About a Possible Nonstrange Cousin of the $\Theta^+$ Pentaquark

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Abstract

We discuss the implications of the suggested interpretation of the recently reported narrow $\pi N$ resonance (width $\approx 25$ MeV at 1680 MeV) as a pentaquark in the same multiplet as the $\Theta^+$. We consider a diquark-triquark pentaquark model involving a recoupling of the five quarks into a diquark-triquark system in non-standard color representations. We estimate the mass using a well-tested simple mass formula. Our rough numerical estimate puts the $\pi N$ pentaquark resonance at 1720 MeV, sufficiently close to the reported value of 1680 MeV to indicate that this approach deserves further more accurate investigation.

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I. THE REPORTED NARROW $\pi N$ RESONANCE

The reported narrow $\pi N$ resonance (width $\approx 25$ MeV at 1680 MeV suggests [1] that it might be a nonstrange pentaquark in same $SU(3)_f$ multiplet as the antistrange $\Theta^+$ pentaquark with mass 1540 MeV. The experimental discovery [2] of the $\Theta^+$ with a very small width $\lesssim 20$ MeV and a presumed quark configuration $uudd\bar{s}$ had given rise to a number of further experiments [3] and an interest in theoretical models [4] for exotic hadrons including models with diquark structures [5].

The controversy between experimental evidence for and against the existence [6,7] of the $\Theta^+$ remains unresolved. There are also questions about isospin asymmetry [8]. The ball now is in the experimental court. New data are needed to pin down whether these states are really there and to give clues regarding their structure.

A. Two proton-neutron asymmetries with different $SU(3)_f$ explanations

Both pentaquark candidates are seen in photoproduction from a deuteron. Both are reported to be photoproduced much more strongly on neutrons than on protons. The two theoretical mechanisms proposed for this asymmetry are very different but both assume $SU(3)_f$ symmetry. Both are violated by $SU(3)_f$ symmetry breaking.

The discrepancy between photoproduction of the reported narrow $\pi N$ resonance on protons vs. neutrons follows directly from an $SU(3)_f$ selection rule if both candidates are classified in the same $SU(3)$ antidecuplet ($\bar{10}$). The analysis is simplified by introducing the "$U$-spin" SU(2) subgroup of $SU(3)_f$ [15], analogous to isospin. $U$-spin interchanges $d$ and $s$ quarks, just like isospin interchanges $u$ and $d$ quarks. In the $SU(3)_f$ limit isospin and $U$-spin are equally valid. Since $d$ and $s$ quarks both have the same electric charge (-1/3), all members of the same $U$-spin multiplet have the same electric charge.

The positively charged members of the ($\bar{10}$) multiplet all have $U$-spin 3/2; the neutral members have $U$-spin 1. The photon has $U$-spin zero [16], the proton has $U$-spin 1/2 and the neutron has $U$-spin 1, as illustrated in Fig. 1.
Fig. 1 (a) Exotic baryon anti-decuplet. The positively charged states $\Theta^+$, $\tilde{N}^+$, $\tilde{\Sigma}^+$ and $\tilde{\Xi}^+$ form a $U$-spin multiplet with $U = \frac{3}{2}$. The neutral states $\tilde{N}^0$, $\tilde{\Sigma}^0$ and $\tilde{\Xi}^0$ form a $U$-spin triplet with $U = 1$.

Fig. 1 (b) Spin-$\frac{1}{2}$ baryons and pseudoscalar mesons. Proton belongs to a $U$-spin doublet with $U = \frac{1}{2}$, while neutron belongs to a $U$-spin triplet with $U = 1$. Similarly, neutral kaons belong to a $U$-spin triplet with $U = 1$, while charged kaons are members of $U$-spin doublets with $U = \frac{1}{2}$. 
This shows how the photoproduction of the charged nonstrange member of a \( \mathbf{10} \) multiplet on a proton is forbidden by \( SU(3) \), while the photoproduction of the neutral nonstrange member on a neutron is allowed. However this selection rule holds only if the nonstrange resonance is a pure \( \mathbf{10} \) of \( SU(3)_f \) with no octet admixture. But octet-antidecuplet mixing is predicted by \( SU(3)_f \) symmetry breaking. This contradiction can only be resolved by more and better experimental data.

A completely different explanation is needed for the apparent isospin asymmetry between null \( \Theta^+ \) photoproduction on protons [9] vs. clear signal on neutrons (via deuteron target; e.g. [10], [11]. It can be resolved if the photon couples much more strongly to \( K^+K^- \) than to \( K^o\bar{K}^o \). A selection rule forbidding the \( \gamma K^o\bar{K}^o \) vertex follows from conservation of \( G_U \) parity, the \( SU(3)_f \) rotation of G-parity with isospin replaced by the \( U \)-spin. [15]. The \( \gamma, K^o \) are odd under \( G_U \) [16], just as the \( \omega, \pi^+ \) and \( \pi^- \) are all odd under ordinary \( G \) parity. Conservation of \( G_U \) parity gives a flavor symmetry selection rule forbidding the \( \gamma K^o\bar{K}^o \) vertex [14], just as conservation of \( G \) parity forbids \( \omega \to \pi^+\pi^- \). In the \( SU(3)_f \) limit the partial widths of both transitions are zero

\[
\Gamma(\gamma \to \bar{K}^oK^o) = \Gamma(\omega \to \pi^+\pi^-) = 0
\]  

This selection rule is confirmed by the experimentally observed asymmetry \( \gamma p \to \Lambda(1520)K^+ \gg \gamma n \to \Lambda(1520)K_s \).

A photon which turns into a \( G_U \) allowed \( K^+K^- \) can make a \( \Theta^+ K^- \) directly on a neutron, but cannot make a \( \Theta^+ \) directly on a proton. A photon which turns into the \( G_U \) forbidden \( K^o\bar{K}^o \) can make a \( \Theta^+ \bar{K}^o \) directly on a proton, but cannot make a \( \Theta^+ \) directly on a neutron. How much of the photon appears as \( K^+K^- \) and how much as \( K^o\bar{K}^o \) depends upon the amount of \( SU(3)_f \) breaking. This is an experimental question that can be clarified by measuring the neutral kaons, e.g. comparing \( \gamma p \to pK^+K^- \) with the analogous reaction with neutral kaons in the final state. One can also do an analogous comparison in \( \gamma d \). The relevant data might in principle be available in the CLAS g11 and LEPS experiments.
B. $\Theta^+$ photoproduction on proton vs neutron targets

An isospin analysis of pentaquark production using the selection rule forbidding the $\gamma K^o\bar{K}^o$ vertex also forbids $\gamma p \rightarrow \Theta^+ K_S$ and allows $\gamma n \rightarrow \Theta^+ K^-$. Thus $\gamma p \rightarrow \Theta^+ K_S$ can be expected to be suppressed in comparison with $\gamma n \rightarrow \Theta^+ K^-$ if $SU(3)_f$ is not badly broken. The validity of the selection rule is tested by the prediction of a strong $p/n$ asymmetry in $\gamma N \rightarrow \Lambda(1520)K$. Recent data on $\Lambda(1520)$ production confirm this picture. LEPS observes a strong asymmetry in photoproduction of $\Lambda(1520)$ on proton and neutron [11]. They measured both $\gamma p \rightarrow \Lambda(1520)K^+$ and $\gamma d \rightarrow \Lambda(1520)KN$ and find that the production rate on the deuteron is almost equal to and even slightly smaller than on the proton. This implies that $\gamma n \rightarrow \Lambda(1520)K_S$ is negligible.

We therefore propose the suppression of the $\gamma K^o\bar{K}^o$ vertex as the likely explanation of non-observation of $\Theta^+$ production on a proton target in the CLAS g11 experiment [9]. To gain confidence in this explanation it is important that other experiments confirm the relative suppression of $\gamma n \rightarrow \Lambda(1520)K$.

In the vector dominance picture the photon is an $SU(3)_f$ octet and a $U$-spin scalar combination of the $\rho$, $\omega$ and $\phi$. In unbroken $SU(3)_f$ they are exactly degenerate and their contributions to $\gamma \rightarrow K^o\bar{K}^o$ cancel exactly. In the real world $SU(3)_f$ breaking as measured by vector meson masses is about 25%-30%, so the relative importance of the $\phi$ component is an open question. Further implications of this breaking are discussed below.

If the $\gamma K^o\bar{K}^o$ vertex is indeed strongly suppressed, then the g11 reaction $\gamma p \rightarrow nK^+K_S$ proceeds via $\gamma p \rightarrow K^+K^-p \rightarrow K^+K_Sn$. It goes via the dominant $\gamma K^-K^+$ coupling and a simple $K^-p \rightarrow K_Sn$ charge exchange. If this is the dominant mechanism, there is no possibility of making the $\Theta^+$ in any simple way in the g11 setup.

The basic physics here is that the photon couples much more strongly to charged kaons than to neutral kaons and charged kaons can make the $\Theta^+$ simply on a neutron and not on a proton.
One test of this picture is to compare the photoproduction of isoscalar baryon resonances with positive and negative strangeness on proton and neutron targets.

Positive strangeness resonances like the $\Theta^+$ will be produced on neutron targets and not on protons, while negative strangeness resonances like the $\Lambda(1520)$ will be produced on proton targets and not on neutrons. The favored reactions with charged kaons are:

$$\gamma p \rightarrow K^+ \Lambda; \quad \gamma n \rightarrow K^- \Theta^+$$

(1.2)

The suppressed reactions with neutral kaons are

$$\gamma p \rightarrow \bar{K}^0 \Theta^+; \quad \gamma n \rightarrow \bar{K}^0 \Lambda$$

(1.3)

C. $SU(3)$ breaking and the $\phi$ component of the photon

So far we have considered the $\gamma K\bar{K}$ with unbroken $SU(3)_f$ as the dominant mechanism for photoproduction of strange baryons. To investigate $SU(3)_f$ breaking we introduce the vector dominance picture with broken $SU(3)_f$ and octet-singlet mixing. The $\rho$ and $\omega$ components of the photon are still degenerate but the $\phi$ is now separate. In this picture for $\Theta^+$ photoproduction the $\bar{s}$ strange antiquark is already present in the initial state in the isoscalar $\phi$ component. The $\rho$ and $\omega$ components contain no strangeness and can produce the $\Theta^+$ only via the production of an $s\bar{s}$ pair from QCD gluons. How much this extra strangeness production costs is still open. This cost does not appear in other treatments [8] which involve only pions and ignore the $\phi$ component of the photon.

An experiment that can check $SU(3)_f$ breaking projects out the $I = 0$ state of a $KN$ state. One example is the photoproduction on a deuteron [11] of the final state $\Lambda(1520)K^+n$.

If the strangeness in the reaction comes from the isoscalar $\phi$ component of the photon, the final $KN$ state is required by isospin invariance to be isoscalar, and the signal is observed against a purely isoscalar background. This is not true for the other $K^-pK^+n$ final states
observed in the same experiment where the $K^-p$ is not in the $\Lambda(1520)$ and the effects of a nonresonant $I = 1$ background can give very different results.*

It is interesting to compare the reactions

$$\gamma p \rightarrow K^- K^+ p \quad (1.4)$$

$$\gamma p \rightarrow \bar{K}^0 K^0 p \quad (1.5)$$

in the neighborhood of the $\phi$ resonance. At the peak of the $\phi$ the two cross sections should be equal. But on the low mass side of the peak the reaction (1.5) should be suppressed relative to the reaction (1.4). Preliminary results support this prediction [19]. An analogous effect has been seen in the photoproduction of tensor mesons [20] in the neighborhood of the hidden strangeness tensor meson $f'_2(1525)$

**II. EXTENSION OF THE DIQUARK-TRIQUARK MODEL FOR $\Theta^+$ TO A NONSTRANGE PENTAQUARK**

**A. Review of the dynamics of the $\Theta^+$ diquark-triquark model**

The choice of a pentaquark wave function is dominated by the short-range hyperfine interaction.

$$V_{hyp} = -V(\vec{\lambda}_i \cdot \vec{\lambda}_j)(\vec{\sigma}_i \cdot \vec{\sigma}_j) \quad (2.1)$$

where $\vec{\lambda}$ is $SU(3)_c$ generator and $\vec{\sigma}$ is a Pauli spin operator. The sign and magnitude are normalized by $\Delta-N$ mass splitting. The sign shows that the $qq$ interaction is attractive in states symmetric in color and spin and repulsive in antisymmetric states.

*We recall old SLAC experiments [17,18] which looked at photoproduction of $K^+$-hyperon from hydrogen and deuterium at 11 and 16 GeV. It would be interesting to re-examine these data in view of [11].
The Pauli principle forces two identical fermions to be in the repulsive antisymmetric color-spin state at short distances where the wave function must be symmetric in space. The hyperfine interaction is therefore repulsive between $uu$ and $dd$ pairs in a nucleon or pentaquark.

The optimum wave function with minimum color-magnetic energy keeps like-flavor $uu$ and $dd$ pairs apart, while minimizing the distance and optimizing the color couplings within the other pairs.

Thus the diquark-triquark model for the pentaquark has unusual color structure; a $\bar{3}_c$ $ud$ diquark is coupled to a $3_c$ $ud\bar{s}$ triquark in a relative $P$-wave to make a state with $J^P = 1/2^+$, $I = 0$. The color-magnetic short-range hyperfine interaction $V_{hyp}$ is dominant for possible binding. The two pairs of identical quarks ($uu$) and ($dd$) which have repulsive short range interactions are separated by placing one in a diquark and one in the triquark, thus eliminating the short range repulsion.

B. The nonstrange pentaquark with dominant symmetry-breaking; $m_s - m_d$

A general pentaquark has two allowed $SU(3)_f$ couplings, an antidecuplet $\bar{10}$ and an octet $8$. Both are found in a system of a diquark in $\bar{3}$ and a triquark in $\bar{6}$ of $SU(3)_f$.

$6 \times 3 = 18 = 10 + 8$

There is no positive strangeness state in the octet. Thus only the $\bar{10}$ antidecuplet is allowed for the positive strangeness $\Theta^+$ with the quark configuration $uudd\bar{s}$.

Two quark configurations are allowed for a nonstrange pentaquark, $uudss$ and $uudd\bar{d}$. These two configurations are orthogonal linear combinations of the octet and antidecuplet. Nonstrange pentaquarks mix octet and antidecuplet like singlet-octet $\omega - \phi$ mixing. If the dominant symmetry-breaking interaction is the quark mass difference, $m_s - m_d$, the mass eigenstates are the $uudss$ with hidden strangeness like the $\phi$ and the nonstrange $uudd\bar{d}$ like the $\omega$. The flavor-antisymmetry principle prefers the $uudss$ configuration which has only one pair of identical quarks. These can be kept apart in the diquark-triquark model by
putting one u-quark in the diquark and the other in the triquark.

To extend the diquark-triquark model for a strange pentaquark to a nonstrange pentaquark we first choose the $uud \bar{s}$ with only one pair of identical quarks. We replace the $ud$ diquark in $\Theta^+$ by a $us$ diquark and keep the same $uds$ triquark. The system is divided into two color non-singlet clusters in a relative $P$-wave which separates pairs of identical flavor by a distance larger than the range of the color-magnetic force.

The clusters are kept together by color electric force; the hyperfine interaction acts only within each cluster. The $us$ diquark is in the $3$ of $SU(3)_c$ and $3$ of $SU(3)_f$ to make a state with $I = 1/2, S = 0$.

The standard treatment using the $SU(6)$ color-spin algebra shows the hyperfine interaction stronger for diquark-triquark system than $\pi N$ system. In $SU(3)_f$ symmetry limit

$$[V(\text{triquark}) + V(\text{diquark})] - [V(K) + V(N)] = -\frac{1}{6}(M_\Delta - M_N) \approx -50\text{MeV}$$

(2.2)

The physics here is simple. The spin-zero diquark is the same as the diquark in a $\Lambda$ with the same hyperfine energy as nucleon. The triquark with one quark coupled with a $\bar{s}$ antiquark to spin zero has same the hyperfine energy as a kaon but no interaction with the other quark. The triquark coupling allows $\bar{s}$ antiquark to interact with both $u$ and $d$ quarks and gain hyperfine energy with respect to the case of the kaon.

An isolated triquark is not color singlet. The triquark color charge is neutralized by the diquark.

With first order symmetry breaking $M(\Lambda) \neq M(N)$ and the mass of the $\pi N$ pentaquark is predicted to be higher than $\Theta^+$ mass by $M(\Lambda) - M(N)$

$$M(\pi N)_{\text{pred}} = M(\Theta^+) + M(\Lambda) - M(N) = 1540 + 180 = 1720; \quad M(\pi N)_{\text{exp}} = 1680$$

(2.3)

**Not bad for such a crude calculation**

The $uud \bar{s}$ pentaquark is a really complicated five-body system. Flavor antisymmetry suggests that the commonly used bag or single-cluster models may be correct to treat normal
hadrons but are not adequate for multiquark systems. These models have identical pair correlations for all pairs in the system. They miss the flavor antisymmetry which requires different short-range pair correlations between pairs with the same flavor and pairs with different flavors.

Had it not been for the cost of the $P$-wave excitation, the triquark-diquark system would be somewhat more bound than a pion and a nucleon. The diquark and triquark will have a color electric interaction between them which is identical to the quark-antiquark interaction in a meson.

If we neglect the $P$-wave excitation energy and the finite sizes of the diquark and triquark we can compare this system with analogous mesons. We can use the effective quark masses that fit the low-lying mass spectrum to find a very rough estimate

$$m_{\text{diq}} = 720 \text{ MeV}, \quad m_{\text{triq}} = 1260 \text{ MeV}, \quad m_r(\text{di-tri}) = 458 \text{ MeV}.$$ 
where $m_{\text{diq}}$ and $m_{\text{triq}}$ denote the effective masses of the diquark and triquark, and $m_r(\text{di-tri})$ denotes the reduced mass for the relative motion of the diquark-triquark system.

A crucial observation has been that the diquark-triquark system may not exist in a relative S-wave. This is because in S-wave the hyperfine interaction acts not only within the clusters but also between them. The repulsive terms may then win and the would be S-wave gets rearranged into the usual meson-baryon system. The situation is different in a $P$-wave, because then the diquark and the triquark are separated by an angular momentum barrier and the color-magnetic interactions operate only within the two clusters.

**SUMMARY AND CONCLUSIONS**

We discuss the implications of the suggested interpretation of the recently reported narrow $\pi N$ resonance (width $\approx 25$ MeV at 1680 MeV) as a pentaquark in the same multiplet as the $\Theta^+$. We consider a diquark-triquark pentaquark model involving a recoupling of the five quarks into a diquark-triquark system in non-standard color representations. We estimate
the mass using the simple generalized Sakharov-Zeldovich mass formula which holds with a single set of effective quark mass values for all ground state mesons and baryons having no more than one strange or heavy quark.

Our rough numerical estimate puts the $\pi N$ resonance in a nonstrange pentaquark with a mass 180 MeV higher than the $\Theta^+$ mass by $M(\Lambda) - M(N)$. This gives a pentaquark mass of 1720 MeV, sufficiently close to 1680 MeV to indicate that this approach deserves further more accurate investigation.

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