Pentaquark Search at BNL


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What are penta-quarks?

- Minimum quark content is 5 quarks.
- “Exotic” penta-quarks are those where the antiquark has a different flavor than the other 4 quarks.
- Quantum numbers cannot be defined by 3 quarks alone.

Example: $uudd\bar{s}$

Baryon number $= \frac{1}{3} + \frac{1}{3} + \frac{1}{3} + \frac{1}{3} - \frac{1}{3} = 1$

Strangeness $= 0 + 0 + 0 + 0 + 1 = 1$

E.g. $uudd\bar{c}$, $uuss\bar{d}$

c.f. $L(1405)$: $uuds\bar{u}$ or $uds$
Q⁺ Baryon


- Exotic: S=+1
- Low mass: 1530 MeV
- Narrow width: ~ 15 MeV
- J⁺p=1/2⁺

\[ M = [1890-180*Y] \text{ MeV} \]
Baryon masses

- Mainly 3 quark baryons:
  \[ M \sim 3M_q + \text{(strangeness)} \]

- 5-quark baryons, naively:
  \[ M \sim 5M_q + \text{(strangeness)} \]
  1900 MeV for \( Q^+ \)

- 5-quark baryons, in chiral quark soliton:
  \[ M \sim 3M_q + \frac{1}{\text{(baryon size)}} + \text{(strangeness)} \]
  \(~1550\text{ MeV for } Q^+\)
Theory

• DPP predicted the $Q^+$ with $M=1530\text{MeV}$, $G<15\text{MeV}$, and $J^p=1/2^+$.  

• Naïve QM (and many Lattice calc.) gives $M=1700\sim 1900\text{MeV}$ with $J^p=1/2^-$.  

• But the negative parity state must have very wide width ($\sim 1\text{ GeV}$) due to “fall apart” decay.

Positive Parity?

• Positive parity requires P-state excitation.  

• Expect state to get heavier.  

• Need counter mechanism.

diquark-diquark, diquark-triquark, or strong interaction with “pion” cloud?

Ordinary baryons

For pentaquark

Fall apart
Why $Q^+$ is so narrow?

$\Theta^+ \to nK^+$ decay

$$\Gamma_\Theta = \frac{3 g_{KN\Theta}^2}{2\pi(m_N + m_\Theta)^2 m_\Theta} \frac{m_N}{5} |p|^3$$

$g_{KN\Theta} \approx \frac{g_A^{\Theta \to NK} (m_N + m_\Theta)}{2 F_K}$ similar to $g_{\pi NN} = \frac{g_A m_N}{F_\pi}$

$$g_A^{\Theta^+ \to nK^+} = \frac{\langle n^{(5)} | J_{05}^{K^+} | \Theta^+ \rangle + \cdots}{\sqrt{N_n^{(3)}} + N_n^{(5)} + \cdots} \sqrt{N_\Theta^{(5)} + \cdots}$$

$\frac{N_n^{(5)}}{N_n^{(3)}} \ll 1$

$\Theta$ decay is suppressed to the extent the 5-quark component of the neutron is less than its 3-quark component. Additional suppression comes from the peculiar flavor structure of the neutron's 5-quark component where the $\bar{Q}$ is in the flavor-singlet combination with one of the four $Q$.

A preliminary crude estimate gives $\Gamma_\Theta = 0.7$ MeV without fitting any parameters!

D. Diakonov, Talk at Pentaquak04
Evidence for Penta-Quark States

Spring8

DIANA

JLab-d

ELSA

COSY-TOF

pp → S+Q+.

This is a lot of evidence. However,…
Mass

Final state:
- $K^+ + n$
- $K_s + p$
- $(K_s + \bar{p})$

A few % difference from zero, but ~20% difference from the KN threshold.
Width

- Again, there is inconsistency:
  - Most measurements give upper limits.
  - DIANA has $G < 9$ MeV.
  - The cross-section implies $G = 0.9$ MeV.
  - HERMES: $G = 13 \pm 9$ stat. (+- 3 sys.) MeV
  - ZEUS: $G = 8 \pm 4$ stat. (+- 5 sys.) MeV
  - Arndt et al. and Cahn et al. analysis of KN phase shifts suggests that $G < 1$ MeV !!
- The small width is the hardest feature for theorists to understand…
Null Results

• HERA-B (Germany):
  – reaction: p+A at 920 GeV
  – measured: K⁻p and K⁰p invariant mass
  – Clear peak for L(1520), no peak for Q⁺
  – production rate: Q⁺/L(1520)<0.027 at 90% C.L.

• BES (China):
  – reaction: e⁺e⁻ → J/ψ → Q⁺Q⁻
  – limit on B.R. of ~10⁻⁵
  
  And many unpublished negative results

(HyperCP, CDF, E690, BaBar, LEP,...).

If the Q⁺ does exist, its production in high energy reactions must be highly suppressed.

→ Model independent experimental search is most desirable.
We propose to

Search for the $Q^*$ in Formation experiment with High intensity kaon beam and Large acceptance detector.
Cross Section for Formation

(Courtesy of M. Praszalowicz)

Breit-Wigner cross-section ($GM + MP$)

\[
\sigma_{BW}(E) = \frac{2J + 1}{(2S_1 + 1)(2S_2 + 1)k^2} \frac{\pi}{k^2} B_{in} B_{out} \frac{\Gamma^2}{(E - M)^2 + \Gamma^2/4}
\]

\[
\sigma_{BW}(M) = \frac{\pi}{k^2} \sim 16.8 \text{ [mb]}
\]

\[
\sigma_{tot} = \frac{\pi}{4k^2} 2\pi \Gamma \sim 26.4 \times \frac{\Gamma}{1 \text{ MeV}} \text{ [mb} \times \text{MeV]}\]

Nussinov (hep-ph/0307357)

\[
\sigma_{K+n}(p) = \frac{4\pi}{p^2} \sum_l (2l + 1) E \sin^2 \delta_l(p)
\]

\[
\sigma_{\Theta^+}|_{res} \sim \frac{4\pi}{p^2} \cdot 3 \cdot \left(\frac{1}{2}\right) \cdot \left(\frac{1}{3}\right) \sim \frac{37}{2} \text{ mb} \sim 18.5
\]
• The background is smooth and well known (~4 mb).
• The $Q^+$ with a narrow width should appear as a bump.
• If not, a strong limit on the width can be put.
The “noisy” K$^+\!n$ database

There are clearly some systematic problems in the KN data!

Note: errors get larger as momentum goes lower.
Previous formation experiment

\[ K^+ \text{ Xe} \rightarrow K^0 \text{ p} \text{ X} \]
\[ (K^+ \text{ n} \rightarrow K^0 \text{ p}) \]

- \( P_{K^+} < 530 \text{ MeV/c} \)
- Require \( q_K < 100 \text{ deg.} \) \& \( q_p < 100 \text{ deg.} \)
- Remove \( \cos f_{pK} < 0 \) \( \leftrightarrow \) back-to-back

\[ K^+ \text{ n} \rightarrow Q^+ \quad \leftrightarrow \quad Q^+ \rightarrow K^+ \text{ n} \]

\[ G = 0.9 \pm 0.3 \text{ MeV} \]

Cahn and Trilling hep-ph/0311245

consistent with KN phase shift analysis by Arndt et. al.

Phys. Rev. C68, 042201(R)
• AGS will be running for polarized protons for RHIC.
  • In principle, available between fills (i.e. most of the time). Flux of $10^{12}$ protons/spill should be easy (AGS ran at 60 times that for E949).
• LEB3 is a doubly-separated beam that goes up to 800 MeV/c.
• Can get 80% pure $K^+$.
• Can get $2.8 \times 10^4$ 475-MeV/c $K^+$ per $10^{12}$ on target.
Technique

1. Trigger on $K_S \rightarrow p^+,p^-$, measure in drift chamber + tgt.
2. $dE/dx$ across 20cm width of tgt spans 40 MeV range in CM energy.
3. Reconstruct proton in target (& sometimes in chamber). Can get momentum except for sign of $P_L$ (but usually is +) from transverse range + energy.
4. From $K_S + p$ reconstruct center of mass - remove Fermi momentum.
5. Multiple cross-checks:
   - Excitation curve (already limits width to 1-2 MeV).
   - $K_S$ missing mass technique
   - Some $p$'s seen in the chamber.
   - Run at different momenta to cover wide range, decouple geometry from kinematics.
   - Run K- and study $L(1520)$. 
E949 Solenoidal Detector

• $K^+$ stopping target made of 400 5-mm square scintillating fibers. Can track and measure charged particles therein.

• Low-mass cylindrical drift chamber in 1-T field can measure momenta in this region to $< 1\%$. In combination with target $\sim 1.5\%$. 

Elevation view of the E949 detector.
Monte Carlo of CM angle acceptance

Distribution generated isotropic in CM

If the decay angle of the $Q^+$ is measured, its spin and parity may be determined through interference with BG.
Sibirtsev et al. in nuc-th/0407011 claim very strong interference. Also very large rescattering in Xenon. Note that we’re working in C-12 vs Xe-131. Still need to worry about resolution! 

$K^+ n \rightarrow K^0 p$

Events/5 MeV

with cuts, $\Gamma_e=5$ MeV

no cuts, $\Gamma_e=5$ MeV

with cuts, $\Gamma_e=1$ MeV

no cuts, $\Gamma_e=1$ MeV
$M_{\pi\pi}$ distribution from E949 showing $K_S \rightarrow \pi^+\pi^-$
$K^*_S$ candidate in the E949 target

Beam’s-eye view of event in E949 target. Kaon enters at ~300 MeV/c. At this low momentum proton doesn’t get very far.
$K_S$ candidate in the E949 detector

End and side views of event in E949 detector. Green rectangles outside of drift chamber are range stack scintillators with in-time energy. Purple drift chamber track is out-of-time random.
2\textsuperscript{nd} $K_S$ candidate in the E949 target

Beam’s-eye view of 2\textsuperscript{nd} event in E949 target. This time the recoil proton either overlaps the incoming K or is absent.
2\textsuperscript{nd} $K_S$ candidate in the E949 detector

End and side views of event in E949 detector.
Rates

1. "Background" rate ~800 \( K_S \)/pulse.
2. For \( Q^+ \) width 1MeV, integrated cross-section is 26.4mb-MeV, which would give about 1/6 as many events, 1/10 with \( K_S \) into \( p^+,p^- \).
3. AGS spill to be optimized, assume e.g. 1.3sec/3.6sec, gives \( 10^5 \) spill per 100 hours or 8M produced \( Q^+ \) per \( 10^{12} \) POT for 1-MeV width.
4. Acceptance for \( K_S \) ~ 10%, so 800,000 \( Q^+ \)/week in which we see \( K_S \). Proton acceptance not yet known, but geometrical acceptance high. Overall shouldn't be <10%, so at least 80,000 \( Q^+ \)/week, going in.

Running requests : \( \sim 10^{12} \) POT for 5 weeks
- need to get detector on air, vary momenta, do \( K^- \) runs.
Things to do

-before deciding if a proposal is warranted.

• Detailed Monte Carlo & studies of E949 data to get resolutions and acceptances. Requires mods to E949 software.
• Studies of pattern recognition in target
• Fine tuning of strategy