Multiquark spectroscopy

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1. Outline

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   - X(3.872)
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2. Multiquarks in constituent models
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   - Flavour-spin alternatives
   - Heavy-heavy and light-light effects
3. Outlook

2. Experimental situation on multiquarks

2.1. Dibaryons, multibaryons

2.1.1. Deuteron

First seen by Urey. Firmly established. More often (p, n) than $(qqqqqq)$. Other nuclei reported.

2.1.2. Dibaryons

NN peaks in the continuum. Often reported. Never firmly confirmed. "Supported" by early bag-models with artificial confinement, i.e., no realistic estimate of the 'fall-apart" width.

2.1.3. Hypernuclei

Several states seen. Recent progress on light hypernuclei, but no $B = 2$ bound state.
$S = -2$ states identified, such as ${}^{6}_{\Lambda\Lambda}\mathrm{He}$.

2.2. Charmed mesons

$D_{s,J}$ states seen at 2317 and 2463 MeV by Babar, Cleo, etc.
Too low for ordinary orbital excitations.
Interpreted as chiral partners $\{0^+, 1^+\}$ of the ground-state multiplet $\{0^-, 1^-\}$.
Or as multiquarks $(cq\bar{s}\bar{q})$.
The higher state $D_s(2.632)$ seen by Selex is not confirmed in other experiments.
This state was considered by Maiani et al. and Nicolescu et al. as reminiscent of the late baryonium.

2.3. X(3.872)

Seen by Babar, Belle, $D0$, CDF, etc. , with a width $\Gamma \leq 2.3$ MeV
Not seen in $\gamma\gamma$ at CLEO, Babar, this restricting the possible quantum numbers.
Production patterns suggest just another charmonium level.
Spectroscopy more in line with a molecular interpretation
$(c\bar{c}q\bar{q}) \sim D\bar{D}^* + \text{c.c.},$
as predicted by Törnqvist, Ericson and Karl, Braaten, Manohar and Wise, etc.
Warning: an earlier molecular assignment (Voloshin et al., De Rujùla et al.) failed for what was later identified as the mere $\Psi(3S)$.

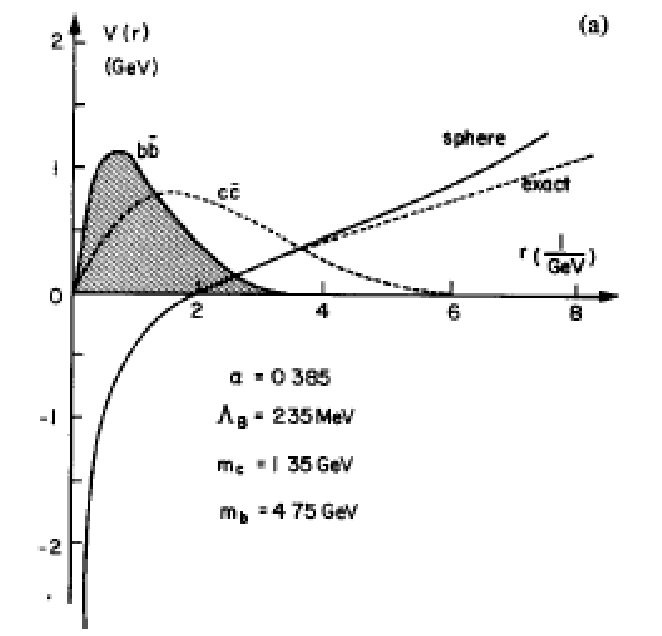
2.4. Hybrids of heavy quarkonia

Early speculations by Giles and Tye (1977), Mandula and Horn (1978), and Hasenfratz, Horgan, Kuti and R. (1980).

The gluon, being coloured, is not only the vector of the interaction, it can also play a constituent role.

Ordinary quarkonium: governed by $V_{Q\overline{Q}}$, a kind of Born–Oppenheimer potential with the gluon field in its gournd-state.

Hybrid quarkonium: Next Born–Opppenheimer potential, with gluon field excited.


(a)
V (r)
(GeV)
2
1
0
-1
-2
$b\bar{b}$
$c\bar{c}$
sphere
exact
r (1/GeV)
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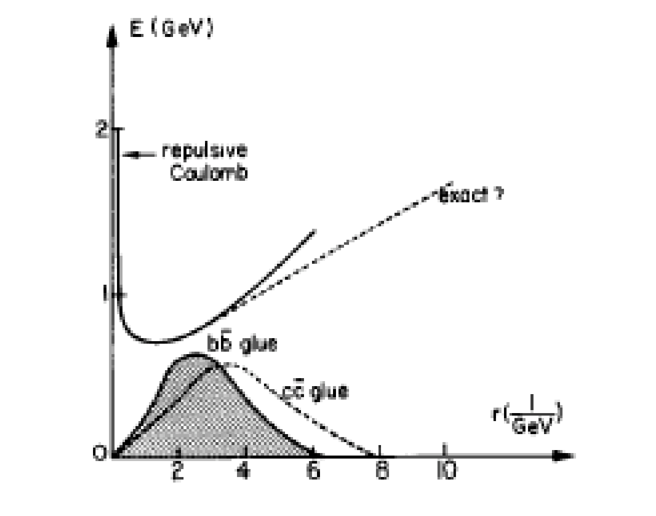
4
6
8
α = 0 385
Λ_B = 235 MeV
m_c = 1 35 GeV
m_b = 4 75 GeV


E (GeV)
2
1
0
repulsive Coulomb
exact ?
$b\bar{b}$ glue
$c\bar{c}$ glue
r (1/GeV)
2
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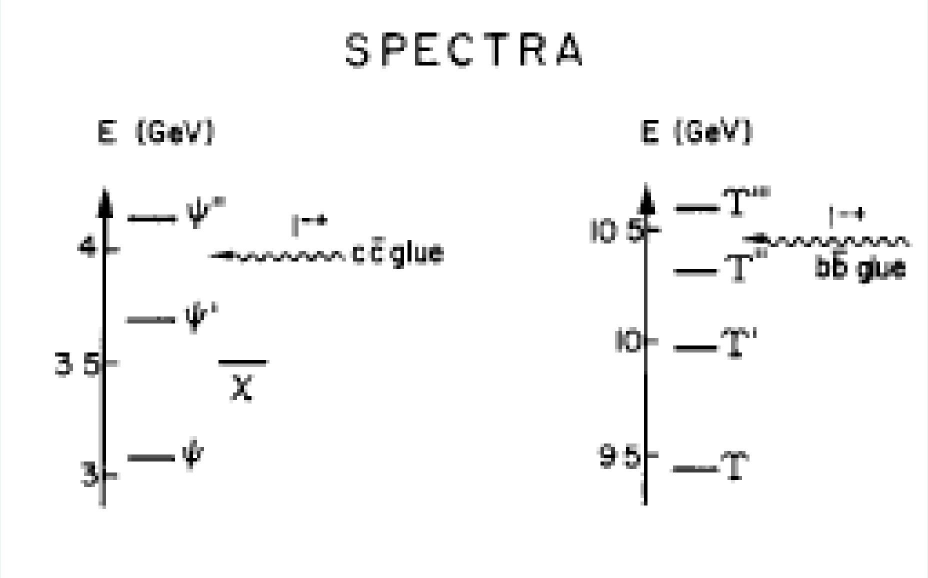
1980 predictions



$c\bar{c}g \sim 4$ GeV $\qquad b\bar{b}g \sim 10.4$ GeV

Further predictions

Flux-tube models, lattice QCD Usually masses a little higher.

Recently discovered state

DISCUSSION

We have observed a strong near-threshold enhancement in the $\omega J/\psi$ mass spectrum in exclusive $B \to K\omega J/\psi$ decays. The enhancement peaks well above threshold and is broad [9]: if treated as a single resonance, we find a mass of 3941 ± 11 MeV and a total width $\Gamma = 92 \pm 24$ MeV. It is expected that any "normal" $c\bar{c}$ charmonium meson with this mass would dominantly decay to $D\bar{D}$ and/or $D\bar{D}^*$; hadronic charmonium transitions should have minuscule branching fractions. The properties of the observed enhancement are similar to those of $c\bar{c}$-*gluon* charmonium hybrid states that occur in Lattice QCD [10] and are expected to be produced in B-meson decays [11]. However, the Lattice calculations indicate that the lightest hybrid states have masses around 4400 MeV, well above the mass of the enhancement reported here.

Belle, hep-ex/0408126

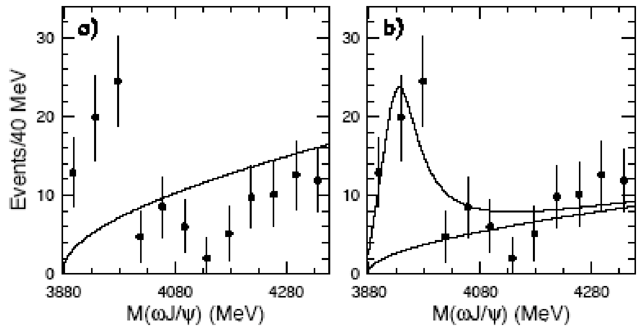


FIG. 6: $B \to K\omega J/\psi$ signal yields *vs* $M(\omega J/\psi)$. The curve in (a) indicates the result of a fit that includes only a phase-space-like threshold function. The curve in (b) shows the result of a fit that includes an S-wave Breit-Wigner resonance term.

2.5. Missing charmonium states

Singlet states of charmonium anticipated to be elusive, but not at that level.

1. A wrong $\eta_c(1S)$ was announced 300 MeV below J/Ψ. Then the true η_c was seen in several experiments, about 120 MeV below J/Ψ.
2. $\eta_c(2S)$ was announced about 90 MeV below Ψ', but resisted confirmation or better determination at Fermilab $p\bar{p}$, LEP $\gamma\gamma$, etc. The solution was found by Belle, with two new production schemes, and a $\psi' - \eta_c'$ splitting much smaller (~ 40).
   - $e^+e^- \to c\bar{c}c\bar{c}$ and trigger on J/Ψ,
   - B decay.
3. $h_c\,(^1P_1)$ tentatively seen in R704 at CERN ISR, seen in E760 (Fermilab $p\bar{b}$), not seen in its continuation E835, eventually seen by E835 in another channel, and at CLEO.

   This means that 30 years of efforts have been necessary!

2.6. Pentaquarks

Recent surveys by Dzierba et al. (hep-ex/0412077), Belle (hep-ex/0411005) and Babar (private communication).

1. Early indications in the 60's for Z resonances with $S = +1$, $B = +1$
2. $\theta^+(1540)$ seen in a couple of experiments but not seen in several others, including expensive experiments with very good particle identification and cross-checks on many channels (Babar, Belle, HyperCP, etc.)
3. θ_c seen in 1 experiment at HERA, not seen by others.
4. $\Xi^{--}(1860)$ seen in 1/2 experiment, and not seen in several $+1/2$ others.

Positive results on pentaquarks

Table 1. Positive signals for pentaquark states. Please see the text regarding the final state neutron in the LEPS, CLAS and SAPHIR experiments.

Experiment	Reaction	State	Mode	Reference
LEPS(1)	$\gamma C_{12} \to K^+K^-X$	θ^+	K^+n	[4]
LEPS(2)	$\gamma d \to K^+K^-X$	θ^+	K^+n	[5]
CLAS(d)	$\gamma d \to K^+K^-(n)p$	θ^+	K^+n	[6]
CLAS(p)	$\gamma p \to K^+K^-\pi^+(n)$	θ^+	K^+n	[7]
SAPHIR	$\gamma p \to K^0_S K^+(n)$	θ^+	K^+n	[8]
COSY	$pp \to \Sigma^+ K^0_S p$	θ^+	$K^0_S p$	[9]
JINR	$p(C_3H_8) \to K^0_S pX$	θ^+	$K^0_S p$	[10]
SVD	$pA \to K^0_S pX$	θ^+	$K^0_S p$	[11]
DIANA	$K^+Xe \to K^0_S p(Xe)'$	θ^+	$K^0_S p$	[12]
νBC	$\nu A \to K^0_S pX$	θ^+	$K^0_S p$	[13]
NOMAD	$\nu A \to K^0_S pX$	θ^+	$K^0_S p$	[14]
HERMES	quasi-real photoproduction	θ^+	$K^0_S p$	[15]
ZEUS	$ep \to K^0_S pX$	θ^+	$K^0_S p$	[16]
NA49	$pp \to \Xi\pi X$	Ξ_5	$\Xi\pi$	[17]
H1	$ep \to (D^*p)X$	θ_c	D^*p	[18]

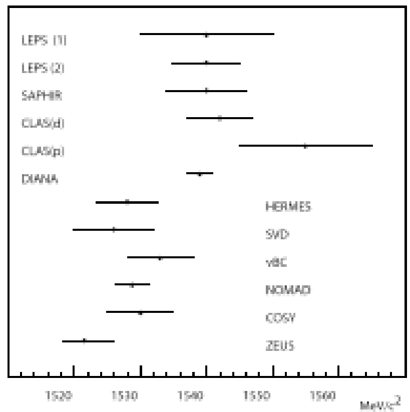


Figure 6. Reported masses, with error bars, of the θ^+.

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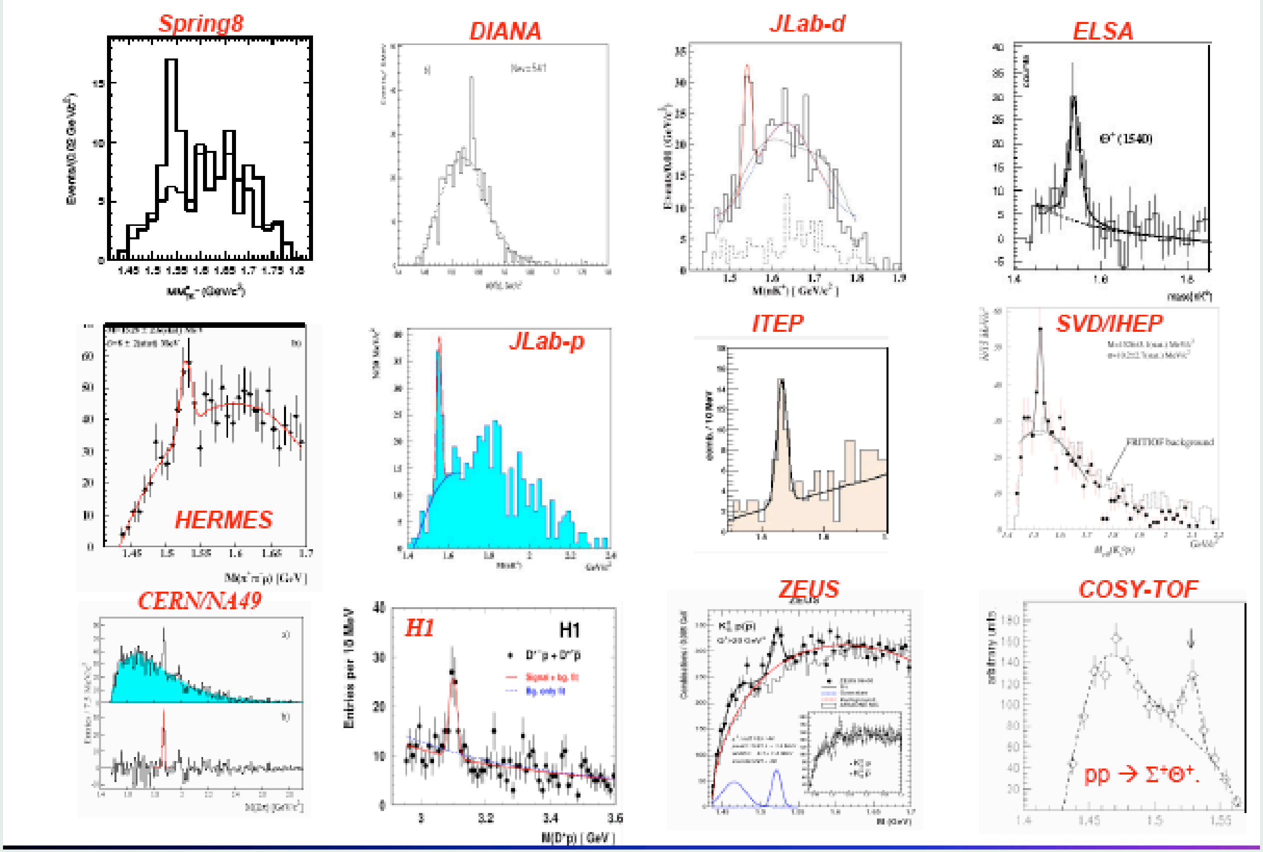
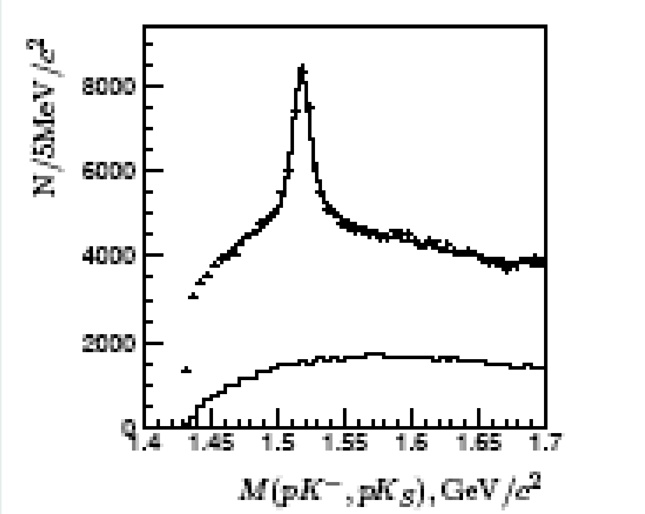
Positive results on pentaquarks



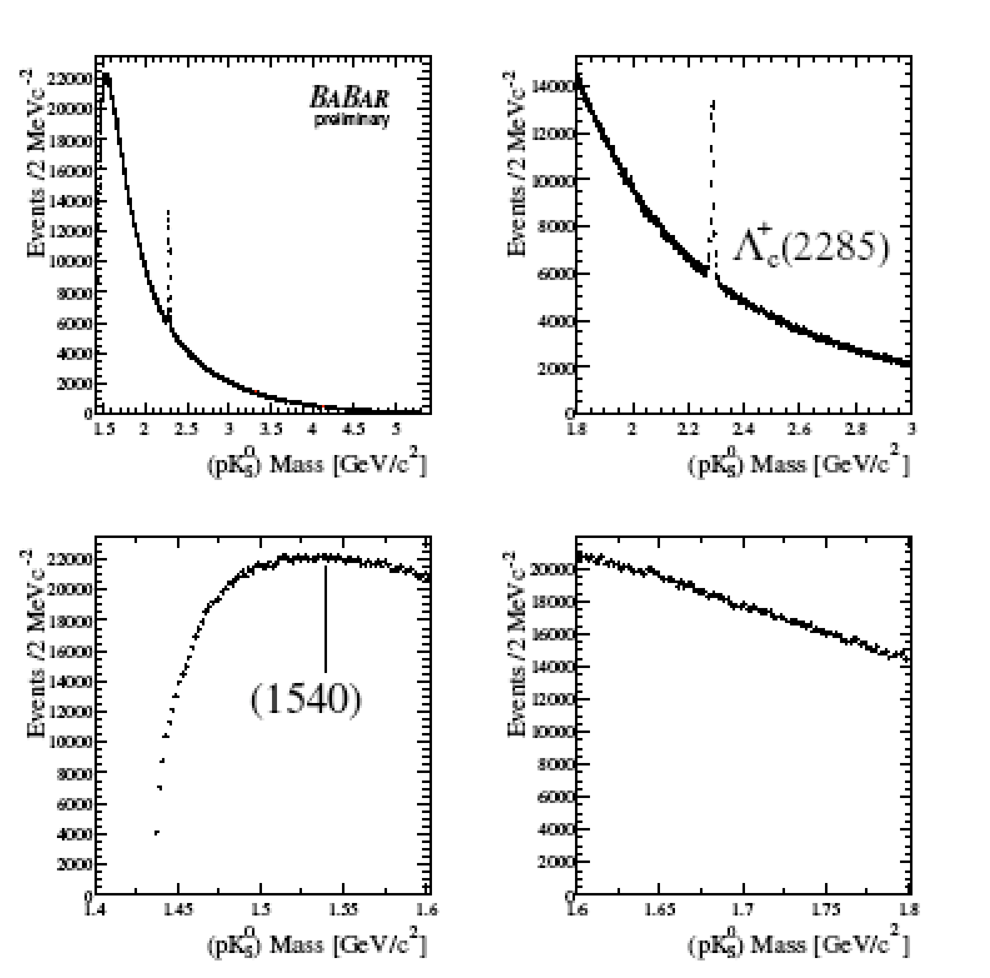
Negative results on pentaquarks

Table 2. Recent negative searches for pentaquark states. For each pentaquark state (P) we indicated with a – that the state was not included in the search while ↓ indicates that the state was searched for and not observed and ↑ indicates that the state was searched for and observed.

Experiment	Search Reaction	θ^+	Ξ_5	θ_c	Reference
ALEPH	Hadronic Z decays	↓	↓	↓	[19]
BaBar	$e^+e^- \to \Upsilon(4S)$	↓	↓	–	[20]
BELLE	$KN \to PX$	↓	–	↓	[21]
BES	$e^+e^- \to J/\psi(\psi(2S) \to \theta\bar{\theta}$	↓	–	↓	[22]
CDF	$p\bar{p} \to PX$	↓	↓	↓	[23]
COMPASS	$\mu^+(^6LiD) \to PX$	↓	↓	–	[24]
DELPHI	Hadronic Z decays	↓	–	–	[25]
E690	$pp \to PX$	↓	↓	–	[26]
FOCUS	$\gamma p \to PX$	↓	↓	↓	[27]
HERA-B	$pA \to PX$	↓	↓	–	[28]
HyperCP	$(\pi^+, K^+, p)Cu \to PX$	↓	–	–	[29]
LASS	$K^+p \to K^+n\pi^+$	↓	–	–	[30]
L3	$\gamma\gamma \to \theta\bar{\theta}$	↓	–	–	[25, 31]
PHENIX	$AuAu \to PX$	↓	–	–	[32]
SELEX	$(\pi, p, \Sigma)p \to PX$	↓	–	–	[33]
SPHINX	$pC(N) \to \theta^+C(N)$	↓	–	–	[34]
WA89	$\Sigma^-N \to PX$	–	↓	–	[36]
ZEUS	$ep \to PX$	↑	↓	↓	[16, 37, 38]



Negative results on pentaquarks



3. Multiquarks in constituent models

Warning: Often misleading statements, even in otherwise excellent papers: constituent models bind everything, or constituent models never bind.
In fact, sometimes confusion between constituent models, unjustified approximation to them, early bag models, mass formulas, etc.

3.1. Central confining forces

Generic Hamiltonian,

$$H\{q_i\} = \sum_i t_i + \sum_{i<j} \tilde{\lambda}_i^{(c)}.\tilde{\lambda}_j^{(c)}\, v_{ij} ,$$

with e.g., $t_i = \boldsymbol{p}_i^2/(2m_i)$ or relativistic, $v_{ij} \propto r_{ij}$, with a colour-dependence corresponding to pair-wise forces and colour-octet exchange,
usually do not bind multiquarks, for instance, with equal masses,

$$\min\left[H(qq\bar{q}\bar{q})\right] = (q\bar{q}) + (q\bar{q}) ,$$

i.e., no normalisable state satisfying Hunziker–van Winter–Zhislin's theorem.

Binding multiquarks?

Hence binding should be sought in

- additional terms
  - chromomagnetism,
  - spin-flavour terms,
  - nuclear-type interaction of light qarks,
  - etc.

- well-chosen mass asymmetry,
- improved model of confinement (3-body, 4-body forces, ...)

We shall now survey some of these possibilities.

3.2. Colour chemistry

- Nice idea of exhibiting internal colour degrees of freedom
- Assume, e.g., $[(qq)--(\bar{q}\bar{q})]$ with orbital barrier (baryonium) and possibly colour sextet (qq)
- Also $[(qqq)--(q\bar{q})]$, or $[(q\bar{q})--(q\bar{q})]$ with octets, etc.
- Baryonium hardly decays into mesons, and not easily into baryon–antibaryon,
- Does not work, unfortunately. This assumed clustering was never justified.
- Unlike $[(qq)--q]$ clustering of orbitally-excited ordinary baryons, explaining $\alpha'_{\text{baryons}} \simeq \alpha'_{\text{mesons}}$ of Regge slopes, and proved in a large class of models.
- Pandora box? If, e.g., $(ud\bar{s})$ low in mass, is $(ud\bar{s})^3$ stable, i.e., $(\overline{\Omega}^+ pn) = (u^3 d^3 \bar{s}^3)$bound?

3.3. Chromomagnetism, the *H*

The simple chromomagnetic Hamiltonian (DGG, etc.)

$$H_{SS} = -C \sum_{i<j} \boldsymbol{\sigma}_i . \boldsymbol{\sigma}_j \, \tilde{\lambda}_i^{(c)} . \tilde{\lambda}_j^{(c)} \, \delta^{(3)}(\boldsymbol{r}_{ij})$$

or its bag model analog, explains the pattern of hyperfine splittings of ordinary hadrons.
In 1977, Jaffe noticed it gives more coherent attraction in some multiquarks than in the sum of the hadrons constituting the threshold.
Estimated

$$H(uuddss) - \Lambda(usd) - \Lambda(usd) = -150\ \mathrm{MeV}.$$

But all corrections weaken the effect:

- $\mathrm{SU}(3)_F$ breaking
- $\langle \delta^{(3)} \rangle$ computed instead of borrowed from ordinary hadrons.

3.4. Chromomagnetism, the P

Gignoux et al. –see also Lipkin –, in 1987, have shown that the same mechanism gives the same -150 MeV energy for

$$P(\overline{Q}qqqq) - (\overline{Q}q) - (qqq)\ ,$$

and used the name pentaquark.
Again, 150 MeV corresponds to $\mathrm{SU}(3)_F$ in the $qqqq$ sector, $m(Q) \to \infty$ and $\langle \delta^{(3)} \rangle$ borrowed from light baryons.

All corrections make this pentaquark less stable.
This pentaquark was searched for at Fermilab (Ashery et al.). Results are not conclusive.

3.5. Flavour–spin alternative

Glozmann, Riska, and many others proposed an hyperfine interaction

$$H_{SS} \propto \sum_{i<j} \boldsymbol{\sigma}_i.\boldsymbol{\sigma}_j\,\boldsymbol{\tau}_i.\boldsymbol{\tau}_j\ , \quad \text{or} \quad \sum_{i<j} \boldsymbol{\sigma}_i.\boldsymbol{\sigma}_j\,\tilde{\lambda}_i.\tilde{\lambda}_j\ .$$

See Stancu later this week.

3.6. Nuclear forces

It is regularly pointed out that the Yukawa mechanism, that is successful for the L.R. part of nuclear forces, also act between other hadrons.
Voloshin et al., Törnqvist, Ericson & Karl, Manohar & Wise, Braaten, etc.
$D\overline{D}^* + \text{c.c.}$ potential weaker than the NN one (which barely binds the deuteron), but experienced by heavier particles. What matters is $g \times m_{\text{red}}$.
Perhaps an explanation of the $X(3872)$.
Several other configurations are favourable
e.g., DD^* on which more shortly,
or $(ccq) + (ccq)$ of Julia-Diaz & Riska: multicharmed multibaryons.

3.7. Borromean binding

This Yukawa mechanism, and other mechanisms, often fail by a small margin to bind two hadrons.

Hence, we are in an ideal situation for Borromean binding: 3-body binding with unbound 2-body subsystems, except if inhibited by the Pauli principle or a requirement of conflicting spin alignments.

Borromean binding explains why $(\alpha n n) = {}^6\mathrm{He}$ is stable,
while neither $(\alpha n) = {}^5\mathrm{He}$ nor (n, n) are bound.

Examples also in molecular physics.

Already $KN\pi$ proposed as a Borromean system to describe the pentaquark. Bicudo and others.

3.8. Heavy–heavy effect

In a given potential, two heavy particles take better benefit of the attraction. For instance

$$E = -\frac{m}{2}\alpha^2\,, \quad E \propto \sqrt{\frac{k}{m}}\,,$$

for Coulomb and H.O.

In quark models, $(QQ\bar{q}\bar{q})$ experiences a QQ attraction that is absent in the threshold $(Q\bar{q}) + (Q\bar{q})$. See Ader et al., Heller et al., Brink et al., Lipkin, etc. Latest calculation by Rosina et al. in FBS.

3.9. Double charm exotics?

The $(QQ\bar{q}\bar{q})$ is one of the most promising configuration, as it benefits from both the heavy–heavy effect and the nuclear forces.

The double-charm production in B-factories is perhaps a production tool.

4. Outlook

4.1. Experiments

- Be patient, it took 30 years for h_c
- $\eta_c(2S)$ was discovered by new modes, not by higher statistics.
- Some sectors not yet explored,
  e.g., double-charm mesons, clusters of heavy baryons.
  Surprises are still possible.

4.2. Constituent models

- Usually no stable bound states.
- Models based on short-range correlations are fragile.
- Heavy–heavy and light–light effects favourable if present in the multiquark and absent in the threshold.
- Multiquark calculations are very delicate,
  the wave function "hesitates" between single vs. multiple clusters.
  Remember Ps_2!

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