Some hot issues in hadron spectroscopy

Jean-Marc Richard

Laboratoire de Physique Subatomique et Cosmologie
Université Joseph Fourier–IN2P3-CNRS
Grenoble, France

Orsay, June 25, 2004
Outline

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2. Double-charm baryons
3. Tetraquarks
4. Pentaquarks
5. Hexaquarks
6. Multiquarks in constituent models and other approaches
Outline

1. Introduction
2. Double-charm baryons
3. Tetraquarks
4. Pentaquarks
5. Hexaquarks
6. Multiquarks in constituent models and other approaches
7. Outlook
1. Introduction

Several recent developments in hadron spectroscopy.

\( Q\bar{Q} \): New states in \((c\bar{c})\) and \((b\bar{b})\)

New means: \(\gamma \gamma\), double charm production, \(e^+e^- \rightarrow J/\Psi + X\), \(B\) decay, \(h_c\) eventually found, close to \(\Psi'\), an effect of coupling to \(D\bar{D}^{(*)}\) channels.

\(h_c\) not confirmed. Needed to test the short-range character of spin–spin forces.

\((b\bar{c})\) states found. Illustrate exp. progress in tracking heavy flavour.
Illustration: evidence for the $\eta'_c$

$B$ decay

Illustration: $e^+ e^- \rightarrow c\bar{c}$

Graph: $N/20 \text{ MeV}/c^2$ vs. Recoil Mass($J/\psi$) GeV/$c^2$

Graph: Events/40 MeV/$c^2$ vs. $M_{K_s\pi}$ (MeV/$c^2$)
\(D_s^*, J\) states at Belle, Babar, Cleo, Selex, etc.

Scalar excitation close to ground state. Too large a spin-orbit force for potential models. Chiral partner of the ground-state? Or 4-quark state?

**Introduction**

**Double-charm**

**Double-charm**

**Tetraquarks**

**Pentaquarks**

**Hexaquarks**

**Theoretical**

**Conclusions**

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**BABAR (B decay)**

**BELLE (B decay)**

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**FIG. 1:** (a) The distribution of \(K^+K^-\pi^+\) mass for all candidate events. Additional selection criteria, described in Ref. [4], are used to enhance signal purity.

**FIG. 2:** The \(D_s^+\pi^0\) mass distribution for (a) the decay \(D_s^+ \rightarrow K^+K^-\pi^+\) and (b) the decay \(D_s^+ \rightarrow K^+\pi^+\pi^0\). The fits to the mass distributions as described in the text are indicated by the curves.

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FIG. 1: Distributions of (a) the masses $M(D_s\pi^0)$ of the $D_s\pi^0$ candidates and (b) the mass differences $\Delta M = M(D_s\gamma) - M(D_s\pi^0)$ when we describe our studies of the $D^*+s\pi^0$ final state.

The kinematics of the $D^0\to K\pi\pi\gamma$ side band regions, defined as $200 < M(D_s\pi^0) < 2463$ (MeV/c$^2$) spectrum where $D_s$ that decays to $s\pi^0\gamma$.

When we describe our studies of the $D^*+s\pi^0$ final state.

The agreement between the Monte Carlo and data distributions in Fig. 1 in normalization is known to a precision of approximately 10% from decays involving known particles, either through the addition, omission or substitution of those particles, especially for events satisfying cuts on $M(D_s\pi^0)$ mass, as described in the text. The points represent the CLEO data, while the solid histogram is the predicted spectrum from the Monte Carlo simulation.
Fig. state events $\Delta M$ Mass Significance $\sigma$ $\Gamma$ $\chi^2/nd$
| 1 | $\eta(548) \rightarrow \gamma\gamma$ | 5087 ± 863 | 544.8 ± 2.9 | 13.9 $\sigma$ | 27.8 ± 4.3 | 1.17 |
| 2 | $D_s^+(2632) \rightarrow D_s^+\eta$ | 45 ± 9.3 | 667.4 ± 2.9 | 7.2 $\sigma$ | 10.7 | 0.95 |
| 3 | $D_s^+(2573) \rightarrow D^0K^+$ | 25 ± 9 | 705.4 ± 4.3 | 5.4 $\sigma$ | 4.9 | 14$^+9_{-6}$ |
| 3 | $D_s^+(2632) \rightarrow D^0K^+$ | 14 ± 4.5 | 767.0 ± 1.9 | 5.3 $\sigma$ | 4.9 | < 17(90%CL) |

Fig. 1: M(KK$^\pm$ $\eta$) mass difference distribution. Charged conjugates are included. The shaded region is the event excess used in the estimation of signal significance. Results for the fit shown are in Table I. (b) Mass difference distribution for mixed events as described in the text.

\[ \Xi_{cc}^+ \] seen in two different decay modes:

\[ \Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+ \]
\[ \Xi_{cc}^+ \rightarrow p D^+ K^- \]

FIG. 3: Gaussian fits for \( \Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+ \) (unshaded) \( \Xi_{cc}^+ \rightarrow p D^+ K^- \) (shaded) on same plot.
1. other ± dedicated experiments, e.g., FOCUS, do not see $(ccq)$
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2. Isospin partners, excitations, tentatively seen by SELEX, need confirmation.
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2. Isospin partners, excitations, tentatively seen by SELEX, need confirmation.
SELEX Double Charmed Baryon States

An exited state and a pair of isodoublets?

The Experimental Discovery of Double-Charm Baryons
3. Double-charm baryons. Th.

Perhaps the most interesting of ordinary hadrons. Combine in a single object two extreme regime:

1. Slow motion of two heavy quarks, as in quarkonium
2. Relativistic motion of a light quark in the field of a static coloured source

The large $M/m$ ratio in $(QQq)$ indicates a quark–diquark structure. But a naive, two-step, calculation

1. Solve $QQ$ with $QQ$ direct interaction, to estimate the diquark
2. Solve $[QQ] - q$ to estimate the baryon

is inaccurate. The light quark modifies the $QQ$ interaction. By 50% for the H.O., i.e., about 25% for the energies.

Moreover, a new diquark is required for each of the first excited states.
Instead, a Born–Oppenheimer approach is perhaps better suited.

1. For a given $QQ$ separation, estimate the light quark energy in the field of two colour sources

2. Add the direct $QQ$ interaction, to build the effective $QQ$ potential

3. Solve the $QQ$ problem.

Tests in simple NR models show that the Born–Oppenheimer approximation is better than accurate (Fleck, R.)

The method could be applied with a better treatment of the light quark. One could also estimate directly the effective $QQ$ potential on the lattice.
Model Predictions for Doubly Charmed Baryons Masses

<table>
<thead>
<tr>
<th>author</th>
<th>year</th>
<th>model</th>
<th>$\Xi_{cc}(J = 3/2)$</th>
<th>$\Xi_{cc}(J = 1/2)$</th>
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<tbody>
<tr>
<td>Bjorken</td>
<td>1986</td>
<td>phenom</td>
<td>3.70 GeV/c^2</td>
<td>3.64 GeV/c^2</td>
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<tr>
<td>Fleck &amp; Richard</td>
<td>1989</td>
<td>bag</td>
<td>3.636</td>
<td>3.516</td>
</tr>
<tr>
<td>Fleck &amp; Richard</td>
<td>1989</td>
<td>quarkonium</td>
<td>3.741</td>
<td>3.613</td>
</tr>
<tr>
<td>Roncaglia et al.</td>
<td>1995</td>
<td>Feynmann/Hellman</td>
<td>3.81</td>
<td>3.66</td>
</tr>
<tr>
<td>Ellis</td>
<td>2002</td>
<td>phenom</td>
<td>3.711</td>
<td>3.651</td>
</tr>
</tbody>
</table>

- ground states near 3.6 GeV/c^2
- ground states Isospin=1/2 multiplets degenerate
- Hyperfine splitting around 60 – 120 MeV/c^2
- Most predict electromagnetic hyperfine transition (but some pionic)
- Model dependent predictions for orbital and radial excitations
- Some Models: Light Quark excitation characteristics similar to meson spectra (heavy (cc) diquark)

Production
- Basically no models (except independent production)
- Expect small production cross section
- But why not look anyway??

The Experimental Discovery of Double-Charm Baryons
**QQq** ground-state baryons weak decays.

\( D^0(c\bar{u}) \) and \( D^+(c\bar{d}) \) have different lifetimes.

The \( c \) quark, when decaying, does not ignore its surrounding. Besides simple \( W^+ \) emission (followed by lepton-pair or quark–antiquark creation), and by hadronization, there is a contribution of \( W \) exchange. Also interferences in the final state.

Applied to single-charm baryons, with qualitative success, but the spread of lifetimes larger than predicted. ∃ predictions for double-charm baryons. Again: simple \( W^+ \) emission, \( W \)-exchange, interferences.

In \( ccq \) (and in \( b\bar{c} \)), the \( c \) quark is deeply bound, discussions on the influence on lifetime.
Comparison of heavy hadron lifetimes (from Cooper)
Some contributions to the weak decay of double-charm baryons

Typical prediction: \( \tau(\Xi_{cc}^+) < \tau(\Omega_{cc}^+) < \tau(\Xi_{cc}^{++}) \)

(Guberina, Kiselev, Fleck, etc.) Interest also in BR (e.g., Semi-lept. vs. hadronic)
Beyond double charm: triple charm

The ultimate goal of baryon spectroscopy (Bjorken)
To study the \((QQQ)\) dynamics
Beyond double charm: triple charm

The ultimate goal of baryon spectroscopy (Bjorken)
To study the (QQQ) dynamics
4. Tetraquarks

Speculations on \((qq\bar{q}\bar{q})\) for many years.

- Low-lying scalar mesons (Jaffe, etc.)
- Excess of scalar mesons (L. Montanet, etc.)
- Some indication of exotics (Obelix)
4. **Tetraquarks**

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- Excess of scalar mesons (L. Montanet, etc.)
- Some indication of exotics (Obelix)

17) **HINTS FOR A \(I = 2\) PI PI RESONANT STATE IN THE ANTI-N P --> PI+ PI+ PI- ANNIHILATION REACTION.**

Published in *Nucl.Phys.A692:287-294, 2001*

- Long-range meson-meson interaction (see below)
- Favourable mass assymmetry in \((QQ\bar{q}\bar{q})\), etc.
Accidental agreement?

\[ X = c\bar{c} \ (2^{-+} \text{ or } 2^{--} \text{ or } \ldots), \]

or a molecular (multiquark) state?

\[ M = 3872.0 \pm 0.6 \pm 0.5 \text{ MeV} \]

\[ M(D^0 + D^{*0}) = 3871.5 \pm 0.5 \text{ MeV} \]

n.b. \[ M(D^+ + D^{*-}) = 3879.5 \pm 0.7 \text{ MeV} \]
5. Pentaquarks

5.1. Light pentaquark
5. Pentaquarks

5.1. Light pentaquark

Plots like have been shown very often in recent months. Here: LEPS and TOF.
Positive results
## Experimental signals for pentaquarks (Zhao and Close)

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Mass  (MeV)</th>
<th>Width  (MeV)</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPring-8 [1]</td>
<td>1540 ± 10</td>
<td>&lt; 25</td>
<td>(nK^+)</td>
</tr>
<tr>
<td>SAPHIR [3]</td>
<td>1540 ± 4 ± 2</td>
<td>&lt; 25</td>
<td>(nK^+)</td>
</tr>
<tr>
<td>CLAS-1 [2]</td>
<td>1542 ± 5</td>
<td>&lt; 21</td>
<td>(nK^+)</td>
</tr>
<tr>
<td>CLAS-2 [4]</td>
<td>1555 ± 10</td>
<td>&lt; 26</td>
<td>(nK^+)</td>
</tr>
<tr>
<td>DIANA [5]</td>
<td>1539 ± 2</td>
<td>&lt; 9</td>
<td>(K^+n \rightarrow K_S^0p)</td>
</tr>
<tr>
<td>HERMES [6]</td>
<td>1528 ± 2.6 ± 2.1</td>
<td>17 ± 9 ± 3</td>
<td>(pK_S^0)</td>
</tr>
<tr>
<td>SVD [8]</td>
<td>1526 ± 3 ± 3</td>
<td>&lt; 24</td>
<td>(pK_S^0)</td>
</tr>
<tr>
<td>ITEP ν [7]</td>
<td>1533 ± 5</td>
<td>&lt; 20</td>
<td>(pK_S^0)</td>
</tr>
<tr>
<td>ZEUS [9]</td>
<td>1521.5 ± 1.5</td>
<td>6.1 ± 1.6</td>
<td>(pK_S^0, \bar{p}K_S^0)</td>
</tr>
<tr>
<td>COSY-TOF [10]</td>
<td>1530 ± 5</td>
<td>&lt; 18 ± 4</td>
<td>(pp \rightarrow \Sigma^+pK_S^0)</td>
</tr>
</tbody>
</table>
References


[9] [ZEUS Collaboration], hep-ex/0403051.

More views of positive results
CLAS at Trento in February

The spectrum has been fitted to a (Gaussian + 5th order polynomial) using an unbinned Likelihood procedure.

A side-band subtraction method (2 and 4 nearest bins) was applied giving similar results.

The spectrum has been compared to MC simulation.

\[
N_{\text{peak}} = \text{sqrt}(N_{\text{bg}})
\]

\[
22 \pm \text{sqrt}(30)
\]

stat. sig. = (3.9 \pm 0.2)\sigma

Mass = 1523 +/- 5 MeV

FWHM ~ 9 MeV

\[
N_{\text{peak}} = \text{sqrt}(N_{\text{bg}})
\]

\[
27 \pm \text{sqrt}(26)
\]

stat. sig. = (6.0 \pm 0.2)\sigma

Mass = 1573 +/- 5 MeV

FWHM ~ 9 MeV

M. Battaglieri - Spectroscopy of Exotic Baryons with CLAS: Search for Ground and First Excited States
CLAS at Bloomington in Mai

\[ \gamma+p \rightarrow \pi^+K^-\Theta^+ \]
\[ \Theta^+ \rightarrow nK^+ \]

\[ \cos \theta^*(\pi^+) > 0.8 \]

V. Kubarovsky et al., PRL, Jan.'04
Negative results by ALEPH, HERA-b, CDF, BES, PHENIX, STAR, OPAL, DELPHI, HyperCP, etc. Other negative results not published.

ALEPH results, for instance
OPAL results

• Nothing to be seen
• But then, of course, people want more cuts, e.g.
  – Demand a $K^+K^-$ in events with $K_0^s$ p/p combinations
  – Tighter dE/dx selections
  – Cuts on candidate momentum
• To ensure avoidance of topiary, I did this “blind”
  – I made 24 mass plots with different, anonymous, cuts, and invited my colleagues to find a peak
  – All agreed there was nothing
• But still people want work on this ... I’m leaving it to Delphi

OPAL, unpublished

21 June 2002
George Lafferty
PHENIX results
DELPHI results

\[ \langle N(\Theta^{++}) \rangle < 0.006 \]

\[ \langle N(\Theta^+) \rangle < 0.015 \]

Thorsten Wengler, CERN @ Moriond '04 QCD, LaThuile, Italy
**$KN$ scattering**

See Cahn and Trilling, Sibirtsev et al., hep-ph/0405099;
Nussinov, hep-ph/0307357;
R.A. Arndt et al., nucl-th/0311030;

A small width is required for this state have escape detection in early or recent analyses of $KN$ data.

But a very small width is hard to understand.
E690 by D. Christian at QNP 2004
CDF by M.J. Wang at QNP 2004

θ+ Search: pK^0_s Mass Spectrum

No evidence of narrow resonance
DATA
Reconstructed $K^0, p$ mass, positive beam, events from thin window.
Babar

\[ K^0_{SP} \]

\[ 1.44 - 1.60 \text{ GeV/c}^2 \]

\[ \Theta^+ (1540) \]
5.2. $\Xi^{--}$ candidate

NA49 claim (part of the collaboration)

**FIG. 3:** (Color online) (a) The sum of the $\Xi^-\pi^-$, $\Xi^-\pi^+$, $\Xi^+\pi^-$ and $\Xi^+\pi^+$ invariant mass spectra. The shaded histogram shows the normalised mixed-event background. (b) Background subtracted spectrum with the Gaussian fit to the peak.
NA49 result (rest of the collaboration)
CDF search for $\Xi^{--}$
Babar search for $\Xi^{--}$

$e^+e^- \rightarrow \Xi^{--} X$ using $(\Xi^{--} \rightarrow \Xi^-\pi^-)$

![Graph showing the decay of $\Xi^{--}$](image-url)
5.3. Heavy pentaquark

5.3.1. Experimental search
5.3. Heavy pentaquark

5.3.1. Experimental search

E791 (with strangeness)  H1 (without strangeness)
6. Hexaquarks

6.1. Light hexaquarks

Various claims for non-strange dibaryons, never considered as confirmed. The $H(uuddss)$ searched for in several experiments. Never seen. In particular, the hypernucleus $^6\Lambda\Lambda\text{He}$ not seen decaying into $\alpha + H$. Speculations on dibaryons with charm $C = 2$ or higher. Never searched seriously.
7. Theoretical studies of multiquark spectroscopy

Usually little interest, except in simple constituent models. Wave of works after the announcement of pentaquark candidates.

7.1. Lattice QCD

At least three groups have estimated the pentaquark and found a possible resonance closely above $KN$ threshold, with negative parity.

Sasaki, Czizor, Negele.

Ting-Wai Chiu and Tung-Hang Tsieh (hep-ph/0403020) assumes the Jaffe–Wilczek type of diquark clustering, and, not surprisingly, found something with positive parity near 1.5 GeV.

Mathur et al. found no resonance, just the $KN$ threshold.
Quenched Wilson $20^3 \times 36$ lattice $\beta = 6$

Range of $m, L, \beta$
MIT group @ QNP 2004

![Graph showing data points and lines for P = +1 and P = -1, with labels M_+, M_-, M_K + M_N at specific values.](image)
Mathur et al.

Theoretical . . .

T etraquarks

Double-charm . . .

states into account in the 1
no need to consider the ghost states. Since our lowest
positive. In the previous lattice calculations [6, 7, 8], the
are for the negative parity channel and they are always
near pion mass around 300 MeV. The right side figures
increases, and decouples from the correlation function.
Note that the ghost states
increases, and decouples from the correlation function. Note that the ghost states
Figures on the left side show the effect of ghost states
and the top 6 figures are for the smaller volume lattice.
As in Fig. 1, the left side figures are for positive parity
In Fig. 2, we plot a few more correlation functions.

\[
J^P_{l=0,1/2} = 0 (1
\]

\[
S\ E\text{-wave}
\]

\[
K N\text{-wave}
\]

\[
L = 2.4\text{ fm} : \quad L = 3.2\text{ fm}:
\]

\[
m_K + m_N:
\]

\[
J^P_{l=0,1/2} = 0 (1
\]
7.2. **QCD sum rules**

See Zhu, Eidemüller, Sugiyama et al.

Some found states in all isospin, so perhaps have not yet removed the threshold.

Eidemüller assumes the same diquark clustering as Jaffe and Wilczek.

Too much dependence on the choice of operator.

Cf. baryons in early days of QCD sum rules.
7.3. **Chiral soliton model**

Dramatic prediction of *something exotic* beyond octet \((N, \Lambda, \text{etc.})\) and decuplet \((\Delta, \ldots \Omega^-)\).

\(\bar{10}\) structure of the new multiplet, \(P = +1\) unambiguous predictions of this approach (Chemtob, Praszaolowicz, Manohar, Diakonov, Petrov and Polyakov, etc. remarkable pioneers).

Adjustment of mass, prediction of width: a lot of luck.

Still many features of this approach to be refined and clarified.
7.4. Constituent models

Main results

1. no multiquark for equal masses and confinement with usual colour dependence (The proliferation of multiquarks comes only in models with ad-hoc clustering hypothesis, not out of tedious few-body calculations.)

2. mass asymmetry favours \((Q\bar{Q}\bar{q}\bar{q})\) as in atomic physics.

3. spin-colour forces have interesting coherences. But …

4. spin-flavour alternative also. Favour positive-parity pentaquarks. (Stancu et al.)
• **Long-range forces.** Good enough to bind $pn$. A Yukawa potential also expected between other particles containing light quarks. A weaker potential can still bind if experienced by heavier particles. → $D\bar{D}^* + cc$ model of $X(3.872)$.

See, for instance, Törnqvist, Ericson and Karl, Manohar and Wise, Braaten, Swanson, etc.

Charmed baryons might also form bound states. (Julia-Diaz + Riska)

• **Borromean binding.** If the potential is slightly too weak to bind two hadrons, it may well bind three hadrons.

See, in particular, the refreshing approach to pentaquark by Bicudo: a borromean $K\bar{N}\pi$ molecule, i.e., heptaquark. See, also, Felipe J. Llanes-Estrada (Madrid U.), E. Oset & V. Mateu.

• **ad-hoc clustering might work** Diquark, for instance, advocated many years ago to explain why mesons and baryons have the same Regge slope ($M^2$ vs. $J$). Same $3 - \bar{3}$ string tension.

Diquark clustering in baryons at high $J$ was proved much later.

• **ad-hoc clustering might fail** see, e.g., some of the speculations on baryonium in the late 70’s.


And, more recently, Zhu, who remarks that a low lying $[ud][ud]\bar{s}$ might
8. Conclusions

- Delicate experiments, but dedicated detectors have lead to spectacular progress.

- Timing problem. If an exotic is on tape, why not look at it immediately? Lack of manpower? Lack of fashion?

- A straight hadron is usually seen in many experiments. A delicate structure might hardly survive brute-force production.
Conclusions (cont.)

- Dramatic come-back of hadron spectroscopy, which was a little fading away.
- Some experiments have very convincing results, in particular in the heavy quark sector.
- Some experimental claims obviously need confirmation, and better statistics.
- Some theoretical models are very elegant but rely on ad-hoc hypotheses that need to be checked.
- If the pentaquark exists and has a complicated structure, it is perhaps not produced copiously in some high-energy experiments with little rescattering in the final state.
THE END