Theta+(1540) and Associated Exotic States

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Based on work in collaboration with
R. Arndt, Ya. Azimov, M. Polyakov, R. Workman

Epiphany2005, Jan 6-8, 2005
Outline

- Prehistory of exotics
- What we know about $\Theta^+$
- How to search for alternatives?
  Modified PWA
- $\Theta^+$ - (non)observation
- Kinematic reflections
- Is $N^* = N(1710)$?
- Theoretical expectation
- Experimental evidences for $N^*$
- Summary
Prehistory of Exotics

- The problem of observing multiquark (exotic and/or `cryptoexotic’) states is as old as quark themselves
- The first experimental results on search for baryon exotics in KN system
  [R. Cool et al, Phys Rev Lett 17, 102 (1966)
  R. Abrams et al, Phys Rev Lett 19, 259 (1967)
  J. Tyson et al, Phys Rev Lett 19, 255 (1967)]
- were published soon after the invention of quarks
  [M. Gell-Mann, Phys Lett 8, 214 (1964)
  G. Zweig, CERN preprints TH-401, TH-412, 1964]

- Resonance peak found in K*N at M = 1910 MeV, Γ = 180 MeV
One of the most convincing way to search for $\Theta^+$ is PWA.

Pole Positions:

<table>
<thead>
<tr>
<th>I</th>
<th>Ampl</th>
<th>ReW (MeV)</th>
<th>-ImW (MeV)</th>
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<tbody>
<tr>
<td>0</td>
<td>P$_{01}$</td>
<td>1831</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>D$_{03}$</td>
<td>1788</td>
<td>170</td>
</tr>
<tr>
<td>1</td>
<td>P$_{13}$</td>
<td>1811</td>
<td>118</td>
</tr>
<tr>
<td></td>
<td>D$_{15}$</td>
<td>2074</td>
<td>253</td>
</tr>
</tbody>
</table>

All suggested resonances are too heavier than known $\Theta^+$ to be its isospin partners.

$T_{lab} = 0$ [20] 1100 MeV
### $\Theta^+$ and $\Phi$ - What is known

[PDG (S. Eidelman et al) Phys Lett B 592, 1 (2004)]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Theta(1540)^+$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEPS</td>
<td>$1540 \pm 10$</td>
<td>$&lt;25$</td>
</tr>
<tr>
<td>DIANA</td>
<td>$1539 \pm 2$</td>
<td>$&lt;9$</td>
</tr>
<tr>
<td>CLAS (d)</td>
<td>$1542 \pm 5$</td>
<td>$&lt;21$</td>
</tr>
<tr>
<td>SAPHIR</td>
<td>$1540 \pm 4 \pm 2$</td>
<td>$&lt;25$</td>
</tr>
<tr>
<td>ITEP (v)</td>
<td>$1533 \pm 5$</td>
<td>$&lt;20$</td>
</tr>
<tr>
<td>CLAS (p)</td>
<td>$1555 \pm 10$</td>
<td>$&lt;26$</td>
</tr>
<tr>
<td>PDG average</td>
<td>$1539.2 \pm 1.6$</td>
<td>-</td>
</tr>
<tr>
<td>GWU</td>
<td>$1545$</td>
<td>$\leq 1$</td>
</tr>
<tr>
<td>LBNL</td>
<td>$1540$</td>
<td>$0.9 \pm 0.3$</td>
</tr>
</tbody>
</table>

### $\Phi(1860)$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA49</td>
<td>$1862 \pm 2$</td>
<td>$&lt;18$</td>
</tr>
</tbody>
</table>

**The measured mass looks similar to expectation of the ChSA**

[D. Diakonov, V. Petrov, M. Polyakov, Z Phys A 359, 305 (1997)]

### Additional Notes

Only one pw $P_{01}$ admits the effect at $1540 - 1450$ MeV with $\Gamma < 1$ MeV

[R. Arndt, IS, R. Workman, Phys Rev C 68, 042201 (2003)]

With additional assumption and unknown systematics

[R. Cahn and G. Trilling, PRD 69, 011501 (2004)]
Narrow Resonances in PWA


- Standard PWA reveals only wide resonances ($\Gamma < 500$ MeV)
- PWA (by construction) tends to miss resonances with $\Gamma < 30$ MeV
- We assume the existence of a Res and refit over the whole database
- Insertion of narrow resonances in PWA for
  elastic case: $e^{2i\delta} \Rightarrow e^{2i\delta_R} e^{2i\delta_B}$
  $e^{2i\delta_R} = (M_R - W + i \Gamma_R/2)/(M_R - W - i \Gamma_R/2)$

  inelastic case: $\eta \ e^{2i\delta} \Rightarrow \langle a|S|a\rangle \ = \ r_a \ A(W) \ e^{2i\delta_R} + (1 - r_a) \ B(W)$
  $r_a = BR(R \rightarrow a) \quad |A(M_R)| = 1 \quad \Sigma r_a = 1$
  $\eta \leq 1 \Rightarrow \ r_a \ |A(W)| + (1 - r_a) \ |B(W)| \leq 1$

- How does this insertion changes $\chi^2$?
  (Will it decrease?)
$\Delta \chi^2$ due to Insertion of a Res into $P_{01}$ ($J^P = \frac{1}{2}^+$)

- Resonance contribution
  $\sim \Gamma_R / (M_R - W)$ at $|M_R - W| >> \Gamma_R$

- For 1540 - 1550 MeV, $\Gamma_R < 1$ MeV

$K^+d \rightarrow K^+np$

$T = 187$ MeV

$M = 1545$ MeV

$\Gamma = 0.5$ MeV
Check other Partial Waves

- $\Delta \chi^2$ due to insertion of a resonance into $S_{01}$ ($J^P = 1/2^-$)

- $\Delta \chi^2$ due to insertion of a resonance into $P_{03}$ ($J^P = 3/2^+$)
Summary on Exotic Baryon Observation

- The measured Mass looks similar to expectation of the ChSA
- The measured Width is only upper limit
- Highest Significance (CLAS) = 7.8 \sigma
- Spin and Parity are not measured yet
- Production Mechanisms are unknown
- Xsections are uncertain
- NA49 results yet to be confirmed
- Search for the other Flavor Partners is underway

⇒

- CLAS fans, please be patient, g10 (*10) and g11 (*15) data are coming soon

- LEPS (*5), DIANA (*2), and COSY-TOF (*5) data are coming as well
Possible Mechanism of $\Theta^+$ Production, $N(2400)$

[Ya. Azimov, IS, Phys Rev C 70, 035210 (2004)]

- **CLAS at JLab:**
  \[ \gamma p \rightarrow \pi^+ n(2400) \rightarrow \pi^+ K^- \Theta^+ \]

- **SPHINX at IHEP:**
  \[ pN \rightarrow Nn(2400) \rightarrow \Sigma^0 K^+, \eta \]

- No $\pi N$ PWA has seen an $N(2400)$ at $\pi^- p \rightarrow \pi N$ with $\Gamma_{tot} \geq 100$ MeV and $\text{BR}(R \rightarrow a) \geq 5\%$ [G. Hoehler, Springer, 1983]

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V. Kubarovsky et al., PRL 92, 032001 (2004)

(Non)observation of $\Theta^+$ (?)

- What we can learn from published High Energy (non)observations of $\Theta^+$?
  - **HERA-B** in pA at $\sqrt{s} = 41.6$ GeV
  - **PHENIX** in dA at $\sqrt{s} = 200$ GeV
  - **BES** in $e^+e^-$ at $J/\psi$ and $\psi(2S)$
  - plus several more measurements

- Some features of data suggest a small $\Theta^+$ signal with very large background. Special selection(s) may be needed.

- Still hint at a possibility to extract a $\Theta^+$

• The Quark Matter 2004 talk with `clear $\Theta^-$ signal’ transformed into the Proceedings text with `no signal’ after a `small correction’. The situation is not clear even to the authors.

![Diagram of invariant mass distribution](image)

• Best illustration of the present uncertain status
• **BES** [J. Bai et al, Phys Rev D 70, 012004 (2004)]

**Analysis** [Ya. Azimov, IS, Phys Rev C 70, 035210 (2004)]

- Data need some (rather soft) dynamical suppression, say $1/5$ in the probability
- Meanwhile, because of necessity to produce directly two more $qq$ pairs (in exotic decays as compared with decays to canonical baryon-antibaryon pairs), some dynamical suppression should naturally arise. One or two order suppression might be quite natural

- Thus, the recent result of BES is only a starting point for investigating exotics in $e^+e^-$-annihilation
Summary on $\Theta^+$ (non)observation

- Different initial particles
- Different energies
- Different production mechanisms
- How to separate?

- Published `Null' Experiments do not really contradict the existence of pentaquarks; need to (im)prove their sensitivity
Kinematic Reflections


- Kinematic reflections due to $f_2(1275)$ and $a_0(1320)$ can generate a narrow enhancement in $K^+n$ eff mass
- Fluctuations of the broad peak could result in a false narrow structure
The contributions from the tensor mesons, $f_2(1275)$ and $a_0^2(1320)$, at $E_\gamma = 2$ GeV are found to be very small.
Summary on Kinematic Reflections


- There are considerable model assumptions that Dzierba et al have made.
- The main exchange particle in their model is the pion (and its higher-mass partners on the Regge trajectory line). However, the $\pi^0$ exchange contributions to production of $f_2$ and $a_0^2$ are absent indeed, in either reggeized or non-reggeized versions of the model, thus diminishing the corresponding cross sections.
- Calculations of kinematic reflections should be due to calculations that have had parameters fixed from on previous data ($K^+K^-$), rather than fit to the spectrum ($nK^+$) where kinematic reflections are suspected.
• If $\Theta^+$ does not survive, ‘damned’ questions revive:

• ‘Why are there no strongly bound exotic states..., like those of two quarks and two antiquarks or four quarks and one antiquark?’
  [H. Lipkin, Phys Lett 45B, 267 (1973)]

• ‘...either these states will be found by experimentalists or our confined, quark-gluon theory of hadrons is as yet lacking in some fundamental, dynamical ingredient which will forbid the existence of these states or elevate them to much higher masses.’
  [R. Jaffe and K. Johnson, Phys Lett 60B, 201 (1976)]
Tentative unitary Antidecuplet with $\Theta$

- **GMO:** $\delta m(\sigma) = (M_\Xi - M_\Theta)/3 = 107$ MeV at $\sigma = 67$ MeV [SAID]
  180 MeV at $\sigma = 45$ MeV [Karlsruhe]

- Current $\delta m$ corresponds to the GW SAID $\sigma$-term

- Mixing is able to shift GMO masses for $N^*$ and $\Sigma^*$

SAID: [M. Pavan et al, hep-ph/0111066]
N(1710) - What was known

[PDG (S. Eidelman et al) Phys Lett B 592, 1 (2004)]

<table>
<thead>
<tr>
<th>Ref</th>
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<td>ChSA</td>
<td>1710 (input)</td>
<td>~40</td>
</tr>
<tr>
<td>PWA</td>
<td>1723±9</td>
<td>120±15</td>
</tr>
<tr>
<td>KH</td>
<td>1700±50</td>
<td>90±30</td>
</tr>
<tr>
<td>CMU</td>
<td>1717±28</td>
<td>480±230</td>
</tr>
<tr>
<td>KSU</td>
<td>1717±28</td>
<td>480±230</td>
</tr>
<tr>
<td>GW</td>
<td>no state!</td>
<td></td>
</tr>
</tbody>
</table>

- It would be more natural for the same unitary multiplet (with \( \Theta^+ \) and \( N^* \)) to have comparable widths
Modified \( \pi N \) PWA

- \( \Delta \chi^2 \) due to insertion of a resonance into \( P_{11} (J^P = \frac{1}{2}^+) \)

- At \( |M_R - W| \gg \Gamma_R \), Res contributes \( \sim \Gamma_{el}/(M_R - W) \)
- Two candidates: \( M_R = 1680 \text{ MeV} \quad 1730 \text{ MeV} \)
  \( \Gamma_{\pi N} < 0.5 \text{ MeV} \quad < 0.3 \text{ MeV} \)
Check other Partial Waves

- $\Delta \chi^2$ due to insertion of a Res into $S_{11} (J^P = 1/2^-)$

- $\Delta \chi^2$ due to insertion of a Res into $P_{13} (J^P = 3/2^+)$
Conclusion from Modified \( \pi N \) PWA

• 1680 MeV - only one partial wave (\( P_{11} \)) reveals the effect: support to the resonance, \( \Gamma_{\pi N} < 0.5 \) MeV

• 1730 MeV - \( P_{11} \) may also reveal a resonance with \( \Gamma_{\pi N} < 0.3 \) MeV but differently: resonance is still possible, if accompanied by different corrections

• Other partial waves, \( P_{13} \) and \( S_{11} \) (less probable), could show effect, if accompanied by different corrections

For example, thresholds: \( N\omega(1720) \), \( N\rho(1710) \), \( K\Sigma(1685) \)
Theoretical Analysis

• Theoretical analysis is rather uncertain but nevertheless may be used for orientation

• Structure of hadron mixing due to violation of $SU(3)_F$
  - $10 \leftrightarrow 8$ for $\Sigma, \Xi$ (no partners for $\Lambda, N, \Delta$)
  - $10 \leftrightarrow 8$ for $\Sigma, N$ (no partners for $\Lambda, \Theta, \Xi$)
  - $10 \leftrightarrow 10$ for $\Sigma$ (no partners for $\Delta, \Theta, N, \Xi$)
    Only higher orders in octet violation
  - Mixing shifts GMO masses of $\Theta$ partners
    may essentially influence decay widths
  - What are mixing with higher multiplets, such as 27 and/or 35?
Mixing

- Mixing is possible only for states with the same strangeness and isospin
- Mixing acts differently for different members of the $10$

- $\Theta \rightarrow \Lambda N$ no mixing in the init state, $10-8$ mixing is efficient in the fin state
- $N^* \rightarrow \pi \Delta$ no mixing in the fin state, $10-8$ mixing is possible in the init state
- Mixing does not shift masses of $\Theta$ and $\Xi_{3/2}$, is able to shift GMO masses for
  - $N^*$: $1650$ MeV $\rightarrow$ $1650-1690$ MeV
  - $\Sigma^*$: $1755$ MeV $\rightarrow$ $1760-1810$ MeV

[D. Diakonov, V. Petrov, Phys Rev D 69, 094011 (2004)]
If $\Gamma_{\Theta} \leq 1$ MeV, then expected structure for decays of the $\Theta$-partners looks as follows:

$\Gamma(N^* \rightarrow \text{all}) \sim 10$ MeV [\(\Gamma_{\pi N}/\Gamma_{\text{tot}} \leq 10\%\)]

Ratio of modes $\pi N$ and $\eta N$ is sensitive to the mixing

$\Gamma(N^* \rightarrow \pi \Delta) \sim 6$ MeV [forbidden for 10, open due to 10-8 mixing]

$\Sigma^*$ is the most uncertain member of the 10, for both mass and width

Estimates of partial widths are not very reliable, but at the level of `handwaving', $\Gamma(\Sigma^* \rightarrow \text{all}) \leq 30$ MeV

For $\Xi_{3/2}$, estimates give general bound $\Gamma(\Xi_{3/2} \rightarrow \text{all}) \leq 5$ MeV

Both $\Gamma_{\text{tot}}$ and ratio of modes $\pi \Xi$ and $\bar{K} \Xi$ are highly sensitive to the mixing
Experimental Evidences for N*

- **GRAAL** in $\gamma n \rightarrow \eta n, K^0\Lambda$, and $K^+\Sigma^-$
- **STAR** in $AuAu \rightarrow \Lambda K_s$
- **COSY-TOF** in $pp \rightarrow \Lambda K^+p$
- **JLab Hall A** in $H(e,e'\pi^+)X^0$
GRAAL [V. Kuznetsov, hep-ex/0409032, NSTAR 2004, March 2004]

\( \gamma n \rightarrow \eta n \) vs \( \gamma p \rightarrow \eta p \)

\( \gamma n \rightarrow \eta n \)

\( \gamma p \rightarrow \eta p \)

\( \theta = 140^\circ \)

N(1670)

SAID PWA-04

Epi05, Jan 6-8, 2005  Igor Strakovsky, GWU
Very preliminary: $\gamma n \rightarrow K^0\Lambda, K^+\Sigma^-$
STAR [S. Kabana, hep-ex/0406032, Jamaica, March  2004]

\( \text{AuAu} \rightarrow \Lambda K_s \)

- \( M = 1734 \pm 0.5 \pm 5 \text{ MeV} \)
- \( \Gamma < 4.6 \pm 2.4 \text{ MeV} \)
- Significance = 6 \( \sigma \)

Min. bias Au+Au collisions 200 GeV, \( \sigma < \) upper 10% \( \sigma \text{(tot)} \)

N(1693)?
Summary

- Narrowness of $\Theta^+$ required reanalysis of all its flavor partners
  We did it for `N(1710)' using modified $\pi N$ PWA

- If $\Theta^+$ is indeed a narrow state with $\Gamma_\Theta \leq 1$ MeV,
  then other members of the flavor 10 are, most probably, narrow as well
  Their properties are sensitive to the structure of mixing which can be rather complicated

- Studies of the 10 (and other non-qqq baryons) promise to be very interesting and exciting, though may appear not easy

- Direct precise measurements are necessary!!
Backup
Unclaimed $\Theta^+$?

[found by V. Burkert, Pentaquark 2003, Nov 2003]
Was Progress delayed by Prejudice?

[PDG (M. Aguilar-Benitez et al) Phys Lett B 170, 289 (1986)]

- “The evidence for strangeness $+1$ baryon resonances was reviewed in our 1976 edition [1], and more recently by Kelly [2] and by Oades [3]. Two new partial-wave analyses [4] 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.”

References:
Standard PWA for $K^+n$

- $K^+d \rightarrow K^0pp - 77$
- $K^+d \rightarrow K^*np - 43$
- $K^+n \rightarrow K^0p - 6$
- $K^+n \rightarrow K^+n - 98$

$P_{01}$
- Pole: 1831-i95 MeV
- Zero: 1840-i127 MeV

$D_{03}$
- Pole: 1788-i170 MeV

Total: 224
Conclusion from KN PWA

For $I = 0$:

- only one partial wave ($P_{01}$) admits the effect at 1540 - 1550 MeV: the resonance, $\Gamma < 1 - 2$ MeV

- other partial waves ($S_{01}$ and $P_{03}$) may have the effect only by accompanied by other corrections
Pentaquark production in direct $e^+e^-$ collisions likely requires orders of magnitudes higher rates than available.

Slope:
- **Pseudoscalar mesons**: $\sim 10^{-2}/\text{GeV/c}^2$ (need to generate one qq pair)
- **Baryons**: $\sim 10^{-4}/\text{GeV/c}^2$ (need to generate two pairs)
- **Pentaquarks**: $\sim 10^{-8}/\text{GeV/c}^2$ (?) (need to generate 4 pairs)
**SPHINX vs HERMES**
[found by A. Dolgolenko]

- **SPHINX at IHEP:**
  \[ pC(N) \rightarrow pK_sK_sN \]

  ![Graph with pK_s distribution and significance = 3.8 \sigma]

- **HERMES at DESY:**
  \[ e^+d \rightarrow pK_sX \]

  ![Graph with pK_s distribution and significance = 5.6 \pm 0.5 \sigma]

Epi05, Jan 6-8, 2005  Igor Strakovsky, GWU
\[ e^+ d \rightarrow p K_s X \]

- \( \Theta^+ \) Mass spectrum with additional \( \pi \)
- \( p \pi^+ \pi^- \)
- \( \text{Signal/Background} = 2:1 \)
- \( \text{Signal/Background} = 1:3 \)

**HERMES vs HERMES**

[W. Lorenzon, Pentaquark 2004, July 2004]

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Was PDG right: 1986 + 15 = 2001±2 ?

- There are over a dozen published evidences
- However...

Epi05, Jan 6-8, 2005  Igor Strakovsky, GWU
Θ⁺ Evidences with EM Probe

- **LEPS at Spring-8:**
  \[ \gamma n^{(12C)} \rightarrow K^+ K^- (n) \]

  - Strangeness = +1
  - Significance \( (N_s/\sqrt{N_b}) = 4.6\pm1 \sigma \)

  \[ T. \text{ Nakano et al, PRL 91, 012002 (2003)} \]

- **CLAS at JLab:**
  \[ \gamma d \rightarrow K^- p K^+ (n) \]

  - Strangeness = +1
  - Significance = 5.3\pm0.5 \sigma

  \[ E. \text{ Klempt, hep-ph/0404270:} \]
  \[ N_s/\sqrt{N_b} \]
  \[ N_s/\sqrt{(N_b+N_s)} \]
  \[ N_s/\sqrt{(2N_b+N_s)} \]

  \[ S. \text{ Stepanyan et al, PRL 91, 252001 (2003)} \]

\[ \text{Epi05, Jan 6-8, 2005 Igor Strakovsky, GWU} \]
**Θ⁺ Evidences with EM Probe**

- **SAPHIR at ELSA**: $\gamma p \rightarrow K_s K^+ n$
- **CLAS at JLab**: $\gamma p \rightarrow K^- \pi^+ K^+(n)$

**J. Barth et al, PL B 572, 127 (2004)**

- Isospin = 0
- Significance = 4.8 $\sigma$

**V. Kubarovsky et al, PRL 92, 032001 (2004)**

- Strangeness = +1
- Significance = 7.8±1 $\sigma$
Evidences with Lepton Probe

- Reanalysis of Bubble Chamber Data from CERN and FNAL via ITEP: $\nu_\mu (\bar{\nu}_\mu) A \rightarrow p K_s X$

- Significance = 6.7 $\sigma$
$\Theta^+$ and $\Phi$ Evidences with Hadron Probes

- **DIANA at ITEP:**
  \[ K^+ n(Xe) \rightarrow K_s p(X) \]
  - $\Gamma < 9$ MeV
  - Significance = 4.4 $\sigma$

- **NA49 at CERN:**
  \[ pp \rightarrow \Xi^- \pi^- + \Xi^- \pi^+ (X) \]
  - Significance = 4$\sigma$

V. Barmin et al, PAN 66, 500 (2003)
C. Alt et al, PRL 92, 042003 (2004)
First Search for Exotic Baryons in $K^+p$ and $K^+d$

[**BNL 1966**]

[R. Cool et al, Phys Rev Lett 17, 102 (1966)]

[**BNL 1967**]

[R. Abrams et al, Phys Rev Lett 19, 259 (1967)]

- “clear” resonance peak found in $K^+N$ at $M = 1910$ MeV and $\Gamma = 180$ MeV
Analysis of the Xenon data

- R. Cahn and G. Trilling, PRD 69, 011501

With additional assumptions and unknown systematics:

\[ \sigma = B_i B_f \pi (\Gamma/2) \sigma_0 = 24 \text{ mb MeV} \]

\[ \sigma_0 (M=1540) = (2J+1)/(2s_N+1) (4\pi/k^2) = 68 \text{ mb} \]

\[ \Gamma = (2\sigma/\pi \sigma_0)(1/B_i B_f) = 0.9 \text{ MeV} \]
Analysis of $K^+d \sigma^{tot}$

- S. Nussinov, hep-ph/0307356
- R.A. Arndt et al, nucl-th/0311030

$\Delta \sigma = 2 - 4 \text{ mb} \Rightarrow \Gamma < 6 \text{ MeV}$

$\Delta \sigma = 1 \text{ mb} \Rightarrow \Gamma < 1.5 \text{ MeV}$
• **BES** [J. Bai *et al.*, Phys Lett B *589*, 7 (2004)]
  
  **Analysis** [Ya. Azimov, IS, Phys Rev C *70*, 035210 (2004)]

  • No double- or single-$\Theta$ production seen in decays of $J/\psi$ and $\psi(2S) \rightarrow K_S p K^- n + \text{ch.conj.}$
• Double $\Theta$ (take branching into account: $\text{Br}(\Theta \rightarrow K^+n) = 1/2$ and $\text{Br}(\Theta \rightarrow K_{Sp}) = 1/4$)

- $\text{Br}(J/\psi \rightarrow \Theta\Theta) < 0.44 \times 10^{-4}$

  Compare:
  $J/\psi \rightarrow \Sigma(1530)\Sigma(1530)$ kinematically similar, but not studied
  $\text{Br}(J/\psi \rightarrow \Lambda\Lambda) < (13.0\pm1.2) \times 10^{-4}$

  $\Theta\Theta$ vs. $\Lambda\Lambda$ - 2 more quark pairs, much smaller phase space
  $(M_{J/\psi} = 3097\text{ MeV}, M_{\text{th}}(\Theta\Theta) = 3080\text{ MeV})$

- $\text{Br}(\psi(2S) \rightarrow \Theta\Theta) < 0.34 \times 10^{-4}$

  Compare:
  $\text{Br}(\psi(2S) \rightarrow \Lambda\Lambda) = (1.81\pm0.34) \times 10^{-4}$
• Single $\Theta$ (again, recall branchings)

- The most stringent boundaries
  \[ \text{Br}(J/\psi \rightarrow K^0 p \Theta) < 0.44 \times 10^{-4} \]
  \[ \text{Br}(\psi(2S) \rightarrow K^0 p \Theta) < 0.24 \times 10^{-4} \]

Compare:
  \[ \text{Br}(J/\psi \rightarrow K^- p \Lambda) = (8.9 \pm 1.6) \times 10^{-4} \]
  \[ \text{Br}(\psi(2S) \rightarrow \pi^0 p p) = (1.4 \pm 0.5) \times 10^{-4} \]
• Summary on Θ+ Nonobservation at BES

- Data need some (rather soft) dynamical suppression, say $1/5$ in the probability

- Meanwhile, because of necessity to produce directly two more $qq$ pairs (in exotic decays as compared with decays to canonical baryon-antibaryon pairs), some dynamical suppression should naturally arise. **One or two** order suppression might be quite natural

- Thus, the recent result of BES is only a starting point for investigating exotics in $e^+e^-$-annihilation
Θ+ Flavor Partner, N*(J^P = 1/2^+)

• If $\Gamma_\Theta \leq 1$ MeV, then expected structure for decays of the Θ-partner N* looks as follows:

- $\Gamma(N^* \rightarrow \pi\Delta) \sim 6$ MeV [forbidden for 10, open due to 10-8 mixing]
- $\Gamma(N^* \rightarrow \eta N) \sim 0.5 - 2$ MeV
- $\Gamma(N^* \rightarrow K\Lambda) \sim 0.5 - 1.5$ MeV
- $\Gamma(N^* \rightarrow \pi N) \sim 0.3 - 0.5$ MeV [non-trivial cancellation due to mixing is required]
- $\Gamma(N^* \rightarrow \pi\pi N)$ [out of πΔ]？
- $\Gamma(N^* \rightarrow K\Sigma)$ is small？

- $\Gamma(N^* \rightarrow \text{all}) \sim 10$ MeV [$\Gamma_{\pi N}/\Gamma_{\text{tot}} \leq 10\%$]

Ratio of modes $\pi N$ and $\eta N$ are sensitive to the mixing.
Σ* (again, recall $\Gamma_\Theta \leq 1$ MeV)

- The most uncertain member of the $\bar{10}$, for both mass and width

- Most decay modes may be essentially influenced by mixing in either initial and/or final states

- Estimates of partial widths are not very reliable, but at the level of `handwaving'

  $\Gamma(\Sigma^* \rightarrow \text{all}) \leq 30$ MeV
$$\Xi_{3/2} \text{ (again, recall } \Gamma_{\Theta} \leq 1 \text{ MeV)}$$

- Kinematically possible decays:
  $$\Xi_{3/2} \rightarrow \pi \Xi(1530)$$ forbidden by SU(3)$_F$
  $$(10 \rightarrow 8+10)$$ could be allowed by (small !)
  mixing 10-8 for $\Xi(1530)$,
  and/or mixing of $\Xi_{3/2}$ with 27, 35, ...

  $\Gamma(\Xi_{3/2} \rightarrow \pi \Xi)$ practically independent of mixing

  $\Gamma(\Xi_{3/2} \rightarrow K \Sigma)$ essentially depends on the final state mixing

- Estimates give general bound
  $\Gamma(\Xi_{3/2} \rightarrow \text{all}) \leq 5 \text{ MeV}$

- Both $\Gamma_{\text{tot}}$ and ratio of modes $\pi \Xi$ and $\bar{K} \Sigma$
  are highly sensitive to the mixing
GRAAL [V. Kuznetsov, hep-ex/0409032, NSTAR 2004, March 2004]

\( \gamma n \rightarrow \eta n \)

**Quasi-free \( \eta n \)**

**Free \( \eta p \)**

**Quasi-free \( \eta p \)**

\( N(1670) \)

Very preliminary: $pp \rightarrow \Lambda K^+ p$

$P_{\text{beam}} : 3.30 \text{ GeV/c}$

$N'(1710)$ contributes strongly

Influence of $p\Lambda$-FSI

In progress: Investigation of Dalitz plots $\rightarrow$ width
JLab Hall A [B. Wojtsekhowski, E-04-012]
Very preliminary, data taken in May of 2004

- $E_0 = 5$ GeV
  - $\theta_{e'} = 6^0$
  - $\theta_\pi = 0^0$
  - $\Delta \Theta = \pm 2^0$
  - $\sigma_{MM} = 1.3$ MeV

- Signal
  - $N(1680)$ from $H(e,e'\pi^+)$
  - $\Sigma(1770)$ from $H(e,e'K^+)$
  (if any) is small (agrees with expectation)
E04-012 Search for Pentaquark Partners

Upper limits on production of narrow resonances
(\( \Gamma = 5 \sim 15 \text{ MeV} \)) at photon energy 3 GeV

- \( \Sigma^o \)
- \( \Sigma^o_5 \)
- \( \Theta^{++} \)

\[ \sigma / \sigma(\Lambda_{1520}) < 0.8\% \]

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Lattice

- The lattice gauge theory is the only QCD based approach which pretends to do hadron spectroscopy computations directly from the first principles.

- However as far as we know, in the current lattice literature there exist three various statements:

  1) The $\Theta^+$ has $J^P=1/2^+$ (1 group)
  2) The $\Theta^+$ has $J^P=1/2^-$ (5 groups)
  3) The $\Theta^+$ does not exist at all (2 groups)

- Therefore, it is worth of referencing...