Exotic Baryons at HERMES

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DESY Student Seminar
July 4, 2005
Overview

Introduction
  QCD
  Exotic hadrons

Experimental overview
  Positive results
  Null results

HERMES
  The HERMES spectrometer
  $\Theta$ analysis
  $\Xi^{--}$ analysis
  Additional $\Theta^+$ studies

Recent results
QCD in a nutshell

Interactions of quarks and gluons

- All $q$ carry a color charge $r$, $g$, $b$ and $\bar{q}$ carry anticolor
- All $g$ carry a combined color charge, i.e. $r\bar{b}$
- Only colorless objects, i.e. $q\bar{q}$, $qqq \Rightarrow$ confinement

Multiquark states

- $q\bar{q} \rightarrow$ mesons (integer spin)
- $qqq \rightarrow$ baryons (half-integer spin)

States with only light quarks ($u$, $d$, $s$)

- Light mesons: $3_f \times \bar{3}_f = 1 + 8$
- Light baryons: $3_f \times 3_f \times 3_f = 1 + 8 + \bar{8} + 10$
Exotic hadrons

More than 3 quarks → exotics
Can also be colorless!

- *Exotic mesons* $(qar{q}qar{q})$: $\geq 4$ quarks, integer spin
- *Exotic baryons* $(qqqqq)$: $\geq 5$ quarks, half-integer spin

Surprise? No, this happens all the time in the quark sea!

Manifestly versus crypto-exotic

- *Crypto-exotic*: quantum numbers also possible with non-exotics (e.g. sea quark fluctuations, $uudd\bar{u}$)
  → mix with corresponding non-exotic states
- *Manifestly exotic*: quantum numbers can only be obtained with more than three quarks (e.g. $uudd\bar{s}$)
Exotic hadrons

Experimental situation

- Searches and sightings in the early years of QCD
- No clear evidence for exotic mesons or baryons

Particle Data Group in 1988

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.

Once again: PDG is right!
Chiral Quark Soliton model

Diakonov, Petrov, Polyakov (1997)

- Extension of Skyrme model: rotations in flavor space and in real space equivalent
- Mass states are rotational excitations with $E \sim J(J + 1)$

For light quarks $u, d, s$:

Baryons in multiplets $8 + 10 + \overline{10} + 27 + \cdots$

- $8$ (octet): non-exotic spin $\frac{1}{2}$ baryons
- $10$ (decuplet): non-exotic spin $\frac{3}{2}$ baryons
- $\overline{10}$ (anti-decuplet): exotic spin $\frac{1}{2}$ baryons
- $27$: exotic spin $\frac{3}{2}$ baryons

Mass splittings for $8$ and $10$ are correctly reproduced!
Chiral Quark Soliton model

- Exotic anti-decuplet $\bar{10}$

$N(1710)$
- $\Theta^+(1530)$
- $\Sigma(1890)$
- $\Xi_5(2070)$

$\Theta^+ (1530)$:
- $nK^+$ or $pK^0$
- $uudd\bar{s}$

$\Sigma(1890)$:
- $\Xi^-\pi^-$ or $\Sigma^-K^-$
- $ddss\bar{u}$

$\Xi_5(2070)$:
- $\Xi^0\pi^+$ or $\Sigma^+\bar{K}^0$
- $uussd$
Experimental status: positive results

LEPS

CLAS ($p$ and $d$)

HERMES

SVD-2

DIANA

Zeus

... and more!
Experimental status: positive results

Legend
- $K^+ n$
- $K^0_S p$

World average: 1532.5 ± 2.4 MeV (yellow band)
Experimental status: null results

**BaBar**
- $e^+ e^- \rightarrow pK_S^0 X$

**HyperCP**
- $pCu \rightarrow pK_S^0 X$

**BES, Belle, LEP**

**H1, Hera-B, Sphinx, CDF, FOCUS, Belle, Phenix**
Experimental status: comments

$\Theta^+$ could be false peak
- Background unknown, statistical fluctuation
- Significance is blown up
- Strangeness unknown (in $pK_S^0$ channel)
- Kinematic reflections
- Ghost tracks

Null results are not sensitive
- High multiplicity
- No structure for $\Sigma$’s
- In $e^+e^-$ difficult to produce baryons
- Large isospin asymmetry
- Acceptance effects
The HERMES spectrometer: overview

- 27.6 GeV $e^{\pm}$ HERA beam on $\vec{H}$, $\vec{He}$, $\vec{D}$ or $H_2$, $D_2$, He, ...
- Resolution: $\frac{\Delta p}{p} = 1.4 - 2.5\%$, $\Delta \vartheta \lesssim 0.6$ mrad
- RICH: identification hadrons ($p$, $\pi$, $K$)
- TRD, Calo and Preshower: hadron/lepton separation
The HERMES spectrometer: PID

- **Hadron/lepton separation:** Combination of
  - TRD
  - Calorimeter
  - Preshower
  - RICH

- **Hadron identification:**
  - Dual radiator RICH
    - aerogel: \( n = 1.03 \)
    - \( \text{C}_4\text{F}_{10} \) gas: \( n = 1.0014 \)
Exotic Baryons at HERMES

$\Theta^+$ analysis: event selection

- Channel: $\Theta^+ \rightarrow pK^0_S \rightarrow p\pi^+\pi^-$
- Topology:
  - Select $K^0_S$ events (2 $\sigma$ window)
  - Remove $\Lambda$ events (3 $\sigma$ window)

$M(\pi^+\pi^-)$ mass spectrum
$K^0_S$ peak at 496.8 MeV

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Θ⁺ analysis: final spectrum

- Spectrum with polynomial fit

Unbinned fit with 3rd order polynomial and Gaussian

Θ⁺ peak:
- $M = 1528 \pm 2.6$ MeV
- $\sigma = 8 \pm 2$ MeV

Significance 3.7 $\sigma$
Θ⁺ analysis: understanding the background

- Spectrum with MC background
- Mixed-event background
  - $p$ from one event
  - $K_S^0$ from other event
- PYTHIA6 Monte Carlo
  - No $\Sigma^{*+}$ resonances
  - Added by hand (cfr. PDG)
- $\Theta^+$ peak:
  - $M = 1527 \pm 2.3$ MeV
  - $\sigma = 9.2 \pm 2$ MeV
- Significance 4.3 $\sigma$
**Exotic Baryons at HERMES**

**Ξ⁻⁻ analysis: event selection**

- **Channel:** \( \Xi^{-} \rightarrow \Xi^{-} \pi^{-} \rightarrow \Lambda \pi^{-} \pi^{-} \)

- **Topology:**
  - Distance between \( \Lambda \) track and pion track (< 1.0 cm)
  - Distance between beam and production vertex \((R < 0.6 \text{ cm}, |Z| < 18.0 \text{ cm})\)
  - Distance between proton and pion track (< 1.5 cm)
  - Distance between \( \pi^{-} \) track and pion track (< 2.5 cm)
  - Distance between \( \Xi^{-} \) decay vertex and production vertex (> 10.0 cm)
  - Distance between \( \Lambda \) and \( \Xi^{-} \) decay vertices (> 7.0 cm)

- **Select \( \Lambda \) events (2 \( \sigma \) window)**
- **Select \( \Xi^{-} \) events (2 \( \sigma \) window)**

**Graphs:**

- \( M(p\pi^{-}) \) with \( \Lambda \)
- \( M(p\pi^{-}\pi^{-}) \) with \( \Xi^{-} \)
Exotic Baryons at HERMES

Ξ−− analysis: results

- **$M(p\pi^-\pi^-\pi^-)$ spectrum**
  - Mixed-event background
  - No Ξ peaks around 1860 MeV
  - Ξ−(1860) seen, as expected

- **$M(p\pi^+\pi^-\pi^-)$ spectrum**
  - Upper limit $\sigma_{\Xi^{0}}^{90\%} = 1.0 - 2.1 \text{ nb}$
  - Upper limit $\sigma_{\Xi^{-}}^{90\%} = 1.2 - 2.5 \text{ nb}$
  - $\sigma_{\Xi^{0}(1530)} = 8.8 - 24 \text{ nb}$

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Additional $\Theta^+$ studies: isospin

In the decay channels:

- $pK^-$: Clear $\Lambda$ peak at 1522.7 MeV
- $pK^+$: no peak, zero counts (91% C.L.)

Not isotensor, probably isosinglet
Additional $\Theta^+$ studies: PID problems

- Correlation $M_{\pi\pi}$ vs. $M_{\rho\pi}$

- PID leaks
  - $\pi^+$ is actually $p$ (mis-ID)
  - $K_S$ combination is a $\Lambda$
  - $\Lambda$ peak at $M_\Lambda = 1116$ MeV not seen
  - No significant mis-ID of $p$ tracks as $\pi^+$!

- Ghost tracks
  - No correlations
  - Examined data files
  - No ghost tracks!

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Additional $\Theta^+$ studies: inefficient cuts

- $\Lambda(1116)$ contribution

PID leaks
- $\pi^+$ is a $p$ (mis-ID)
- $K_S$ is actually $\Lambda(1116)$

Maybe $\Lambda$ cut inefficient

Contribution of $\Lambda$s
- Events with $\Lambda$ (blue)
- Peak not from $\Lambda$!
Additional $\Theta^+$ studies: is $\Theta^+$ a $\Sigma^{*+}$?

- $\Sigma^{*+}$ would decay to $\Lambda\pi^+$
- $Br(K_S\pi)/Br(\Lambda\pi^+) = 2/3$

→ Not a $\Sigma^{*+}$ resonance!

$M_{p\pi\pi}$ spectrum (black)

Mixed events (green)
Additional $\Theta^+$ studies: require extra hadron

- With 4th hadron (black)
- 4th hadron $= \pi$ (red)
- 4th hadron $\neq \pi$ (green)

Require extra $\pi$

- Background down
- Signal stays!
Additional $\Theta^+$ studies: require extra hadron

Why does the additional $\pi$ help?

- $\phi$ production: $p \gamma \rightarrow p\phi \rightarrow pK_S^0K_L^0 \rightarrow p\pi^+\pi^-(K_L^0)$
- Requiring extra $\pi$ removes this $p\pi\pi$-only process

Can we clean even more?

- Remove $K^*\pm \rightarrow K_S\pi^\pm \rightarrow \pi^+\pi^-\pi^\pm$
- Remove $\Lambda \rightarrow p\pi_4$ from $K_S^0\Lambda \rightarrow p\pi\pi\pi$
New results: CLAS g10 and g11

- **g10**: $\gamma d \to nK^+K^-p$

- **Preliminary!**

- **$\sigma_{\gamma n \to \Theta^+K^-} < 5$ nb (95% C.L.)**

- **g11**: $\gamma p \to nK^+K^0_S$

- **$\sigma_{\gamma p \to \Theta^+K^0_S} < 2$ nb (95% C.L.)**

- **$\frac{N(\Theta^+)}{N(\Lambda(1520))} < 0.2\%$ (95% C.L.)**
New results: CLAS g10 and g11

**g10 vs. CLAS-d**
- Background underestimated
- Now only $3\sigma$ signal...

**g11 vs. CLAS-p**
- $5\sigma$ turned out to be wrong

**g11 vs. Saphir**
- $G2a$ published
- $G10$ scaled by $0.169$

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New results: STAR at RHIC

- Preliminary!
- High statistics, good resolution, minimal cuts
- $5\sigma$ observation of $\Theta^{++}$, also $\Theta^+$ with lower significance

"The observed yield at STAR is so small, such that many experiments would not have the sensitivity to see it."
New results: LEPS at SPring-8

Reaction: $\gamma d \rightarrow \Lambda(1520)\Theta^+ \rightarrow pK^-X$

- Liquid D$_2$ target
- $E_\gamma$ known between 1.5 – 2.4 GeV
- Missing mass technique

- Possible reaction mechanism
- Main source of background
New results: LEPS at SPring-8

\( pK^- \) missing mass

Background determination:
- \( \Lambda(1520) \) on \( H_2(l) \) target
- Contribution \( \Lambda(1520) \) sidebands
- Total background (sum)

Excess around 1.53 GeV
- Naïve significance: 5 \( \sigma \)
- Width consistent with resolution
- Mostly from \( p_{nK} \approx 0.42 \text{ GeV} \)

Outside CLAS acceptance...

Preliminary!
Conclusions

Experimental status:

- $\Theta^+$: ±10 sightings ↔ ±10 null results
- $\Xi^{--}$: 1 sighting, several null results
- $\Theta_C$: 1 sighting, several null results

Contributions of HERMES:

- $\Theta^+$ is seen
- Isotensor is unlikely
- Extra $\pi$ improves signal → production mechanism
- $\Xi^{--}$ is not seen → upper limit on cross-section

Recent results:

- Small $K^*$ coupling
- Large isospin asymmetry (Karliner-Lipkin)

_Pentaquarks are in very bad shape, but they are still alive._
Both experimental and theoretical study should continue.