $D^{\star}\overline{D} + c.c.$ molecule (Törnqvist, Voloshin, Manohar and Wise, Ericson and Karl, ...) and further described in this framework (see Swanson's review for refs.)
-

Composite	J^{PC}	Deuson
$D\bar{D}^*$	0^{-+}	η_c ($\approx$ 3 870)
$D\bar{D}^*$	1^{++}	χ_{c1} ($\approx$ 3 870)
$D^*\bar{D}^*$	0^{++}	χ_{c0} ($\approx$ 4 015)
$D^*\bar{D}^*$	0^{-+}	η_c ($\approx$ 4 015)
$D^*\bar{D}^*$	1^{+-}	h_{c0} ($\approx$ 4 015)
$D^*\bar{D}^*$	2^{++}	χ_{c2} ($\approx$ 4 015)
$B\bar{B}^*$	0^{-+}	η_b ($\approx$10 545)

Acknowledgements. I thank J.-M. Richard for discussions and for pointing out the numerical method used in this paper. Also comments by T.E.O. Ericson, A.M. Green, G. Karl, J. Paton and D.O. Riska have been useful in this work.

- This picture faces some difficulties. E.g., $X \to \psi(2S) + \gamma / X \to \psi(1S) + \gamma$
- It also predicts other molecules, in $D^{\star}\overline{D}^{\star}$ and in the charm = 2 sector.

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Tetraquarks

Tetraquarks with hidden beauty

- $\Upsilon(10860)$ significantly broader than $\Upsilon(4S) = 10580$
- $\Gamma = 110\,\text{MeV}$ vs. $20\,\text{MeV}$
- Thresholds $B\overline{B} = 10560$, $B^\star\overline{B} = 10605$ $B^\star\overline{B}^\star = 10650$
- Ali et al.: Tetraquark with maximal isospin violation, $[bu] - [\bar{b}\bar{u}]$ and $[bd] - [\bar{b}\bar{d}]$ as mass eigenstates (charged partners??)
- With predictions such as $\Upsilon(10860) \to \Upsilon(1S)K^+K^- / \ldots K^0\overline{K}^0 = 4$
- Not endorsed by e.g., Bugg [1101.1659], who suggests a strong coupling to $B^{(\star)}\overline{B}^\star$ channels
- The model of Törnqvist, if extrapolated here, induces
-
    - a bound state in 0^{++} with about $-50\,\text{MeV}$
    - a radial excitation very close to the threshold
    - an orbital excitation very close to it
- a coherent $(b\bar{b})$ – Tetraquark – molecule very likely

Tetraquarks

Genuine exotics?

- ∃ tetraquarks that can not be confused with ordinary $q\bar{q}$?
- All charm? (Vary et al.)
-

All-charm tetraquarks

Richard J. Lloyd and James P. Vary
Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA
(Received 5 November 2003; published 27 July 2004)

We investigate four-body states with only charm quarks. Working in a large but finite oscillator basis, we present a net binding analysis to determine if the resulting states are stable against breakup into a pair of $c\bar{c}$ mesons. We find several close-lying bound states in the two models we examine.

- To be confirmed (Vary, private communication)
- In this chromelectric regime, with colour additive forces ($\propto \sum \tilde{\lambda}_i.\tilde{\lambda}_j v(r_{ij})$), the system is usually found unbound (see next slides)
- and unequal masses are required ($QQ'\bar{q}\bar{q}'$) (next to next slides)

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Equal masses

QED vs. QCD-1

- (e^+, e^+, e^-, e^-) proposed by Wheeler in 1945
- Found to be likely unstable by Ore in 1946
- **Binding Energy of Polyelectrons**

  Aadne Ore

  Sloane Physics Laboratory, Yale University, New Haven, Connecticut

  June 10, 1946

  Although the evidence here presented against the stability of the polyelectron composed of two electrons and two positrons is not conclusive in a strict mathematical sense, it counsels against the assumption that clusters of this (or even of higher) complexity can be formed.
- Demonstrated to be stable by the same Ore in 1947
- ICAL REVIEW VOLUME 71, NUMBER 8 APRIL 1!

  Binding Energy of the Positronium Molecule

  Egil A. Hylleraas

  Institute of Theoretical Physics, University of Oslo, Oslo, Norway

  and

  Aadne Ore*

  Sloane Physics Laboratory, Yale University, New Haven, Connecticut

  (Received December 26, 1946)

  A system of two electrons and two positrons is shown to possess dynamic stability. The
- Found in 2007

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Equal masses

QED vs. QCD-2

- Why the Ps_2 problem of QED and the additive (..) $\sum \tilde\lambda_i.\tilde\lambda_j v(r_{ij})$ pairwise quark model any different?
- Little to do with Coulomb vs. linear
- in $H = \sum \boldsymbol{p}_i/(2m) + \sum g_{ij} v(r_{ij})$,
- With $\sum g_{ij}$ fixed for both the threshold and the 4-body,
- Due to charge conservation or colour singlet,
- $E = \min(H)$ maximal is all g_{ij} equal,
- E decreases if $\{g_{ij}\}$ more asymmetric, i.e., if Δg larger
- Now, if you compare Ps_2 and quark models: Ps_2 favoured.

$(abcd)$	$v(r)$	g_{ij}	$\bar g$	Δg
(1,3)+(2,4)	$-1/r, r$	$\{0,0,1,0,1,0\}$	1/3	0.22
Ps_2	$-1/r$	$\{-1,-1,1,1,1,1\}$	1/3	0.89
$[(qq)_{\bar 3}(\bar q\bar q)_3]$	$-1/r, r$	$\{1/2,1/2,1/4,1/4,1/4,1/4\}$	1/3	0.01
$[(qq)_6(\bar q\bar q)_{\bar 6}]$	$-1/r, r$	$\{-1/4,-1/4,5/8,5/8,5/8,5/8\}$	1/3	0.17

Tetraquarks with unequal masses

- In a pure static interaction (spin-independent) $m \nearrow$ means $E \searrow$, e.g., $E \propto 1/\sqrt{m}$ for HO and $E \propto -1/m$ for Coulomb, but in large systems, the effect often benefits more the threshold than the system, e.g., $(p, e^+, \bar{p}, e^-)$ in QED unstable while (e^+, e^+, e^-, e^-) is stable,
- For the same reason, in most models, $(qqqQQQ)$ hardly bound, as the lowest threshold, $(qqq) + (QQQ)$ benefits maximally from the large masses.
- On the other hand, $(QQ\bar{q}\bar{q})$ takes profit of the heavy–heavy interaction that in absent in the threshold $(Q\bar{q}) + (Q\bar{q})$. It is predicted to be stable by many authors, but was never investigated experimentally.

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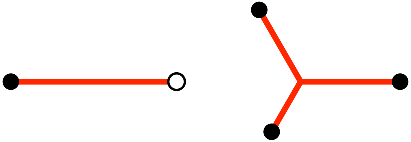
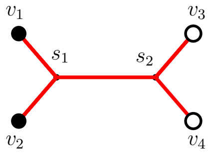
Improving the pairwise ansatz

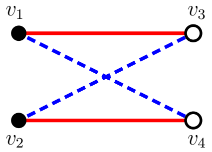
- The colour-additive model $V \propto \sum \tilde{\lambda}_i^{(c)}.\tilde{\lambda}_j^{(c)}\, v(r_{ij})$
  - used for mesons vs. baryons (Stanley and Robson, Lipkin, . . .)
  - exact in the quark–diquark limit
- now routinely replaced by the *Y*-shape ansatz
- 
- as anticipated by Artru, Dosch, Merkuriev, 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.

Flip-flop and Steiner-tree for tetraquarks

- *Y* shape ext. to tetraquarks as



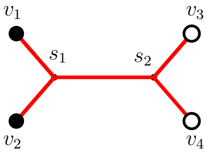
- But the dynamics is dominated by



- *V* taken as the minimum at each point

Flip-flop and Steiner-tree for tetraquarks

- Y shape ext. to tetraquarks as



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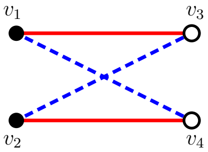

- V taken as the minimum at each point

- 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 confinement

Results

- First estimate

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Absence of exotic hadrons in flux-tube quark models

- Second estimate (Vijande et al.)

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Stability of multiquarks in a simple string model

- This corresponds to the Born–Oppenheimer limit, without antisymetrisation constraint.
- Next step (in progress): coupled channel interaction, of which the lowest eigenvalue is the minimal Steiner-tree.
- Notice: without antisymetrisation (i.e., different quarks), the same model binds several pentaquark and hexaquark (q^6 or $q^3\bar{q}^3$) configurations.

Configuration mixing

- If model $|a\rangle$ has some interesting properties, and $|b\rangle$ some other nice properties
- not obvious that $\cos\vartheta\,|a\rangle + \sin\vartheta\,|b\rangle$, makes any sense.
- Simple mixing schemes of close neighbours significantly depart from serious coupled-channel calculations,
- For instance, a $(c\bar{c})$ admixture into a $(c\bar{c}q\bar{q})$ with $J^{PC} = 1^{++}$ is not necessarily a radial excitation,
- Hence is not convincingly a solution to the $X \to \gamma\psi(2S)/X \to \gamma\psi(1S)$ problem,
- A simpler example is $S - D$ mixing. At first, $\psi(3686) = 2S$ and $\psi(3770) = 1D$
- If a tensor force is introduced in a pure potential picture, then $\psi(3770)$ acquires a nodeless S-wave component,
- While most *empirical* pictures assume $\cos\vartheta\,|1D\rangle + \sin\vartheta\,|2S\rangle$,
- Now, the mixing is probably due also to coupling to meson–meson channels, and the picture becomes even more involved.

Conclusions

- Intense activity in the tetraquark sector,
- Molecules bound with nuclear forces: if it works for $X(3872)$, other configurations predicted,
- Diquark–antidiquark: clustering remains to be justified. Again, other configurations expected (charged states, dibaryons, etc.)
- Constituent models: The Steiner tree confinement gives more attraction than the empirical colour-additive ansatz,
- But its application to configurations with identical quarks remains to be worked out,
- Mixing requires a lot of care.