The Narrow \( \Theta(1543) \)–A QCD Dilemma: Tube or Not Tube?

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We argue that a width of less than MeV of the new \( \Theta \) resonance is inconsistent with the observed ratio of resonance and background events in the various photon initiated experiments if the latter can be described by \( KK^* \), etc., exchange. An evaluation of the Feynman diagrams which were believed to be relevant is presented and supports the general claim in the one case where a cross section has been given by the experimental group.

More detailed arguments based on the flux tube model explaining the narrow widths and the apparent conflict with the production rates are presented. We predict narrow Tetra-quarks at mass \( \sim O(1-1.2 \text{ GeV}) \) which the analysis of LEAR may have missed.

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I. General Phenomenological Considerations

Enhancements in \( K^+n \) and \( K^0p \) invariant mass at \( M(KN) \sim 1540 \text{ MeV} \) seen in several experiments \[\text{1, 2, 3, 4}\] using different reactions with a range of incident energies, different detectors with different acceptances and cuts suggest a new, exotic “Penta-quark”. Such a low-lying, narrow state, \( \Gamma(\Theta) < \text{Exp resolution} \sim 20 \text{ MeV} \), \[\text{(1)}\]
with \( J^P = 1/2^+ \) has been predicted \[5\] using Skyrmion large N approach \[6\] and ipso facto explained in simpler ways \[5, 7, 8\]. It may mark the beginning of a new “era of exotics” in hadron physics.

Two puzzles emerge in connection with the width \( \Gamma(\Theta) \). The eventual resolution of both may be a triumph of (non-perturbative!) QCD.

The first puzzle is:

P(1): The absence of any indications for the new \( KN \) resonance \( K^+ \) deuteron scattering implies an anomalously low \( \Theta \) decay width \[\text{7, 10}\]:

\[\Gamma(\Theta(1543)) < 0(\text{MeV})\] \[\text{(2)}\]

The second is the following: Within \( K \) exchange models, significantly higher values of \( \Gamma(\Theta) \) are inferred from production rates in photonic reactions. We elaborate on this point next.

Let us assume that for the \( \theta \) production experiments, all done at medium energies, the hadronic (rather than perturbative QCD) description is more appropriate. The \( \theta \) then forms via \( KN \) or \( K^+N \) intermediate processes with the \( K \), say, being relatively close to its mass shell. If \( K \) exchange dominates, we can estimate \( \Gamma(\Theta) \) from the production cross sections. For meaningful comparisons the Feynman diagram calculations should be done in parallel with MC simulations including acceptance and signal improvement cuts. This is beyond the scope of the present paper and the capabilities of the authors.

We can nonetheless estimate \( \Gamma(\Theta) \) independently of these complications. We assume that the \( K \)-exchange model holds equally well for \( KN \) invariant mass in the “true” resonance region:

\[m(KN) = m(\Theta) \pm \Gamma(\Theta)\]

and within the broader region of effective width \( \Gamma(\text{obs}) \) where enhancements in the experimental \( KN \) invariant mass, \( m(KN) \), distributions were observed.
The pion exchange model for the reaction $\pi + \text{proton} \rightarrow \pi\pi + \text{Nucleon}$ applies both off and on $\pi$ resonances and is used to map $\pi - \pi$ scattering. When extrapolated to the on-shell pion limit the reaction rate at a given invariant mass $m(\pi - \pi)$ is proportional to the $\pi - \pi$ cross section at this CMS energy. All we need is that the $K$ exchange share these qualitative features.

The number of events in the “enhancement” (lying above a smooth curve interpolating between the regions to the right and left), $N(R)$, is identified with the number of $\Theta$s, and the remaining $N(B)$ events in the same region under this curve represent the non-resonant slowly varying background.

Integrating the Breit-Wigner distribution of the resonance with the “true” narrow width $\Gamma(\Theta)$ the expected $N(R)$ is:

$$N(R) = F \cdot \frac{\Gamma(\Theta)}{2\pi} \sigma(R),$$

(3)

where $\sigma(R)$, the peak resonance cross section, is $2\pi/k^2 \sim 33 \text{ mb}$. Likewise, the number of background events under the peak expected in the same $K$ exchange model should be:

$$N(B) = F \cdot \Gamma(\text{obs}) \cdot \sigma(B)$$

(4)

$\sigma(B)$, the off resonance $K(\pm)$ neutron total cross section, is $\sim 14 \text{ mb}$ at these energies [11]. The common factor $F$ representing dynamical/kinematical aspects of the computed Feynman diagram and/or cuts applied to events in the enhancement region cancels in the ratio of the last two equations and

$$\Gamma(\Theta) = \frac{N(R)}{N(B)} \cdot \frac{(\sigma(B)/\sigma(R)) \cdot \pi/2 \cdot [\Gamma(\text{obs})]}{[N(R)/N(B)] \cdot 1/2[\Gamma(\text{obs})]}.$$  

(5)

Equation (5) constitutes the second puzzle:

P(2): Even for a minimal $\Gamma(\text{obs}) \sim 20 \text{ MeV}$ effective width of the $\sim 4 \text{ bins}$ enhancement region, the observed $N(R)/N(B)$ which exceeds .5 in all the experiments, implies

$$\Gamma(\Theta) \sim 5 - 15 \text{ MeV}$$  

(estimate based on K exchange model)

(6)

conflicting with the upper bound of Eq. (2) above. Would the apparent difficulty be evaded if $\theta$ production is not dominated by exchanging $K(490)$, but rather by the vector $K^*(890)$ exchange or the tensor $K(1420)$ exchange, etc.? Even this in itself is insufficient and a large $O(10)$ double ratio of resonant and non-resonant $K(*)N \rightarrow KN$ and $KN \rightarrow KN$ cross sections is required.

II. Calculations of $\Theta$ Production Rates Via $K$ Exchange in Photon-Nucleon and Photon-Deuteron Collisions

For completeness we present the cross section for $\Theta$ production in $\gamma - p/n$ collisions within a $K$ exchange model (with possible rescattering on the remaining $n/p$ for deuteron targets) in:

- (a) $\gamma + p \rightarrow \Theta + K(S)$ [Saphir]
- (a’) $\gamma + d \rightarrow \Theta + K^- + p$ [Spring 8][Jeff Lab]
- (b) $\gamma + p \rightarrow \Theta + K^- \pi^+$ with the final kaon and pion in the $K^*(890)$ resonance.[Jeff Lab]

In the $\Theta$ discovery in (a’) by the Spring 8 collaboration, the final $K^-$ could be very forward and the undetected final proton have very low energy as $K$ exchange with a spectator proton implies. The same holds for the forward-going $K(S)$ in Saphir but not for the class detector. Its limited forward coverage required measuring the final protons which is possible only if $k(p(\text{final})) \sim 0.35 \text{ GeV}$. The rate observed is then suppressed by the small probability of having such momentum in the deuteron. Also the diagram where the final $K^+/K^- \text{ re-scatters on} n/p \text{ to form } \Theta / \text{ Kick the } K^-$ and $p$, is suppressed by the (related!) extended configuration space wave function of the deuteron.

We next sketch the computations starting with the $K$-exchange “tree” diagram in Fig 1.
The coupling $g = g(\Theta NK)$, the analog of $g[NN\pi] \sim [4\pi \cdot 14]^{(1/2)}$ nucleon $\gamma(5)$ coupling in the lower vertex of Fig. 1(a) and 1(b) is fixed by $\Gamma(\Theta)$. The $\gamma^0K^0$ and $\gamma K^+K^-$ coupling in the upper vertex are $e/3$ and $e$ for reactions (a) and (a'), respectively, and the $g^* K^* \gamma$ coupling for reaction (b) is fixed by $\Gamma(K^+) \rightarrow (K + \gamma) = 0.115$ MeV. This yields:

\[ \frac{d\sigma}{dt}(\gamma + N \rightarrow \Theta + K^+) = F \{ (1/2)\Gamma(\Theta)/0.0226 \} \]
\[ \times \left\{ \left[ 2 + (m[\Theta] - m[N])^2 \right] \cdot \left\{ (t + m[K])^2 / (t + m[K])^2 \right\} \right\} \] (7)

\[ \frac{d\sigma}{dt}(\gamma + p \rightarrow \Theta + K^*(890)) = F \cdot (6.44 \cdot 10^{-3})(1/2)(\Gamma(\Theta)/0.0226) \]
\[ \times \left\{ \left[ 2 + (m[\Theta] - m[N])^2 \right] \cdot \left\{ (t + m[K^*])^2 / (t + m[K])^2 \right\} \right\} \] (8)

$F = \pi/[(m(N)\cdot(E(\gamma))]$ is the flux factor. The first and second $\{\}$ brackets were generated by $N - \Theta$ spinor and photon/K$^*$ polarization sums. $p(f)p(i)$ in Eq. (4) are the final/initial center mass momenta of the $K$/photon. The [square] of the Kaon propagator appears in the denominators, and the momentum transfer $t$, the virtual kaon squared momentum, varies between $t(-)$ and $t(+)$. Since $\Theta$ decays equally to $K^+n$ and $K^0p$, we use $1/2$ $\Gamma$ in determining $g(\Theta NK)^2$, and $(2/3)/(1/2)$ are branchings for $K^* \rightarrow K^+\pi^-$ and $\Theta \rightarrow K^+n$.

Comparing the integral of (4) between $t(-)$ and $t(+)$. with the 300 nb cross section quoted in Saphir we obtain

\[ \Gamma > 30 \text{ MeV} \] (Saphir exp and the kaon exchange model) (9)

(An inequality arises since form factors suppressing the vertices with off-off shell kaons have been omitted.)

Equation (8) applies to $\gamma + p \rightarrow \Theta + K^*$.

We next consider the one-loop diagrams like Fig. 2 for $\Theta$ production off deuterons. These complex diagrams with "anomalous thresholds" can be estimated since the deuterons' size $R \sim 2$ Fermis exceeds all other distances in the problem. The Kaon traveling a large distance from production on the proton/neutron to rescattering on the remaining neutron/proton is effectively on shell. The process $\gamma + d \rightarrow K\bar{K}pn$ then factorizes into two parts as explained next for $K$-neutron re-scattering.

Assume that we first have the process $\gamma + p \rightarrow K^+K^-p$ (rather than the $\gamma N$ interaction depicted in Fig. 2. This then serves as a source of $K^+$'s with energies $E(K^+)$ emanating from $r(p)$ where the struck proton was. Alongside
The $K^+$ of interest emerge also the $K^-$ and proton at momenta $P(p)$ and $P(K^-)$ which are unaffected in the next scattering. Next, the $K^+$ scatters on the neutron which, in the first scattering, was just a spectator located at $r(n)$ at a distance $R = |r(p) - r(n)|$.

In the second scattering $\Theta$ manifests via the enhanced $K^+n$ resonant scattering cross section at invariant masses: $m(KN) = m(\Theta) \pm \Gamma(\theta)/2$. The two processes are then compounded classically by multiplying probabilities yielding:

$$d(\sigma \gamma + d \rightarrow K^-p\Theta \gamma) = \{<1/[4\pi R^2]>\} \cdot d(\sigma \gamma + p \rightarrow K^-PK^+) \cdot d(E(K^+) \cdot \Gamma \cdot \pi/2) \cdot \{m(N)/m(\Theta)\} \cdot \sigma[KN](\text{Res})$$

(10)

The $d(\sigma)$ on the right-hand side refers to a differential (or partially integrated) cross section with respect to the momenta of the $K^-$ and proton which do not participate in the second collision. In the case of $K^-n$ re-scattering considered here first, we fix the energy $E(K^+)$ of the almost on-shell Kaon to correspond to the $\Theta$ resonance in the collision with the almost stationary neutron. Thus the differential cross section with respect to $E(K^+)$ is evaluated at the resonant energy. The BW integral then yields $(\pi/2)\Gamma\sigma[KN](\text{res})$ with the resonant (Peak) cross section $\sim 32$ mb, $m(N)/m(\Theta)$ is the Jacobian of the transformation from invariant mass to lab energy in the $K^-N$ collision, and $\sigma[KN]/(4\pi R^2)$ is the probability that the $K^+$ emitted from $r(p)$ will scatter at $r(n)$. We use the expectation value $<>$ in the (isotropic) deuteron ground state.

To evaluate the $\Theta$ production cross section we need to input information on the differential/partially integrated (apart from the $E(K^+)$ dependence) $\gamma + p \rightarrow K^+K^-p$ cross sections, available from other experiments.

For $K^-$ re-scattering—which is, in fact, the one depicted in Fig. 2—the first process is $\gamma + n \rightarrow \Theta K^-$ with a spectator proton. In the $K$ exchange model it yields mostly forward-going $K^-$ and slow final protons. The second $K^-p$ scattering “Kicks” the $K^-$ away from the forward direction and augment the protons’ kinetic energy: $E(p) - m[N] \sim t/2m[N]$, making both visible in the Class detector. Using similar arguments as in the previous case we find:

$$d(\sigma \gamma + d \rightarrow K^-p\Theta) = \{<1/R^2>\} \cdot d(\sigma \gamma + n \rightarrow K^-\Theta) \cdot d(E(K^-) \cdot \Gamma \cdot \pi/2) \cdot \{m(N)/m(\Theta)\} \cdot \sigma[KN](\text{res})$$

(11)

The coupling of a photon to a charged Kaon is $\sim$ an order of magnitude stronger than that to the neutral Kaon.

FIG. 2: $\Theta$ production on the deuteron with a re-scattering on the nucleon. The diagram shown refers to re-scattering of $K^-$ on the proton (lower right black dot) after $\Theta^+K^-$ have been produced off the neutron. The upper left black dot indicating the latter process could be dominated by $K$ exchange diagram of the type shown in Fig 1, or involve more general local interactions which cannot be represented by $K, K^*(890), K(1420)$, etc., exchanges. A similar diagram with $K^-\rightarrow K^+$ and $n,p \rightarrow p,n$ describes the process where the primary $\gamma p$ collision generates out-going $pK^+K^-$ with $E(K^+)$, the laboratory energy of the $K^+$ constrained to be at resonance so that the $\Theta$ is produced in the $K^+$ re-scattering off the “spectator” neutron. It is this last process that is discussed first in Sec. II above.
Hence $\Gamma(\Theta)$ emerging from an eventual cross section supplied by the Class collaboration may be somewhat smaller than the width implied by the Saphir cross sections. The general considerations of Sec. I suggest, however, that also here the required $\Gamma$ may be unacceptably high

### III. Color Suppression of Tetra- and Penta-Quarks in the Chromoelectric Flux Tube Model

\[ \Gamma(\Theta) < 0(\text{MeV}) \text{ is low for } m(\Theta) - [m(K) + m(N)] \sim 110 \text{ MeV}. \]  

Our discussion above reinforces this conclusion: The small values of $\Theta KN$ and other meson $N\Theta$ couplings which such a small width implies, fall short of explaining the observed cross section for $\Theta$ production in photon initiated reactions. This naturally happens if the $\Theta \rightarrow KN$ (or $K(*)N$, etc.) transitions were suppressed by a selection rule. The following alternatives come to mind:

- (a) A new–hitherto unknown–quantum number is possessed by $\Theta(1540)$.
- (b) The $\Theta$ is an $I=2$ isotensor.
- (c) There are no strict new selection rules, but the complex “topology” of the “Color Network” in the $\Theta$ penta-quark reduces its coupling to states with only “simple” baryons and mesons.

Alternative (a) is most radical. Since the $\Theta$ is produced together with ordinary non-exotic hadrons it is difficult to envision a new conserved quantum number. QCD, flavor dynamics and symmetries are well understood and radical, new physics may be contemplated only if all other efforts to explain the peculiarities of $\Theta(1540)$ fail.

The suggestive idea (b) \[12\] that isospin is violated by a $KN\Theta$ (or any $K(*) - N - \Theta$) immediately explains the second puzzle pointed above. Unfortunately it is untenable: First, the $I=2$ state should be much higher, \[7\] and, second, the other members of the isospin quadruplet are missing.

We will focus here on alternative (c) which was briefly alluded to before \[13\]. The idea is that the new narrow exotic states are ground states in a new family of hadrons. Ordinary $q\bar{q}$ mesons contain in a chromoelectric flux tube picture–just one flux tube connecting the $q$ and $\bar{q}$ and $qqq$ baryons have “Y” shaped color networks with the three flux tubes emanating from the three quarks merging into one “junction”. The new quadri- and penta-quark states consist of more complex networks with junction–anti-junction or two junctions–one anti-junction as indicated in Fig. 1(a) and 1(b) of Ref.\[13\].

Generic $qqqq$ or $q\bar{q}qq$ meson-meson or baryon-meson do not belong in the new family. In collisions of ordinary hadrons transient association due to hadron-hadron attraction can form and may have some four or five quark, “single bag” components. Such states are likely to have short lifetimes of order 1/c with 1 ~ Fermi hadronic sizes and large O(200 MeV) widths. Their density increases rapidly due to coupling to multi-particle channels and these broad exotic resonances then merge into a continuum.

The longest range, one- or two-pion exchange, hadronic interactions are attractive. For mesons containing heavy $c/b$ quarks, such forces can suffice to form weakly bound states \[14\ 15\]. It is important to distinguish two types of quadri-quarks; namely, $MM'=\{QqQ'q'\}$ and $MM'\{=QQ'qq'\}$ states. The newly discovered $cc\{(u\bar{u} + d\bar{d})/2^{(1/2)}\}$ in $B$ decays at Belle \[16\] is of the first type. Its small decay width $\sim 20 \text{ MeV}$ to $J/\psi + \pi\pi$ may be due to a small overlap with the physically small $c\bar{c}$ state. To the extent that it can be viewed as, say, $D(*)D$ bound state, it also may not belong in the new family considered.

The second type of $MM'$, say, $DD(*)\{c\bar{c}ud\}$ bound states–if existing–are more likely to be of the special form of interest \[17\] here. The two heavy quarks $QQ'$ and, separately, the two light $q\bar{q}'$ should couple to a $3\{3\}$ of color. Such couplings like in baryons, involve $\epsilon(abc)Q'^qQ'^q'$ and $\epsilon(edc)\bar{q}(c)q'(d)$, respectively, and these resulting structures with 3 and 3 $SU(3)$ color, should then join via $3^* \cdot 3$, to make the overall color singlet state.

In the chromoelectric flux model this is represented via a junction/anti-junction where the two flux tubes emerging from $QQ'$ entering into $q\bar{q}'$ are incident. The junctions in turn are connected by the same standard “minimal flux” tube going from the anti-junction to the junction. Such $> - <$ coupling patterns occur also for systems with light quarks only, say, $q^1q^2\bar{q}^3q$. We assume that the $\Theta(1540) = \bar{s}(ud)^1(ud)^2$ has two junctions, $J^1$ and $J^2$, where the flux
tubes of quarks in \((ud)^1\) and those in \((ud)^2\) converge, respectively, and one anti-junction \(\bar{J}\) from which the three flux tubes ending at \(\bar{s}\) and \(J^1\) and \(J^2\) emerge. A key observation is that a quadri/penta-quark with these color networks can decay into two mesons/meson and baryon, only if (a) junction and the anti-junction annihilate. Also a \(K\) or \(K(*)\), etc., nucleon collision produce the penta-quark only if an extra \(J\) and \(\bar{J}\) are “pair” created in addition to the junction in the initial nucleon.

If such junction pair creation and annihilations are suppressed, both difficulties pointed above may be resolved. The decay width to the (only open) \(KN\) channel will be small and \(\theta\) production via collision with a nucleon of real or off-shell \(K\)’s, \(K(*)\)’s, \(K(**)\)’s, etc., may be so small that an altogether different production mechanism needs to be invoked.

Amusingly, \(J - \bar{J}\) production was implicitly discussed in a paper on \(q - \bar{q}\) pair production in the chromoelectric field inside the flux tube. \[18\]

For any instantaneous, say, Red-Red configuration of the end \(Q\) and \(\bar{Q}\) anti-quarks and corresponding \(E\) fields, production of a red – red \(\bar{q}q\) new pair is preferred with the red/red\(\bar{q}/q\) pulled towards the Red/Red end-quarks. For \(Q - \bar{Q}\) jets in \(e^+e^(-)\) colliders this basic process repeats many times. It occurs also when the energy available is more limited, say, in the decay of an excited \(QQ\) vector meson produced in \(e^+e^(-)\) collision into two lighter \(\bar{Q}q + qQ\) mesons with \(qq\) creation occurring only once.

Denoting the field strength operative here by \(E\), the masses of the light quarks produced by \(m\) and their momentum transverse to the \(Q - \bar{Q}\) separation (or in high energies, the “jet” axis) by \(p\), the rate of \(\bar{q}q\) pair creation is proportional to:

\[
d(n)/d(p^2) \mid \text{“standard”} \sim \{(gE)^2\}exp - \{\pi \cdot [m^2 + p^2]/(gE)\}
\]

(12)

Even in the above “Red” field inside the flux we have (due to peculiarities of \(SU(3)\) color) in addition to the preferred \(\bar{r}\bar{q}/q\) pair production, also the production of blue-blue or white-white light quarks. Unlike before, here the produced quark/antiquark is attracted by and moves towards the end-quark/antiquark. If the process stops here, then a diquark/anti-diquark \(Qq\) and \(\bar{q}Q\) connected by a standard flux tube, namely, the tetra-quark of interest is created!

Baryon-anti-baryon production happens when the missing white-white (or blue-blue) pair is created.

The chromoelectric field strength relevant for this “disfavored” production mode is \(E/2\) rather than \(E\), yielding:

\[
d(n)/d(p^2) \mid \text{“disfavored”}, \; SU(3) \; \text{color} \sim \{(g[E/2]^2)\}exp - \{2\pi[m^2 + p^2]/(gE)\}
\]

(13)

The factor \(1/2\{1/(N - 1)\} for \(SU(N)\) is readily explained: In the fundamental representation 3 of \(SU(3)\) drawn in two \(\{\:\text{rank of } SU(N) \}\) dimensions the R, B, W quarks point along the directions of the three complex roots of unit: \(1, -1/2 + i(3/4)^{1/2}, -1/2 - i(3/4)^{1/2}\). The chromoelectric field of size \(E\) produced by \(R\) has a component \(-1/2 \times E\) along B (or W) and a blue (or white) quark–rather than \(\bar{r}\)–can be produced but with half the effective field strength.

Similarly the \(SU(N)\) fundamental representation is a symmetric \(N - 1\) simplex and the angle between any pair of unit vectors is \(cos(\cdot)\{1/(N - 1)\}.\) The analog of Eq. (13) is then:

\[
d(n)/d(p^2) \mid \text{“disfavored”}, \; \text{SU(N) color} \sim \{g[E/(N - 1)]\}^2exp - \{(N - 1)\{\pi[m^2 + p^2]/(gE)\}
\]

(14)

Note that for large \(N(\alpha)\) implicit in Skyrmion models, the “disfavored” mode is exponentially suppressed in \(N\) which, indeed, is likely for baryon-anti-baryon and monopole-anti-monopole pair production \([19, 20]\) with \(N \to 1/\alpha\). (A similar exponential suppression is expected also in the time-reversed process of annihilation of an \(N\)-fold junction and anti-junction. The suppression can be understood in this case also in simple combinatorial terms: each of the tubes of \(N\) colors in the junction has to match up with the anti-tube of the same color in the anti-junction. Thus only one out of \(1/N!\) pairing can lead to \(JJ\) annihilation.) For the \(N = 3\) case of interest we have the \(1/4\) in the \(E^2\) prefactor and an extra suppression by \(\sim .2\) due to the doubled exponent \([18]\). The overall suppression \((1/10)-(1/20)\) is consistent with the multiplicity of anti-nucleons observed in jets or \(Z\) decays.
In gamma-nucleon collisions studied in the above-mentioned experiments the photon can virtually transform into a pair of energetic $Q\bar{Q}$ quarks [$Q = \bar{s}$] and the diquarks next form via the disfavored $\bar{u}u$ or $\bar{d}d$ creation as above. Alternatively, the photon can impart a large energy to one, say, $u$-quark in the target nucleon and the disfavored creation—now of $\bar{s}s$—happens later somewhere along the resulting prolonged flux tube originating at the struck $u$-quark.

Once the “junction barrier” has been overcome and an intermediate entity like an $s\bar{s} > \sim \bar{s}\bar{d}$ tetra-quark has formed, the remaining process, Tetra$+N \to$ Penta$+K(\text{or } K(\ast))$, required to obtain the final state of the above experiments is straightforward. It involves only standard quark exchanges and fusion/cutting of flux tubes which are familiar from ordinary meson-baryon and meson-meson processes. Thus the above factor of $(1/10)$-$\sim (1/20)$ approximates the suppression of $\Theta$ production relative to ordinary resonance in the above photonic experiments. This concurs with the above estimates of the “effective $\Theta$ width” of $5$-$15\text{ MeV} \sim (1/10)$-$\sim (1/20)$ of normal hadronic widths. Recall that the true width of $\Theta$ inferred from independent purely hadronic $K$-neutron data is smaller, say, O(1 MeV). This small $\Gamma$ and the disagreement with the effective width required in “naive” $K$, $K(\ast)$, etc., exchange models constitute the difficulties (1) and (2) above.

It has been argued [13] that longevity of some Tetra-quarks and Penta-quark states may reflect the difficulty of annihilating a junction $J$ and anti-junction $\bar{J}$. This could be due to the smallness of the junction radius $b$ as compared with the hadronic size $\sim 0.7\text{ Fermi}$. The suppression becomes more dramatic $\sim (b/a)^5$ if we have a centrifugal barrier due to a relative $\ell = 1$ angular momenta between the junctions (or diquarks). Such barriers are present when an isolated $\Theta$ decays into or forms out of a meson $K$ and baryon $N$, but not necessarily in the higher energy $\gamma-N$ collisions. This may explain the apparent discrepancy between the true $\Gamma < 0(1\text{ MeV})$ and the effective $\Gamma$ of 5-15 MeV required to explain the production rate.

The extra color dynamics-related suppression that the early work implies for $J - \bar{J}$ production is likely to affect also in the $J - \bar{J}$ annihilation in tetra- and penta-decays. A future, more complete model incorporating both this with the earlier geometric size arguments for the small width will hopefully provide a more compelling explanation for the remarkably small $\Gamma(\Theta)$.

IV. Possible Manifestation of the New Narrow Resonances in Nucleon/Anti-Nucleon Annihilations and Some Concluding Remarks

We sketched in the previous section a possible scenario for the anomalously small $\gamma(\Theta)$ and the apparent contradiction between the latter and $\Theta$ production rates in photon-induced reactions which seem to require larger widths. Is this scenario viable?

One difficulty is the lack of evidence for narrow tetra-quark states which our scenario requires. The lightest member of this family should not be heavier than $\sim 1200$-$1100\text{ MeV}$-lying 300-$400\text{ MeV}$ below the $\ast$ penta-quark. (The scalar $a, f(980)$ may indeed be four quark/single bag states [22]. Yet the normal widths of these states suggest that these are not the $> \sim < \text{ tetra a that we discuss here.}$

The formation of junction-anti-junction pairs or the disappearance of such, is the essence of $\bar{N}N$ pair creation/annihilation. The latter does not require that (anti-)quarks from the respective (anti-)nucleon annihilate. Rather, $[\bar{q}q] - qq$ rearrange into three $\bar{q}q$ pairs. These could be pseudoscalar, vector and some higher mesons. For $\bar{p}p$ at rest the rate of “genuine” annihilations of $\bar{q}-q$’s is expected to be larger than at higher energies. Annihilations of just one $\bar{q}q$ pair yield final states with two, rather than three, mesons, happen in $\sim 25\%$ of the cases.

In the chromoelectric flux picture we can readily envision a $q - \bar{q}$ annihilation occurring prior to the annihilation of the junction $J$ in the nucleon and the anti-junction $\bar{J}$ in the anti-nucleon. Such events involving the fusion of the flux tube segments emerging from/terminating on the specific $q$ and $\bar{q}$ which annihilated yield tetra-quarks with two junctions of the type considered here: $> -q + \bar{q} - \leftrightarrow - - - <$, namely, the tetra-quark of interest.

One would expect to see in careful studies of $p - \bar{p}$ annihilations at low energies in experiments like LEAR these narrow resonances precisely in the "two meson" final states. Indeed, annihilation models favor formation of such states.

The $N - \bar{N}$ potential is attractive at all ranges causing the initial $\bar{N}N$ to accelerate and move towards each other. Thus, annihilation at low energies has a much larger cross section than the small junction area $\pi \cdot b^2$ as expected at
The annihilation separates into two stages: during the acceleration pions are emitted and eventually the $J - \bar{J}$ annihilate with further pions emitted.

Tetra-quarks can form at the end of the first stage. If further we have $\ell = 1$ between the two junctions the $(b/a)^5$ suppression of the $JJ$ may be operative and the tetra state can be narrow. Note, however, that excited tetra states decay to lower tetras via fast pionic emissions. Only the ground tetra state and very nearly higher states will be narrow. If this state is as low as 1100-1200 MeV, then $0(3)$ pions are emitted both prior to its formation and in its decay. The large combinatorial factor may explain the absence of these narrow tetra-quarks in the LEAR experiments which focused on near $\bar{N}N$ threshold states recoiling against one photon or pion. States which are within less than $m(\pi)$ from the lowest tetra-quark will decay emitting fairly sharp $\gamma$s of energy $E \sim M(ex) - m(gr)$.

Full QCD lattice simulations recently performed for baryons with three quarks pinned down at relative distances of 0.7 Fermi clearly indicate via contours of equal action density the “Y” configuration with a narrow $b = 0.2$ Fermi junction. If this is so, in reality then the $b/a$ ratio of $0.3$ may lead to a $(b/a)^5 \sim 0.25 \cdot 10^{-3}$ suppression of $P$-wave quadri- and penta-quark decays which is clearly sufficient for our purpose. However, in ground state nucleon or mesons the fast light quarks are likely to tangle up the short flux tubes into a uniform spherical distribution. Note that spherical symmetry is not the issue: The latter obtains for $S$-wave meson ground states, even if we had “needle-like” narrow flux tubes, by superposing, with equal amplitudes all states $| \theta \phi >$ where the “needle” points in a particular direction on the unit sphere. Still, just to achieve semiclassical constructs and narrow flux tubes, in particular, we need to employ many quantum states with high quantum numbers. Can QCD generate such a rich family of states already at energies of $\sim 1$ GeV in order to explain the peculiarities of these recent experiments? The same question can be rephrased as: Is it conceivable that the complex $\Theta(1543)$ state that we envision with three junctions and seven flux tube segments is that light? In view of the title of the paper, we surely hope that the answer is in the affirmative.

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[Note added: After completing this work, the paper by Liu and Ko has been brought to our attention. These careful calculations of $KK$ exchanges confirm one specific point which we made: namely, our estimated large $\Theta$ width required to explain the Saphir production cross sections.]

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