WHY PENTAQUARKS ARE SEEN IN SOME EXPERIMENTS AND NOT IN OTHERS

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The Θ⁺ Pentaquark is a Very narrow Γ ~ 1 MeV KN Resonance. Why do some experiments see it and others do not? The lowest quark configuration that can describe it is exotic \( uudd \bar{s} \). Why have no exotics been seen before? Is this the beginning of a new spectroscopy? Can it help teach us about How QCD makes hadrons from quarks and gluons?

1 Introduction

1.1 A wrong question

People keep asking whether the pentaquark really exists. This is the wrong question. They recall the \( a_2 \) splitting and the zeta particle which went away. But I am now haunted by a different memory, In the summer of 1964 Jim Smith told me about evidence from their kaon experiment at Brookhaven for a \( 2\pi \) decay of the long-lived kaon. He asked me whether this could be explained without CP violation. I didn’t see how and stupidly believed that there must be something wrong with their data. But their data were right and appeared as the second published evidence for CP violation¹.

My response to the wrong question about pentaquark existence is what I should have told Jim Smith in 1964, Nature is providing us with new data that theorists do not understand. The right question is how can we understand the meaning of these data and how can we point experimentalists in the right direction to clarify the physics which may be very interesting,

1.2 Guidance from the wisdom of Feynman and Wigner

1. Feynman told us that we learned from sharpening contradictions.
2. Wigner told us that a few free parameters can fit an elephant. A few more can make him wiggle his trunk
3. Wigner’s response to questions about a particular theory he did not like was: “I think that this theory is wrong. But the old Bohr - Sommerfeld quantum theory was also wrong. Could we have reached the right theory without going through that stage?

Apply this wisdom to the pentaquark

1. Contradictions between different pentaquark experiments are not sharp enough.
2. Too many theoretical calculations blur contradictions with free parameters.
3. The diquark-triquark (wrong?) model² without many free parameters may lead us in the right direction.
2 Experimental contradictions between searches for exotics

Some experiments see the pentaquark; others definitely do not\(^3\). No theoretical model addresses this problem. Comprehensive review\(^4\) analyzes different models.

2.1 Different initial states with different final state overlaps

1. The new \(D_s^+ \rightarrow D_s \eta\)

SELEX has \(\Sigma^-\) \((\bar{s}d\bar{d})\) beam

\[
\Sigma^- (\bar{s}d\bar{d}) + e^- \rightarrow (\bar{s}d\bar{c}) \text{triquark} \rightarrow \bar{D}_s \eta.
\]

Is \(sd\) in \(\Sigma^-\) beam needed to produce \(D_s \eta\)?

Evidence that the \(s\) quark in the beam goes into the final state is given by the charge asymmetry. \(D_s \eta\) is seen; but \(D_s \eta\) not.

\(sd\) in beam can produce \((\bar{s}d\bar{d}) \rightarrow \bar{D}_s \eta\),

But cannot produce \((\bar{s}d\bar{d} \rightarrow D_s \eta)\)

2. The \(\Theta^+\) pentaquark

In low-energy photoproduction experiments the baryon and \(\bar{s}\) antiquark in the \(\Theta^+\) are initially present in the target baryon and the \(\bar{s}\bar{s}\) in the photon. In other experiments that do not see the \(\Theta^+\), the cost of baryon-antibaryon and/or \(s\bar{s}\) production by gluons must be used to normalize the production cross section for comparison with the photoproduction cross sections.

\(\gamma p\) sees \(\Theta^+\); \(e^+e^-\) doesn’t. Can the cost of producing \(\bar{B}\bar{B}\) and \(s\bar{s}\) explain the difference between \(\gamma p\) and \(e^+e^-\)?

2.2 \(\Theta^+\) production via \(N^*(2400)\)

A specific production mechanism that may be present in experiments that see the \(\Theta^+\) and absent in those that do not is suggested by CLAS data on \(\gamma p \rightarrow \pi^+ K^- K^+ n\). The \((K^+ K^- n)\) mass distribution show a peak at the mass of 2.4 GeV that might indicate a cryptoexotic \(N^*\) resonance with hidden strangeness. Searches for such baryon resonances\(^5\) have indicated possible candidates but did not go up to 2.4 GeV. Further \(N^*\) resonance evidence is hinted in preliminary results\(^3\) from NA49.

Some experimental checks of this mechanism\(^3\) are:

1. Experiments which see the \(\Theta^+\) should examine the mass spectrum of the \(K^- \Theta^+\) and \(K_s \Theta^+\) systems.

2. Experiments searching for the \(\Theta^+\) should check for possible production of a 2.4 GeV \(K^- \Theta^+\) or \(K_s \Theta^+\) resonance.

3. In the photoproduction reactions

\begin{align*}
\gamma p & \rightarrow N^*(2400) \rightarrow \bar{K}^0 \Theta^+ \\
\gamma p & \rightarrow N^*(2400) \rightarrow \bar{K}^0 \Theta^+ \rightarrow \pi^- K^+ \Theta^+
\end{align*}

the \(K\) or \(K^*\) angular distribution should show no forward-backward asymmetry.

4. If the photoproduction reaction

\[
\gamma p \rightarrow \pi^+ K^- K^+ n \rightarrow N^*(2400),\text{ the pion goes forward and everything else is in the target fragmentation region.}
\]

5. Search for other \(N^*(2400)\) decay modes.

SU(3) predicts \(N^*(2400) \rightarrow \pi^- N^\ast\) where \(N^\ast\) is the nonstrange SU(3) partner of the \(\Theta^+\). Decays into \(K\Lambda, K\Sigma, K\Sigma^*\) and \(\phi N\) are allowed in some models but suppressed in a diquark-triquark model\(^2\) by the centrifugal barrier against passage of a quark in the triquark from joining the diquark.

6. Both charge states \(N^{\ast+}(2400)\) and \(N^{\ast-}(2400)\) should be observed.

2.3 Production via meson and baryon exchanges

In \(\gamma p \rightarrow \bar{K}^0 \Theta^+ \rightarrow \pi^- K^+ \Theta^+\) and \(\gamma p \rightarrow \bar{K}^0 \Theta^+\) meson exchange, predicts a forward-peaked \(K\) or \(K^*\) angular distribution. Baryon exchange predicts backward peaking\(^6\) and the same baryon exchange with equal production in \(\gamma n \rightarrow K^- \Theta^+\).
$\Theta^+$ production by baryon exchange is related to reactions between nonexotic hadrons via $\Theta^+$ or other exotic baryon exchange. An appreciable contribution of the diagram proposed for $\Theta^+$ photoproduction with an outgoing backward kaon indicates an appreciable $KN\Theta^+$ vertex that should also contribute appreciably to backward $K^-p$ charge-exchange. Some previously ignored backward $K^-p$ charge-exchange may still be available.

Models\textsuperscript{6} which explain the narrow width of the $\Theta^+$ by a suppressed $NK\Theta^+$ coupling relative to $NK^\ast\Theta^+$ predict that $\Theta^+$ production with a backward $K^+$ is stronger than the production with a backward kaon.

3 QCD Guide to exotic search

3.1 BJ’s question in 1986

In $e^+e^-$ annihilation a created $q\bar{q}$ fragments into hadrons. The $q$ can pick up a $\bar{q}$ to make a meson or a $q$ to make a diquark ($qq$). The $qq$ can pick up another $q$ to make a baryon but might pickup a $\bar{q}$ to make a “triquark” ($qq\bar{q}$) bound in a color triplet state. Picking up two more quarks makes a pentaquark.

BJ asked: “Should such states be bound or live long to be observable as hadron resonances? What does the quark model say?”

The quark model says that a pentaquark is a five-body problem with no feasible exact solution. The simplest approach assuming space factorization and symmetrization explains absence of low-lying exotics and gives negative parity pentaquarks, but does not predict $\Theta^+$. A positive parity $\Theta^+$ suggested by the chiral soliton model\textsuperscript{2} requires a p-wave pentaquark and may imply a stable lower s-wave baryon\textsuperscript{9}. A five-body system has ten possible pairs for p-wave giving too many possible states.

3.2 Color-magnetic interaction and flavor antisymmetry

QCD motivated models\textsuperscript{7,8,9} show that breakup of exotic multiquark color singlet states into two separated color singlets loses no color electric energy and gains kinetic energy.

$$|\text{singlet}\rangle \rightarrow |\text{singlet}\rangle + |\text{singlet}\rangle \quad (1)$$

Extending to multiquark states\textsuperscript{10} the remarkably successful\textsuperscript{2} DGG model\textsuperscript{9} showed that only the short-range color-magnetic interaction can produce binding in single cluster or bag models.

The Pauli principle requires flavor-symmetric quark pairs to be antisymmetric in color and spin at short distances and therefore to have a repulsive short-range color-magnetic interaction. The best candidates for multiquark binding should have a minimum number of same-flavor pairs.

The nucleon has only one same-flavor pair: $\Delta^{++}(uuu)$ has three. Two extra same-flavor pairs cost 300 Mev. Flavor antisymmetry principle\textsuperscript{11} explained absence of low-lying exotics and suggested search for $H$ dibaryon $uudds$. Extension to heavy quarks\textsuperscript{11} suggested exotic tetraquarks and anticharmed strange pentaquark\textsuperscript{12} ($cuuds$).

Quark model calculations with flavor antisymmetry told experimenters to look for ($cuuds$) pentaquark with only one same-flavor pair; not the $\Theta^+(suud)$ with two. Ashery’s E791 search for $cuuds$ found events\textsuperscript{13}; not convincing enough. Better searches with good vertex detectors and particle ID\textsuperscript{12} are needed; one gold-plated event showing a proton emitted from a secondary vertex and defining a new unknown baryon is enough without statistics.

Finding the $\Theta^+$ suggests a two-cluster model\textsuperscript{2}. A diquark-triquark in p-wave $|ud; ud\bar{s}\rangle$ with a centrifugal barrier separates repulsive identical $uu$ and $dd$ pairs. The $ud$
pairs are bound fermion pairs, not bosons, with wave functions not uniquely defined and depending on external environment. The diquark is in an external color triplet field like the \(ud\) pair in the \(\Lambda\) and is assumed to have the same unique wave function and mass. The \(ud\) pair interacting with the \(\bar{s}\) has a very different environment. Two different color-spin couplings and different \(ud\) wave functions arise for the triquark with roughly the same color-magnetic energy\(^4\). These two \(ud\) pairs are thus very different and cannot be considered as identical bosons\(^6\).

The two nearly degenerate states \(\Theta_1\) and \(\Theta_2\) both coupled to a \(KN\) final state are mixed by the loop diagram\(^6\) \(\Theta_1 \rightarrow KN \rightarrow \Theta_2\). Diagonalizing the loop diagram gives approximate mass eigenstates \(\Theta_L\) not coupled to \(KN\); \(\Theta_b\) broad and lost in continuum\(^6\). Exact calculation of the narrow width depends upon unknown parameters.

The color-magnetic force keeps the triquark \((ud\bar{s})\) stable against \(ud\bar{s} \rightarrow d + K^+\) breakup, while \(|us; ud\bar{s}\rangle \rightarrow |udd\rangle + K^+\) crosses centrifugal barrier. A d-wave \(|us; ud\bar{s}\rangle\) model for \(N^*(2400)\) can explain \(N^*(2400) \rightarrow K^0 + \Theta^+\) via diquark transition \(|us\rangle \rightarrow K^0 + |ud\rangle\).

### 3.3 Tests for antidecuplet purity

Does the antidecuplet mix with octet?

Experimental tests for a pure \(10N^*\)

\[
\gamma p \rightarrow N^{*+}\text{forbidden; }\gamma n \rightarrow N^{*0}\text{allowed}
\]

\[
\sigma(\gamma p \rightarrow K^+\pi^\pm\Sigma^+) = \sigma(\gamma p \rightarrow K^+K^0N^*) = \sigma(\gamma p \rightarrow \pi^+\pi^-N^{*+}) = \frac{1}{3}\sigma(\gamma p \rightarrow \pi^+K^-\Theta^+)
\]

But if \(\gamma p \rightarrow \pi^+N^{*0}(2400) \rightarrow \pi^+M^-B^+\)

\(SU(3)\) breaking gives a factor 3 difference

\[
\sigma(\gamma p \rightarrow \pi^+\pi^-N^{*+}) = \sigma(\gamma p \rightarrow \pi^+K^-\Theta^+).
\]

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\(^{6}\)Treating diquarks whose wave functions depend upon external environment as elementary bosons misses essential physics just like treating Cooper pairs as bosons misses superconductivity. Boson condensates cannot superconductor because any moving boson can lose energy by collision with an impurity. A moving Cooper pair in a BCS superconductor cannot lose energy by collisions. Changing one pair wave function changes the environment of all other pairs and creates the energy gap which is the key to BCS superconductivity.