Quirks in the Search for Pentaquarks

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Outline

• What’s a pentaquark?
• Some theoretical predictions for pentaquarks
• Experimental claims for three pentaquarks:
  – $\Theta_5(1540)$, $\Xi_5(1850)$, $\Theta_c(3100)$
  – Two examples: LEPS and CLAS
• Negative searches for pentaquarks:
  – Two examples: BABAR and E690
• Summary of positive and negative searches
• Conclusions
Bound States of Quarks

Baryon: $n$ (nucleon): $d$, $u$, $d$

Meson: $K^+$: $u$, $\bar{s}$

Theta: $\Theta^+_5$

Pentaquark: $u$, $d$, $d$, $u$, $s$
Early 2003, claims of $K^+n$ resonance at $\sim 1540$ MeV.

$\Rightarrow$ proliferation of theory papers

... and eventually negative results

Figures from “Pentaquarks -- Facts and Mysteries or Sisyphus at Work”, Josef Pochodzalla, hep-ex/0406077
Claims of $\Theta^+ \rightarrow NK$ signal followed by claims for two other exotic baryons:

- $\Theta^+ (uudd\bar{s}) \rightarrow NK$
  - 12 claims
- $\Xi^- (ddss\bar{u}) \rightarrow \Xi^- \pi^-$
  - 1 claim (NA49)
- $\Theta_c (uudd\bar{c}) \rightarrow D^{*-} p$
  - 1 claim (H1)
Color singlet combinations of quarks and antiquarks:

Mesons: $q \bar{q}$  
\[ 3_f \otimes 3_f^* = 1_f \oplus 8_f \]

Baryons: $q q q$  
\[ 3_f \otimes 3_f \otimes 3_f = 1_f \oplus 8_f \oplus 8_f \oplus 10_f \]

Pentaquarks: $q q q q \bar{q}$  
\[ 3 \otimes 3 \otimes 3 \otimes 3 \otimes 3^* = (3)1 \oplus (8)8 \oplus (4)10 \oplus (2)10^* \oplus (3)27 \oplus 35 \]
Ordinary Baryons

Baryon Octet
\((J^P=1/2^+)\)

\(n\) \(p\) \(\Lambda\) \(\Sigma\) \(\Xi^*\)

Baryon Decuplet
\((J^P=3/2^+)\)

\(\Delta\) \(\Sigma^*\) \(\Omega^-\)
Baryon Decuplet

Pentaquark Anti-Decuplet

\[ \begin{align*}
\text{Baryon Decuplet} & : \\
& \begin{array}{c}
\Delta \\
\Sigma^* \\
\Xi^- \\
\end{array} \\
\text{Pentaquark Anti-Decuplet} & : \\
& \begin{array}{c}
\Theta_5 \\
N_5 \\
\Xi_5 \\
\end{array}
\end{align*} \]
Pentaquark Anti-Decuplet

Pentaquark states at each corner have exotic quantum numbers.
Chiral soliton picture applied to flavor SU(3):

- predicts two lowest-lying baryon multiplets to be $J^P = 1/2^+$ octet and $J^P = 3/2^+$ decuplet.

- predicts third excitation to be exotic antidecuplet with $J^P = 1/2^+$.

- predicts equal mass splitting within antidecuplet.

Dynamical Model I

Diquark-Diquark model (Jaffe and Wilczek)  

Quarks combine in correlated pairs to form flavor, color and spin antisymmetric states.

Motivation:
- light-quark scalars seem to have significant component of $[qq][\bar{q}\bar{q}]$.
- evidence of pairing also exists in baryon spectrum.

(Basis of “color superconductivity”.)
Dynamical Model I

Diquark-Diquark model (Jaffe and Wilczek)

Predicts $8_f \oplus 10_f^*$. Strange quark mass breaks $SU_f(3)$ symmetry.
$\Rightarrow 8_f$ and $10_f^*$ mix according to their strange-quark content.

Significant differences in predicted mass spectrum compared to chiral soliton picture.
Mass Spectrum of Anti-Decuplet

Chiral Soliton Picture

Diquark Model (Jaffe, Wilczek)

Predications for doubly-strange $\Xi_5$ masses are very different.

Accommodate two $J^p=1/2^+$ N states:

- $N(1710)$ and Roper resonance $N(1440)$?
- $N(1710)$ should then couple to states with hidden strangeness, like $K\Lambda$. 
Dynamical Model II

Diquark-Triquark (Karliner and Lipkin)

Use color-magnetic interaction model augmented by Jaffe’s color-spin algebra for multiquark systems.

Motivation for diquark-triquark:
- Keep pairs of identical quarks apart to minimize repulsive hyperfine color-magnetic interaction.
- P-wave ⇒ diquark and triquark are separated by an angular momentum barrier.
Dynamical Model II

Diquark-Triquark (Karliner and Lipkin)

Predicts $M(\Theta_5^+) = 1592$ MeV  
but close agreement to experimentally claimed mass ($\sim 1540$ MeV) “may be fortuitous since several additional model-dependent effects need to be taken into account.”

$\Theta^+$

$L = 1$

$J^P = 1/2^+$
Lattice Predictions

• A number of lattice calculations have been done for pentaquarks but results are not in agreement.

• No conclusive lattice predictions for
  – the existence of a bound pentaquark state,
  – its mass,
  – its width,
  – its parity.
Now, let’s switch to the experimental view…
The evidence for strangeness +1 baryon resonances was reviewed in our 1976 edition, and more recently by Kelly and by Oades. Two new partial-wave analyses have appeared since our 1984 edition. Both claim that the P$_{13}$ and perhaps other waves resonate. However, the results permit no definite conclusion -- the same story heard for 15 years. The standards of proof must simply be much more severe here than in a channel in which many resonances are already known to exist. The general prejudice against baryons not made of three quarks and the lack of any experimental activity in this area make it likely that it will be another 15 years before the issue is decided.

Particle listings were dropped for these S=+1 baryon states after 1986.
First Claim for the $\Theta^+_5$

LEPS: Laser Electron Photon Facility at SPring-8 in Japan.
- photons produced in back-scattered laser photons from 8-GeV $e^-$
- look for $\gamma n \rightarrow K^- (K^+ n)$ by measuring missing mass due to $n$.
- signal for $\Theta^+_5 \rightarrow K^+ n$ in missing mass first announced in October 2002 PANIC
- Jan. 14, 2003: submitted evidence for a $K^+ n$ peak at 1540 MeV.
LEPS Missing Mass Plots for $\gamma N \rightarrow K^+K^{-}N$ events:

$\Lambda(1520) \rightarrow p K^-$

$m(N K^-)$

Quantum numbers not exotic.

$\Theta_5(1540)$

$\Gamma < 25 \text{ MeV}$

$4.6 \sigma$

$m(N K^+)$

Quantum numbers are exotic.

solid line: $n K$
dashed line: $p K$
Another highly-cited observation:

- tagged photon beam from CEBAF electrons.
- Two experiments:
  - $\gamma p \rightarrow \pi^+ K^- K^+ n$ ($E_\gamma = 3.2 - 5.5$ GeV)
  - $\gamma d \rightarrow p K^- K^+ n$ ($E_\gamma = 1.5 - 3$ GeV)

CLAS has since accumulated and is now analysing $\gamma d$ and $\gamma p$ samples that are $> 10$ times larger.
CLAS Missing Mass Distributions

146 citations

\[ \Theta_5^+ \] proton target

Mass = 1555 ± 10 MeV
Width < 26 MeV
Significance = 7.8 \( \sigma \)

285 citations

\[ \Theta_5^+ \] deuteron target

Mass = 1542 ± 5 MeV
Width < 21 MeV
Significance = 5.2 \( \sigma \)
First Nine $\theta_5^+(uudd\bar{s}) \rightarrow K N$ “sightings”

Data replotted by Josef Pochodzalla with statistical errors and no fits. From “Pentaquarks -- Facts and Mysteries or Sisyphus at Work”, hep-ex/0406077
First Nine $\theta_5^+(uudd\bar{s}) \rightarrow K N$ “sightings”

Data replotted by Josef Pochodzalla with statistical errors and no fits. From “Pentaquarks -- Facts and Mysteries or Sisyphus at Work”, hep-ex/0406077
Decay modes of $\Theta_5^+$

Two possible decay modes:

$\Theta_5^+$ (uudd$\bar{s}$) → n (udd) $K^-$ (u$\bar{s}$)

$\Theta_5^+$ (uudd$\bar{s}$) → p (uud) $K^0$ (d$\bar{s}$)

But neutral kaon will be detected as $K_s^0$, which has ambiguous strangeness.

A number of the claimed signals are detected in the $K_s^0$ p final state, which is not necessarily exotic (could be uud d$\bar{s}$).
$K_s \ p$ final state $\Rightarrow$ not necessarily exotic

However, some experiments use other particles in initial or final state to tag strangeness (e.g., $K^+$, $\Sigma^-$).
Indirect limit on width of $\Theta_5(1540)^+$

Resonant cross-section in scattering experiments is determined entirely by the width of the resonance $\Gamma$ and its branching fractions into the initial and final states.

Cahn and Trilling (hep-ph/0311245) use data on $K^+$ collisions on Xenon (DIANA) and Deuterium (from 1960’s and 1970’s) to derive limits on the width of the $\Theta_5(1540)^+$:

- Xenon experiments $\Rightarrow$ $\Gamma_\Theta = 0.9 \pm 0.3$ MeV.
- Other experiments $\Rightarrow$ $\Gamma_\Theta < 1$ to 4 MeV.

$\Rightarrow$ “… they point to such a narrow width that, if the $\Theta_5(1540)^+$ truly exists, it is exotic dynamically as well as in its quantum numbers.”
NA49 candidates for $\Xi_5(1860)$

158-GeV protons on Hydrogen target.

Evidence claimed for two different charge states at a mass of $\sim 1860$ MeV:

$\Xi_5^{--}$ and $\Xi_5^0$.

$\Gamma < 18$ GeV
H1 candidates for $\Theta_c(3100)$

28-GeV electrons on 820-GeV and 920-GeV protons

Mass = $(3099 \pm 3 \pm 5)$ MeV
s = $(12 \pm 3)$ MeV
51 ± 11 events
Turning to the negative experimental results…
Dalitz plots from old bubble chamber experiments for $K^+N\rightarrow KN\pi$, compiled by George Trilling for RPP2004 “A Possible Exotic Baryon Resonance”

Diagonal bands show where one would expect to see the $\Theta_5(1540)^+$. 
The BABAR Experiment at PEP-II

**Electromagnetic Calorimeter**
- 6580 CsI crystals
- $e^+$ ID, $\pi^0$ and $\gamma$ reco

**Cherenkov Detector (DIRC)**
- 144 quartz bars
- $K, \pi$ separation

**Instrumented Flux Return**
- 19 layers of RPCs
- $\mu^+$ and $K_L$ ID

**Drift Chamber**
- 40 layers
- Tracking + dE/dx

**Silicon Vertex Tracker**
- 5 layers of double sided silicon strips

**e^+ [3.1 GeV]**

**e^- [9 GeV]**
BABAR Searches for Strange Pentaquarks

\[ |\text{udd}(u\bar{u}, s\bar{s})\rangle \rightarrow |\bar{\Xi}^-\rangle \]
\[ |\text{dsds}\bar{u}\rangle \rightarrow |\Xi^-\bar{\pi}^-\rangle \]
\[ |\text{uss}(u\bar{u}, d\bar{d})\rangle \rightarrow |\Lambda K^-\rangle \]
\[ |\text{dss}(u\bar{u}, d\bar{d})\rangle \rightarrow |\Lambda K_s, \Xi\pi^+\rangle \]
\[ |\text{uud}(d\bar{d}, s\bar{s})\rangle \rightarrow |\Xi^+\rangle \]
\[ |\text{uus}(d\bar{d}, s\bar{s})\rangle \rightarrow |\Lambda K^+\rangle \]

\[ |\text{udud}\bar{s}\rangle \rightarrow pK_s \]

\[ |\Theta^+_8\rangle \rightarrow pK_s \]
Search for $\theta_5^+(1540) \rightarrow p K_s^0$

$\Lambda_c^+(2285)$, 52k events

No Signal for $\theta_5^+$

1540 MeV
Upper Limit on $\Theta_5^+$ Production

\[ \text{BABAR} \text{ preliminary} \]
Search for $\Xi_5^{--} \rightarrow \Xi^- \pi^-$, $\Xi_5^0 \rightarrow \Xi^- \pi^+$

$\Xi(1530)$, $\sim$5k events

$\Xi_c^0$, $m=2472$ MeV, $\sim$2k events

$\Xi_5^{--}$

No Signal for $\Xi_5^{--}$

$\Xi_5^0$

No Signal for $\Xi_5^0$
Search for $\Xi^0_5 \rightarrow \Lambda^0 K_{s0}$

$\Xi_c^0$, ~2k events

- $\mathbf{p}^* < 3 \text{ GeV/c}$
- $\mathbf{p}^* > 3 \text{ GeV/c}$ (x10)

1862 MeV

No Signal for $\Xi^0_5$
Search for $\Xi_{5}^{-} \rightarrow \Lambda^{0} K^{-}$

- $\Omega^{-}$, ~8k events
- $p^{*} < 3$ GeV/c
- $p^{*} > 3$ GeV/c (x10)

No Signal for $\Xi_{5}^{-}$

$m(\Lambda^{0} K^{-})$ [GeV]
Additional Searches

- We have also studied $\Sigma^0 K^+$, $\Sigma^0 K^-$, $\Sigma^0 K_S^0$.
- No unexpected narrow structure observed.

$\Sigma_5^+(uudss) \rightarrow pK_s^0$

$N_5^+(uudss) \rightarrow \Lambda^0 K^+$

$N_5^0(uudss) \rightarrow \Lambda^0 K_s^0$

$\Xi_c^0$, $\sim 2k$ events
Hadron production in $e^+e^-\rightarrow$Hadrons

For total particle+antiparticle rate:
$\times(2J+1)$ where $J=$total angular momentum
$\times2$ if particle/antiparticle states distinct
$e^+ e^- \rightarrow \text{Hadrons}$

BABAR upper limits

For total particle+antiparticle rate:
- $\times (2J+1)$ where $J=$ total angular momentum
- $\times 2$ for particle+antiparticle states

Assume $\text{Br}(pK^0_s) = 25\%$

Assume $\text{Br}(\Xi_c \to \Xi^- K) = 50\%$
Pentaquark Searches from E690

- Fermilab fixed-target experiment E690
- 800 GeV proton beam on proton target
- 5 billion events recorded in 1991
- hundreds of thousands of clean reconstructed hyperons.

Key Features of E690:
- Liquid hydrogen target
- Magnetic spectrometer
- Open geometry
- Large geometric acceptance
- Thin-gap drift chambers
- Helium between chambers
- Excellent momentum resolution
- Excellent mass resolution
- Particle identification was not used for the exotic baryon search (not needed)

* Same apparatus used in BNL E766 for \( \Lambda \) and \( \Sigma \) mass measurements. PRL 72, 1322 (1994) & PRD 56, 2544 (1997).
E690 search for $\Theta_5^+ \rightarrow pK_s$ in pp $\rightarrow pK_sK^-\pi^+p$

Monte Carlo

- $pK_s$ mass resolution ($\sigma$) at 1540 MeV is 1.5 MeV.
- $\Lambda(1520)$, ~5k events
  FWHM ~ 14 MeV
E690 Search for

\[ \Xi_5^{--} \rightarrow \Xi^- \pi^-, \quad \Xi_5^0 \rightarrow \Xi^- \pi^+ \]

Monte Carlo mass resolution (\(\sigma\)) for \(\Xi\pi\):
3.3 MeV at 1750 MeV; 4.5 MeV at 1862 MeV.

Arrows at 1750 MeV & 1860 MeV
Is $\theta_5^+( \text{uudd}\bar{s}) \rightarrow K\Lambda$ signal real?

<table>
<thead>
<tr>
<th>Experiment</th>
<th># of $\Lambda(1520) \rightarrow K^- p$ signal events</th>
<th>Control Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEPS</td>
<td>$\sim 25 / 160$</td>
<td>S/B~2/1</td>
</tr>
<tr>
<td>CLAS</td>
<td>212 events</td>
<td>S/B~2</td>
</tr>
<tr>
<td>HERA-B (p nucleus)</td>
<td>$\sim 3k$ events</td>
<td>S/B~1/3</td>
</tr>
<tr>
<td>CDF (p$\bar{p}$)</td>
<td>$\sim 3k$ events</td>
<td>S/B~1/6</td>
</tr>
<tr>
<td>ALEPH (e$^+e^-$)</td>
<td>$\sim 3k$ events</td>
<td>S/B~1/6</td>
</tr>
<tr>
<td>E690 (pp)</td>
<td>$\sim 5k$</td>
<td>S/B~2</td>
</tr>
<tr>
<td>BABAR (e$^+e^-$)</td>
<td>$\sim 40k$</td>
<td>S/B~1</td>
</tr>
</tbody>
</table>

{\text{Claim evidence for } \theta_5^+}

See no evidence for $\theta^+$
### Is $\Xi_5^{-}$(ddss$\bar{u}$) $\rightarrow \Xi^{-}\pi^{-}$ signal real?

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\Xi_5^{-}$(1860)</th>
<th>$# \Xi^{-}$</th>
<th>$# \Xi(1530)^0 \rightarrow \Xi^{-}\pi^+$</th>
<th>Control Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA49 (pp)</td>
<td>~ 45 evts, S/B~1</td>
<td>~1,600</td>
<td><del>20, S/B</del>2/3</td>
<td></td>
</tr>
<tr>
<td>ALEPH (e$^+e^-$)</td>
<td>No signal</td>
<td>~1,800</td>
<td><del>300, S/B</del>1</td>
<td></td>
</tr>
<tr>
<td>ZEUS (e p)</td>
<td>No signal</td>
<td>~2,600</td>
<td><del>160, S/B</del>1</td>
<td></td>
</tr>
<tr>
<td>HERA-B (p nucleus)</td>
<td>No signal</td>
<td>~19,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDF (p$\bar{p}$)</td>
<td>No signal</td>
<td>~36,000</td>
<td><del>2k, S/B</del>1</td>
<td></td>
</tr>
<tr>
<td>BABAR (e$^+e^-$)</td>
<td>No signal</td>
<td>~258,000</td>
<td><del>5k, S/B</del>1</td>
<td></td>
</tr>
<tr>
<td>E690 (pp)</td>
<td>No signal</td>
<td>~512,000</td>
<td><del>15k, S/B</del>2</td>
<td></td>
</tr>
<tr>
<td>WA89 ($\Sigma^-$ C/Cu)</td>
<td>No signal</td>
<td>~676,000</td>
<td><del>20k, S/B</del>1</td>
<td></td>
</tr>
</tbody>
</table>
Is $\theta_c(uuudd\bar{c}) \rightarrow D^*- p$ signal real?

H1:
- 3.4k $D^*$ events ($S/B \sim 2.5$)
- Number of events in narrow peak in $D^*p$ mass spectrum near 3.1 GeV: $51 \pm 11$

$\Rightarrow (1.5\pm0.3)\%$ of $D^*$’s come from pentaquark decays?!

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZEUS</td>
<td>No signal $\Rightarrow &lt; 1%$ of $D^*$’s from pentaquarks.</td>
</tr>
<tr>
<td>FOCUS</td>
<td>No signal with 36k very clean $D^*$ signal events.</td>
</tr>
<tr>
<td>CDF</td>
<td>No signal with 540k very clean $D^*$ signal events.</td>
</tr>
</tbody>
</table>
Future Experimental Outlook

- more $\gamma d$ data was analysed from LEPS; still see signal.
- factor of 10 more $\gamma p$ and $\gamma d$ data from CLAS being analyzed.
- more $pp$ data from COSY-TOF (x few) will be accumulated next year.
- proposal at KEK has been approved.
  - $K^+ p \rightarrow p^+ \Theta^+$
  - 1 MeV mass resolution $\Rightarrow$ precise measurement of mass and width.
What have we learned about pentaquark production?

My personal conclusions:

The many high-statistics searches for pentaquarks, motivated by the reported low-statistics sightings, have strengthened the evidence against the production of pentaquark states.

The pentaquark saga may end up providing one of the clearest demonstrations of the importance of developing searches that minimize experimenters’ bias, and the importance of publishing negative as well as positive results.