# Pentaquark

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# Combining heavy and light

Already important in atomic physics. For instance, if you give the electron a mass $m_e = 1$ GeV, much less excitations, much less ions, much less molecules.

In quark physics, there is some analogy in the chromo-electric sector, but the magnetic part plays a more important role.

Already noticed that some configurations with $u$, $d$, and $s$ are interesting for exotics (Isgur, Lipkin, Jaffe, etc.)

The $c$ is not just another flavour. $s \to c$ reduces some chromomagnetic effects, and some candidates can disappear in the change $s \to c$. But $c$ has sometimes better chromoelectric effects, and thus some new candidates can emerge from $s \to c$ or $q \to c$.

# Combining heavy and light

## 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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**Do narrow heavy multiquark states exist?**

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(Received 11 August 1981)

**Possibility of Charmed Hypernuclei**

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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)

**NEW POSSIBILITIES FOR EXOTIC HADRONS – ANTICHARMED STRANGE BARYONS** ☆

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Received 1 June 1987

**POSSIBILITY OF STABLE MULTIQUARK BARYONS**

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Received 8 April 1987

# *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 $Z_1(2500)$.

**References**


1. Particle Data Group, Rev. Mod. Phys. **48**, S188 (1976).
2. R.L. Kelly, in *Proceedings of the Meeting on Exotic Resonances* (Hiroshima, 1978), ed. I. Endo *et al.*
3. G.C. Oades, in *Low and Intermediate Energy Kaon-Nucleon Physics* (1981), ed. E. Ferrari and G. Violini.
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# Colour chemistry

Much excitation in the late 70s and in the 80s about baryonium.
States seen in $\bar{p}p$ scattering and in $\bar{p}p \to \gamma + X$
Already two interpretations

- Molecules: $\bar{N}N$ bound states. Fermi-Yang, Ball-Scotti-Wong revisited. $\bar{N}N$ not aimed at describing ordinary mesons, but new states! See Shapiro et al., Dover et al., etc.
- Multiquarks: $(\bar{q}\bar{q}qq)$ states. See Rosner, Veneziano et al., Jaffe, Chan H.-M. et al.

The latter group was more adventurous. They introduced clusters made of exotic colour states, e.g., $(qq)$ in colour sextet, while $(qq)$ is always antitriplet in ordinary baryons. In particular, they distinguished true-baryonium states, $(\bar{q}\bar{q}) - (qq)$ of $\bar{3} - 3$ structure, that they shared with Rosner and the others, from mock-baryonium states of $6 - \bar{6}$ colour structure.
Other states were built within colour chemistry. In particular, DeSwart et al., and Sorba et al. studied 5-quark baryons $(\bar{q}qqqq)$ in some details.

# The 1987-vintage pentaquark

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**POSSIBILITY OF STABLE MULTIQUARK BARYONS**

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

# The 1987-vintage pentaquark

## Chromomagnetic operator

Start from

$$H_{ss} = \sum \tilde{\lambda}_i.\tilde{\lambda}_j \, \boldsymbol{\sigma}_i.\boldsymbol{\sigma}_j \, \frac{C}{m_i \, m_j} \, \delta^{(3)}(\boldsymbol{r}_{ij})$$

in the SU(3)$_\mathrm{f}$ limit, and $m_Q \to \infty$, and $\langle \delta^{(3)}(\boldsymbol{r}_{ij}) \rangle$ universal!!!
Reads

$$\tilde{H}_{ss} = \sum_{\text{light}} C' \, \tilde{\lambda}_i.\tilde{\lambda}_j \, \boldsymbol{\sigma}_i.\boldsymbol{\sigma}_j$$

Then in units of $C'$, you get $+8$ for $\Delta$, $\Sigma^*$, etc., and $-8$ for $N$, $\Lambda$, etc.
Thus $-16$ for $\Lambda\Lambda$ and $-24$ for $H = (uuddss)$.
This is the beginning of the story for the $H$ in 1977.
You also get $-16$ for $P_Q$ vs. $-8$ for the $(\bar{Q}q) + (qqq)$ threshold.
This is the beginning of the story of the $P_Q$ in 1987.

# The 1987-vintage pentaquark

## More refined quark models

Many corrections studied for $H$ and $P_Q$:

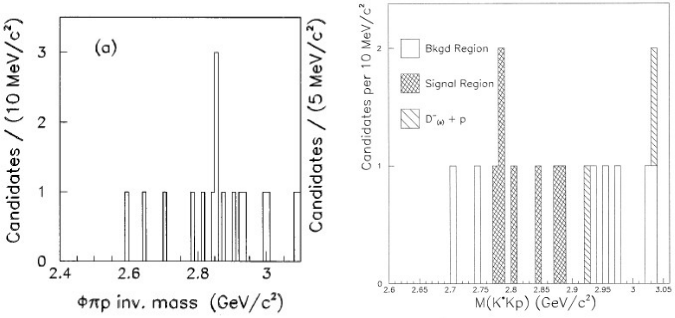
- $\mathrm{SU}(3)_\mathrm{f}$ breaking
- $\langle\delta^{(3)}(\boldsymbol{r}_{ij})\rangle$ self-consistent, i.e., not borrowed from ordinary baryons and non-perturbative (requires regularization)
- $m_Q$ finite for the pentaquark

See, Oka and Yazaki, Rosner, Karl et al., etc.
All effects weaken the binding, and eventually, the stability is seemingly lost. But the 5- or 6-body calculation could perhaps be improved.
For instance $(cc\bar{u}\bar{d})$ has been calculated by several groups using the same benchmark model. It was first found unbound, but refined computations got it stable!
See, also, the $\mathrm{Ps}_2$ story.

# The 1987-vintage pentaquark

## Search at Fermilab

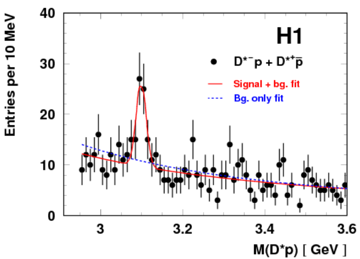
Aitala et al. searched for $P_c^0 = (\bar{c}suud) \to K^{*,0} K^- p$ and $\phi\pi^- p$. Not conclusive.

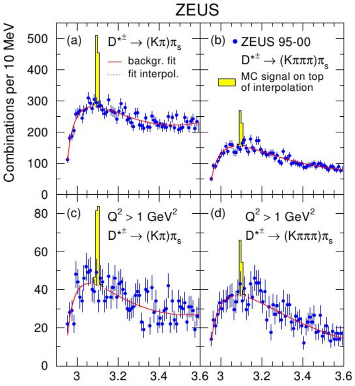



A fraction of this collaboration was interested in doing some search at CERN or at some hadron factories, but this was never approved as a priority.

# The 1987-vintage pentaquark

## Search at Hera



# The light pentaquark

- The HERA search was motivated by the light pentaquark
- Predicted in some developments of chiral dynamics (Chemtob, Diakonov et al., ...)
- A group in Japan was adventurous enough to look at it,
- They found a signal
- Confirmed by some other collaborations from their recorded data, never scanned before for such states!
- Eventually not confirmed by CLAS at Jlab, nor by high-energy experiments (Babar, etc., ) that do not find the double-charm baryons either!

# 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.

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(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∼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

# Molecular model

Pandora box?

- Many other predictions
- Almost any hadron, or even excited, forming a resonance with any other hadron
- Back to Chew-Low,, with improved modeling of the hadron-hadron interaction
- For instance, meson-baryon, baryon-baryon, etc.
- Sometimes vector-meson exchange, i.e., not really very long-ranged
- Unlike nuclear physics, no hard core to keep the hadrons separated
- Hence any new states is followed the next morning by a dozen of papers on ArXiV

# Diquark model

## Pandora box?

- Other multiquarks predicted
- See, e.g., early paper by Frederikson on dibaryons
- Or the recent paper by Maiani et al.

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.

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**Diquark Deuteron**

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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.

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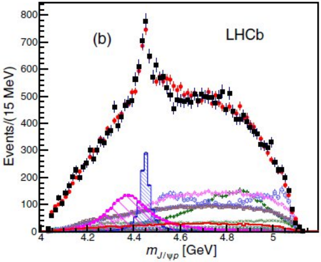
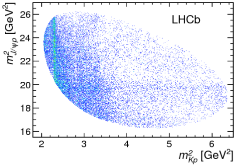
# The LHCb pentaquarks

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




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!

# Chromomagnetic model

- The discovery of heavy pentaquarks by LHCb has stimulated some renewed interest on multiquark calculations
- In particular the series of papers by Leandri and Silvestre-Brac and by Yuan, Wei, He, Xu and Zou
- This study shows the possibility of attraction in some channels, with two main conclusions,
  - a state $(1/2)^-$ likely to exist
  - also in the $\bar{c}cusd$ sector

# Towards a quark model calculation of the hidden-charm pentaquark

- Revisit Leandri et al., and Yuan et al.
- Start a genuine 5-body calculation

$$H = \sum_i T_i + V_{\text{chromolectric}} + V_{\text{chromomagnetic}}$$

- Extrapolate to $(\bar{b}cuud)$, $(\bar{c}buud)$, $(\bar{b}buud)$, etc., in the heavy sector
- Extrapolate to $(\bar{c}cuds)$, $(\bar{c}cssu)$, etc., in the light sector

# Outlook

- New states not always were they are expected
- Most models suffer from the Pandora-box syndrome
- Double-charm mesons and anti-charmed baryons to be searched for