Pentaquark

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

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Table of contents

History: The *Z* baryons

- *KN* resonances?, analogues of the $\bar{K}N$ ones.
- For years reviewed in PDG.
- Last time in 1992
- The *Z*-baryon section has now disappeared.

Z BARYONS
($S = +1$)

NOTE ON THE $S = +1$ BARYON SYSTEM

The evidence for strangeness +1 baryon resonances was reviewed in our 1976 edition,[1] and has also been reviewed by Kelly[2] and by Oades.[3] New partial-wave analyses[4,5] appeared in 1984 and 1985, and both claimed that the P_{13} and perhaps other waves resonate. However, the results permit no definite conclusion — the same story heard for 20 years. The standards of proof must simply be more severe here than in a channel in which many resonances are already known to exist. The skepticism about baryons not made of three quarks, and the lack of any experimental activity in this area, make it likely that another 20 years will pass before the issue is decided. Nothing new at all has been published in this area since our 1986 edition,[6] and we simply refer to that for listings of the $Z_0(1780)P_{01}$, $Z_0(1865)D_{03}$, $Z_1(1725)P_{11}$, $Z_1(2150)$, and $Z_1(2500)$.

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Baryonium, glueballs, . . .

- 70s and early 80s
- Peaks in the $\bar{p}p$ cross-sections and in $\bar{p}p \to \gamma + X$
- New mesons preferentially coupled to baryon + antibaryon, as predicted by Rosner et al.
- Already two schools
  - Molecular or "quasi-nuclear" Shapiro et al., Dover et al., . . . $\bar{N}N$
  - Multiquarks: Veneziano et al., Jaffe, Chan H.M. et al., . . .

$$(qq) - (\bar{q}\bar{q})$$

- Colour chemistry diquark with colour 6 also introduced
- And many variants, including $(\bar{q}qqqq)$ (DeSwart et al., Sorba et al.)
- Baryonium was not confirmed at LEAR (CERN) in the 80s.

Baryonium, glueballs, . . .

- Many other episodes, either theoretical or experimental
- $(qq\bar{q}\bar{q})$ picture of scalar mesons,
- Hybrids $(q\bar{q}g)$ or $(qqqg)$
- Glueballs
- For instance

Evidence for exotic meson production in $\pi^- p$ interactions at 18 GeV /c

Alexander Ostrovidov[1] and Brookhaven E852 Collaboration
+ VIEW AFFILIATIONS

Download PDF

AIP Conf. Proc. **432**, 263 (1998); http://dx.doi.org/10.1063/1.56047
Conference date: 25-30 Aug 1997
Location: Upton, New York (USA)

< PREVIOUS ARTICLE | TABLE OF CONTENTS | NEXT ARTICLE >

Abstract | References (0) | Cited By (0) | Data & Media | Metrics | Related

A general overview of the latest E852 results is presented. The description of the experimental apparatus is given. Data sample of 1.3 billion events collected so far by the experiment is summarized. A $J^{PC}=1^{-+}$ exotic state of mass $(1370\pm16^{+50}_{-30})$ MeV /c^2 and width $(385\pm40^{+65}_{-105})$ MeV /c^2 is observed in the reaction $\pi^- p\to\eta\pi^- p$. A strong 1^{-+} signal is present in the $\eta\pi^0$, $\pi^+\pi^-\pi^-$, $\pi^-\pi^0\pi^0$, $\eta'\pi^-$ and $f_1(1285)\pi^-$ final states. In $\eta\eta$, a 0^{++} state around 1.5 GeV /c^2 is seen. A brief summary of the preliminary results for the $\omega\pi^-\pi^0$, $\omega\pi^0$, $\omega\eta$ and $\eta\pi^+\pi^-$ final states is included.

Key Topics
Exotic mesons
Meson meson interactions

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Light dibaryons

- Several claims at Saclay, Dubna, . . .

PHYSICAL REVIEW C VOLUME 59, NUMBER 4 APRIL 1999

Evidence for narrow dibaryons at 2050, 2122, and 2150 MeV observed in inelastic pp scattering

B. Tatischeff,[1] J. Yonnet,[1] M. Boivin,[2] M. P. Comets,[1] P. Courtat,[1] R. Gacougnolle,[1] Y. Le Bornec,[1] E. Loireleux,[1] F. Reide,[1] and N. Willis[1]
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- Famous proposal by Jaffe in 1977, based on the coherence properties of $\sum \tilde{\lambda}_i.\tilde{\lambda}_j \,\boldsymbol{\sigma}_i.\boldsymbol{\sigma}_j$ applied to *(uuddss)*

Perhaps a Stable Dihyperon*

R. L. Jaffe†
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and Department of Physics and Laboratory of Nuclear Science,‡ Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 1 November 1976)

In the quark bag model, the same gluon-exchange forces which make the proton lighter than the Δ(1236) bind six quarks to form a stable, flavor-singlet (with strangeness of −2) $J^P=0^+$ dihyperon (H) at 2150 MeV. Another isosinglet dihyperon (H^*) with $J^P=1^+$ at 2335 MeV should appear as a bump in ΛΛ invariant-mass plots. Production and decay systematics of the H are discussed.

Light Pentaquarks

Evidence for a Narrow $S = +1$ Baryon Resonance in Photoproduction from the Neutron

T. Nakano,[1] D. S. Ahn,[2] J. K. Ahn,[2] H. Akimune,[3] Y. Asano,[4,5] W. C. Chang,[6] S. Daté,[7] H. Ejiri,[7,1] H. Fujimura,[8] M. Fujiwara,[1,5] K. Hicks,[9] T. Hotta,[1] K. Imai,[10] T. Ishikawa,[11] T. Iwata,[12] H. Kawai,[13] Z. Y. Kim,[8] K. Kino,[1] H. Kohri,[1] N. Kumagai,[7] S. Makino,[14] T. Matsumura,[1,5] N. Matsuoka,[1] T. Mibe,[1,5] K. Miwa,[10] M. Miyabe,[10] Y. Miyachi,[15,*] M. Morita,[1] N. Muramatsu,[5] M. Niiyama,[10] M. Nomachi,[16] Y. Ohashi,[7] T. Ooba,[13] H. Ohkuma,[7] D. S. Oshuev,[6] C. Rangacharyulu,[17] A. Sakaguchi,[16] T. Sasaki,[10] P. M. Shagin,[1,†] Y. Shiino,[13] H. Shimizu,[11] Y. Sugaya,[16] M. Sumihama,[16,5] H. Toyokawa,[7] A. Wakai,[18,‡] C. W. Wang,[6] S. C. Wang,[6,§] K. Yonehara,[3,‖] T. Yorita,[7] M. Yoshimura,[19] M. Yosoi,[10] and R. G. T. Zegers[1]

Many papers on this pentaquark, with this conclusion in PDG

> The whole story—the discoveries themselves, the tidal wave of papers by theorists and phenomenologists that followed, and the eventual "undiscovery" —is a curious episode in the history of science.

Singly heavy Pentaquarks

1987: prediction of $(\bar{c}uuds)$
plus $\mathrm{SU(3)_f}$ analogues with *ddus* and *ssud*

POSSIBILITY OF STABLE MULTIQUARK BARYONS

C GIGNOUX [a], B SILVESTRE-BRAC [a] and J M RICHARD [a b]
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[b] *Laboratoire de Physique Theorique et Hautes Energies* [1], *T16-E1, Universite Pierre et Marie Curie, F-75252 Paris Cedex 05, France*

Received 8 April 1987

The candidates We consider a configuration $(\bar{Q}uuds)$, hereafter called P (for *pentaquark*, rather

NEW POSSIBILITIES FOR EXOTIC HADRONS – ANTICHARMED STRANGE BARYONS☆

Harry J. LIPKIN
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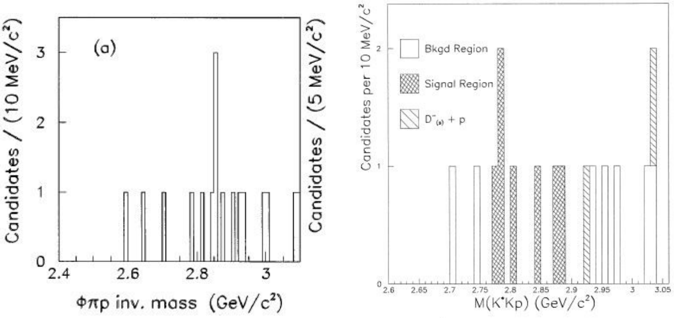
Received 1 June 1987

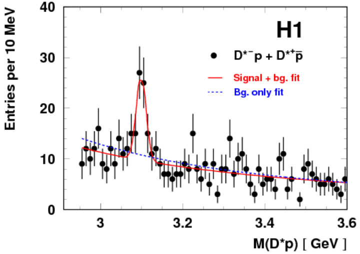
The 1987-vintage pentaquark: Search at Fermilab

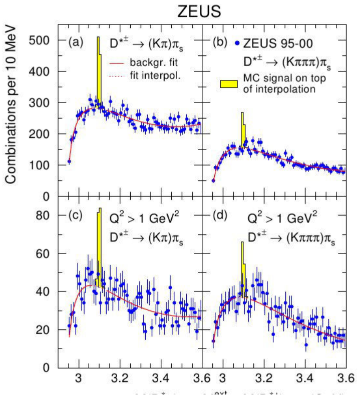
Aitala et al. searched for $P_c^0 = (\bar{c}suud) \to K^{*,0}K^- p$ and $\phi\pi^- p$. Not conclusive.



A fraction of this collaboration was interested in doing some search at CERN or at some hadron factories, but this was never approved as a priority.

The 1987-vintage pentaquark: Search at Hera





Combining heavy and light quarks or antiquarks

Exotics with a mixing of light and heavy quarks: Rather old idea

ON THE POSSIBLE EXISTENCE OF STABLE FOUR-QUARK SCALAR MESONS WITH CHARM AND STRANGENESS ☆

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Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
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Received 4 September 1980

Do narrow heavy multiquark states exist?

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(Received 11 August 1981)

Possibility of Charmed Hypernuclei

C. B. Dover and S. H. Kahana
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(Received 10 August 1977)

We suggest that both two-body and many-body bound states of a charmed baryon and nucleons should exist. Estimates indicate binding in the ${}^1S_0$ state of C_1N $(I = \frac{3}{2})$ and SN $(I = 1)$. We further estimate the binding energy of C_0, C_1 in various finite nuclei.

On the existence of stable dimesons

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(Received 11 August 1986)

POSSIBILITY OF STABLE MULTIQUARK BARYONS

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Received 8 April 1987

NEW POSSIBILITIES FOR EXOTIC HADRONS – ANTICHARMED STRANGE BARYONS ☆

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Received 1 June 1987

The *XYZ* states: Theory predictions-1

- Anticipated before the discovery of $X(3872)$ and other analogous states
- Iwasaki, Rosenzweig,Bander, Voloshin, DeRujúla et al., Minami etc.

Yoichi IWASAKI

Research Institute for Fundamental Physics
Kyoto University, Kyoto

(Received January 20, 1975)

We assign $\phi(3695)$ to an exotic meson $c\bar{c}(p\bar{p}+n\bar{n})$ and $\phi(3105)$ to a vector meson $c\bar{c}$, respectively. Then we can explain naturally two facts: 1) $\phi(3695)$ decays strongly to $\phi(3105)+2\pi$ and 2) there is very little $\phi(3695)$ production compared with $\phi(3105)$ production in pN scattering at Brookhaven. In this model we expect two broad resonances at 3.7∼4.1 GeV and at ∼4.1 GeV.

- To "explain" some properties of the higher 1^{--} states
- Eventually attributed to the nodes of the radial excitations (Le Yaouanc et al., Eichten et al., . . .)

The *XYZ* states: Theory predictions-2

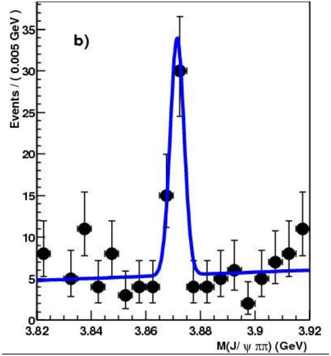
- New wave of papers on $D^{(*)}\bar{D}^{(*)}$ molecules: Ericson and Karl, Manohar and Wise, etc., and, especially, Törnqvist,
- So the discovery of the $X(3872)$ at Belle great as a success of this approach,
- Though there is now a tendency to describe X as a mixture of quarkonium and meson-meson

X, Y, Z: discovery

VOLUME 91, NUMBER 26 PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2003

Observation of a Narrow Charmoniumlike State in Exclusive $B^\pm \to K^\pm \pi^+ \pi^- J/\psi$ Decays

S.-K. Choi,[5] S. L. Olsen,[6] K. Abe,[7] T. Abe,[7] I. Adachi,[7] Byoung Sup Ahn,[14] H. Aihara,[43] K. Akai,[7] M. Akatsu,[20]



confirmed in many other experiments

X, Y, Z: summary

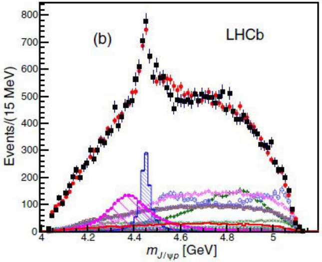
From Braaten et al.

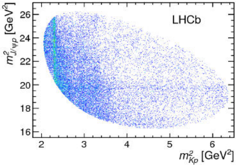
(i) $X(3872)$, discovered by the Belle Collaboration in 2003 [1]. It has comparable branching fractions into $J/\psi\rho$ and $J/\psi\omega$, implying a severe violation of isospin symmetry.
(ii) $Y(4260)$, discovered by the *BABAR* Collaboration in 2005 [2]. It has J^{PC} quantum numbers 1^{--}, but it is produced very weakly in e^+e^- annihilation.
(iii) $Z^+(4430)$, discovered by the Belle Collaboration in 2007 [3]. It decays into $\psi(2S)\phi$, which implies that it must be a tetraquark meson with constituents $c\bar{c}u\bar{d}$.
(iv) $Y(4140)$, discovered by the CDF Collaboration in 2009 [4]. It decays into $J/\psi\phi$, which suggests that it might be a tetraquark meson with constituents $c\bar{c}s\bar{s}$.
(v) $Z_b^+(10610)$ and $Z_b^+(10650)$, discovered by the Belle Collaboration in 2011 [5]. They both decay into $\Upsilon\pi^+$, which implies that they must be tetraquark mesons with constituents $b\bar{b}u\bar{d}$.
(vi) $Z_c^+(3900)$, discovered by the BESIII Collaboration in 2013 [6]. It decays into $J/\psi\pi^+$, which implies that it must be a tetraquark meson with constituents $c\bar{c}u\bar{d}$.

An updated list of the XYZ mesons was given in Ref. [7]

LHCb pentaquarks: Dalitz plot and mass spectrum

$\Lambda_b \to J/\psi\, p\, K^-$





Preferred assignment:
$J^P = (3/2)^-$ for $P_{c\bar{c}}(4380)^+$
$J^P = (5/2)^+$ for $P_{c\bar{c}}(4450)^+$
See, e.g., Burns, for a review and useful remarks.
In particular, the second one requires some internal orbital excitation!

LHCb pentaquarks: Analysis

The data are analysed as

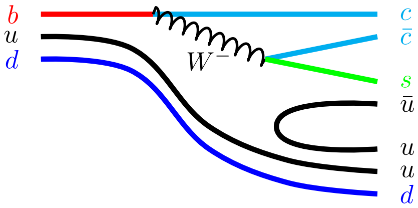
$$\Lambda_b \to J/\psi + (K^- p)$$

$$(K^- p) = \Lambda, \Lambda^*, \Lambda^{**}, \ldots$$

this fitting the background, and then peaks are added in the $(J/\psi, p)$ subsystem.
In summary, the favoured results are

- P, mass $4380 \pm 8 \pm 29$ MeV, width $205 \pm 18 \pm 36$ MeV and $J^{PC} = (3/2)^-$
- P^*, mass $4449.8 \pm 1.7 \pm 2.5$ MeV, width $39 \pm 5 \pm 19$ MeV and $J^{PC} = (5/2)^+$

LHCb pentaquarks: Production mechanism



Molecular model

$$X(3872) = D\bar{D}^* + \text{c.c.}$$

Tends to favour $I = 0$ states of X, Y, Z, but does not exclude a few $I = 1$.
As in the study of mesons in early bootstrap theory (Ball, Scotti, Wong, 1966)

Similarly

$$P_c = \bar{D}^{(*)} + \Sigma_c^{(*)} + \cdots$$

$$P_c^* = \chi_1 + p$$

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Diquark model

$$P = \{\bar{c}\,(cq)\,(qq)\}$$

in line with the previous model

$$X, Y, Z = \{(cq)\,(\bar{c}\bar{q})\}$$

Efficient, but rather ad-hoc, especially in the treatment of the spin-dependent interaction.
Note that the problem of the quark-diquark structure of baryons has not been clearly solved.

Constituent quark models: Brief review

- First developed by Dalitz et al., in $\gtrsim$ 1964 to explain the baryon states
- Continuation by Isgur, Karl, etc.
- Renewal of interest in 1974 for charmonium and 1977 for bottomonium
- Legitimated by lattice QCD using static heavy quarks
- Applied to multiquarks $\pm$ rigorously

The simplest version of the constituent quark model uses effective quark masses and empirical potentials, and reads

$$H = \sum_i \frac{\boldsymbol{p}_i^2}{2\, m_i} - \frac{3}{16} \sum_{i<j} \tilde{\lambda}_i.\tilde{\lambda}_j v_c(r_{ij}) - \frac{3}{16} \sum \tilde{\lambda}_i.\tilde{\lambda}_j\, \boldsymbol{\sigma}_i.\boldsymbol{\sigma}_j \frac{v_{ss}(r_{ij})}{m_i\, m_j}$$

i.e., kinetic, electric and magnetic parts.
For instance, the intrinsic Hamiltonian of the η_c is

$$h = \frac{\boldsymbol{p}^2}{m_c} + v_c(r) - \frac{3}{m_c^2}\, v_{ss}(r)$$

Chromomagnetism and multiquarks

- Jaffe (1977) studied (*uuddss*) with

$$\tilde{H} = \sum_i \tilde{m}_i - C \sum_{i<j} \tilde{\lambda}_i.\tilde{\lambda}_j \, \boldsymbol{\sigma}_i.\boldsymbol{\sigma}_j$$

  - SU(3)$_f$ symmetry
  - Same short-range correlation C as for baryons,
- the colour-spin algebra reveals a good surprise,
- $\delta M = -8C$ for N, Λ, Ξ, ...
- Thus $\delta M = -16\,C$ for the degenerate thresholds $N\Xi$, $\Lambda\Lambda$
- And $\delta M = -24\,C$ for (*uuddss*), i.e., 150 MeV below threshold
- But removing the approximations (Oka, Yazaki, Rosner, Karl et al., ...) reduces the attraction and eventually spoils the binding

Chromomagnetism and multiquarks

- Same exercise repeated in 1987 for $P = (\bar{Q}uuds)$ (or $ddus$ or $ssud$)
- Same assumptions: $\mathrm{SU}(3)_f$, C borrowed from baryons
- and $m_Q \to \infty$ in the chromomagnetic operator
- $\delta M = -16\,C$ vs. $\delta M = -8\,C$ for $(\bar{Q}q) + (qqq)$
- Again, any correction reduces the binding
- Silvestre-Brac and Leandri (Grenoble) and Yuan et al. (China) extended the estimate to other configurations, including $(\bar{c}cqqq)$, and found interesting candidates, especially for $J^P = (1/2)^-$
- Not followed by a more detailed 5-body calculation

Chromomagnetism and multiquarks: $X(3872)$

- Høgaasen et al. have analysed $X(3872)$ using

$$\tilde{H} = \sum_i \tilde{m}_i - \sum_{i<j} C_{ij}\, \tilde{\lambda}_i.\tilde{\lambda}_j\, \boldsymbol{\sigma}_i.\boldsymbol{\sigma}_j$$

  with the C_{ij} deduced from ordinary hadrons,
  e.g., $C_{\bar{c}q}$ from $D^* - D$.
- Good surprise that one state, with $J^{PC} = 1^{++}$ has almost exactly the mass and the properties of $X(3872)$, in particular, in its $(c\bar{c}) - (q\bar{q})$ projection, is pure octet-octet and vector-vector. Hence the decay

$$\mathrm{X} \to \mathrm{charmonium} + \mathrm{light\ meson}$$

  is suppressed.
- The model predicts an $I = 1$ partner slightly above, with $J^{PC} = 1^{++}$, unlike the $X(3900)^{\pm}$ seen at BESIII, Belle, and CLEO.
- (Preliminary) the conclusions are supported by a more detailed 4-body calculation
- See also Stancu et al.

Chromoelectricity and multiquarks

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

- does not bind $(qq\bar{q}\bar{q})$ with equal masses
- binds $(QQ\bar{q}\bar{q})$ if M/m large enough
- the result is confirmed in *QCD* sum rule (Nielsen et al.), lattice QCD (Michael et al;, Bicudo et al., etc.) and in the molecular approach (Manohar et al, ...)
- same favourable symmetry breaking that benefits to $H_2(ppe^-e^-)$ as compared to $Ps_2(e^+e^+e^-e^-)$
- hence the spin-independent quark model can produce stable multiquarks in extreme circumstances

Combining chromo- and chromo-magnetic effects

- For instance, Rosina et al., Yasui et al. $(cc\bar{u}\bar{d})$ with $J^P = 1^+$ has favourable chromoelectric binding and favourable chromomagnetic interaction as compared to $D + D^*$
- this requires an accurate solution of the 4-body problem, or 5-body for Pentaquark
- a method is based on correlated Gaussians

$$\Psi = \sum_{cs} \sum_{i} \gamma_{i,cs} \left[\exp(-\sum_{j<k} a_{jk}\, r_{jk}^2) \pm \cdots \right]$$

where $\cdots$ means terms deduced by permutation

- For given $\{a_{jk}\}$, variational energy E and coefficients γ_i given by a generalised eigenvalue equation
- Non linear parameters $\{a_{jk}\}$ deduced by astute methods (Kamimura et al., Suzuki et al., ...)
- $\sum_{cs}$ spin-colour states, ≥ 15 for pentaquark with spin $1/2$

Preliminary results on LHCb pentaquarks

- Hidden charm ($\bar{c}cuud$)
  - $J^P = (5/2)^-$ Unbound
  - $J^P = (3/2)^-$ Unbound, possibility of resonance
  - $J^P = (1/2)^-$ At the edge of binding
- Naked anticharm ($\bar{c}suud$) at the edge of binding
- Technical improvements: include explicitly $\Psi_A\,\Psi_B\,\varphi(r_{AB}$ if (A, B) is the lowest threshold
- Improvements of the dynamics: relativity, spin-orbit and tensor forces, three-body and higher n-body forces

Outlook: The Pandora box syndrome

- The constituent quark model suggests very few bound states, and its resonances are usually broad
- It involves intricate few-body calculations
- The molecular model is very appealing, with its analogy with nuclear physics, but it predicts many many states.
- For instance, Riska and Julia-Diaz have a whole periodic table of double-charm nuclei.
- If $X(3872) = D\bar{D}^*$ at the edge of binding, $DD\bar{D}^*$ should exist and perhaps develop Efimov recurrences

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Outlook: The Pandora box syndrome

- The diquark model was rediscovered for explaining the light pentaquark, and re-rediscovered for the X, Y, Z mesons.
- It is at last realised that if it leads to pentaquarks, it also lead to dibaryons, etc.

From pentaquarks to dibaryons in $\Lambda_b(5620)$ decays

CrossMark

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ABSTRACT

Pentaquarks and dibaryons are natural possibilities if diquarks are used as the building blocks to assemble hadrons. In this short note, motivated by the very recent discovery of two pentaquark states, we highlight some possible channels to search for dibaryons in $\Lambda_b(5620)$ decays.

Diquark Deuteron

Sverker Fredriksson and Magnus Jändel
Department of Theoretical Physics, Royal Institute of Technology, S-100 44 Stockholm 70, Sweden
(Received 9 October 1981)

It is speculated that an almost stable state of hadronic and nuclear matter can be built from *diquarks*. It is suggested that this alternative form of matter has already revealed itself in existing experimental data in the form of a diquark "deuteron" with $J^P = 0^-$ and with several other anomalous properties.

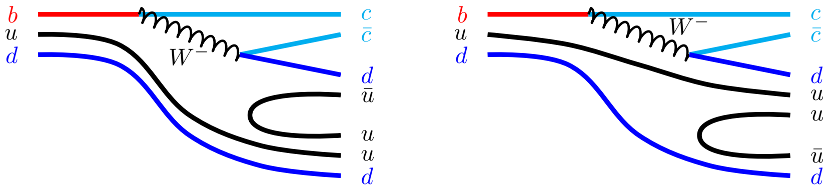
PACS numbers: 12.35.Ht, 14.20.Pt

Outlook:Some other states to look at

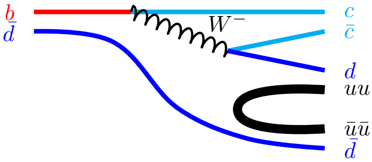
- At least isospin partners,
- At least alternative production modes
- Also strange partners, and hidden-beauty partners
- Naked anticharm pentaquark
- Double-charm mesons
- Involving different triggers!

Outlook: Production mechanism

$$\Lambda_b \to J/\psi\pi^- p$$



$$B \to J/\psi\bar{p}p$$



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Outlook: Heavy dibaryons

- Dibaryons ($QQ'qqqq$) tentatively combine
  - The chromoelectric interaction QQ'
  - The chromomagnetic interaction in $qqqq$ (triplet of SU(3)$_f$) as in the 1987-vintage pentaquark
- while the thresholds such as $(QQq) + (qqq)$ and $(Qqq) + (Qqq)$ get only one effect.
- If its works, it means that one has many discoveries awaiting in the double charm sector
  - double -charm baryons
  - double -charm mesons
  - double -charm dibaryons
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