2003

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Repository Citation

Capstick, Simon; Page, Philip R.; and Roberts, Winston, "Interpretation of the Θ+ as an Isotensor Pentaquark With Weakly Decaying Partners" (2003). *Physics Faculty Publications*. 30.
https://digitalcommons.odu.edu/physics_fac_pubs/30

Original Publication Citation

Capstick, S., Page, P. R., & Roberts, W. (2003). Interpretation of the Θ^+ as an isotensor pentaquark with weakly decaying partners. *Physics Letters B, 570*(3–4), 185-190. doi: http://dx.doi.org/10.1016/j.physletb.2003.08.010

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PHYSICS LETTERS B

Physics Letters B 570 (2003) 185–190

www.elsevier.com/locate/npe

Interpretation of the Θ^+ as an isotensor pentaquark with weakly decaying partners

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Received 17 July 2003; accepted 7 August 2003

Editor: H. Georgi

Abstract

The $\Theta^+(1540)$, recently observed at LEPS, DIANA and CLAS, is hypothesized to be an isotensor resonance. This implies the existence of a multiplet where the Θ^{++}, Θ^+ and Θ^0 have isospin-violating strong decays, and the Θ^{+++} and Θ^- have weak decays and so are long-lived. Production mechanisms for the weakly-decaying states are discussed. The J^P assignment of the Θ is most likely $1/2^-$ or $3/2^-$.

PACS: 11.30.Hv; 12.15.-y; 12.39.Mk; 14.80.-j

Keywords: Pentaquark; Isotensor; Weak decay

1. The $\Theta^+(1540)$ as an isotensor pentaquark

Recently the LEPS Collaboration at SPring-8 reported the 4.6σ discovery of a new resonance, Θ^+, in the reaction $\gamma\,^{12}\mathrm{C} \to \mathrm{C}' K^- \Theta^+ \to \mathrm{C}' K^- K^+ n$, with a mass of 1.54 ± 0.01 GeV and a width of less than 25 MeV [1]. Subsequently, the DIANA Collaboration at ITEP reported a 4.4σ discovery of the *same* resonance in $K^+\mathrm{Xe} \to \Theta^+\mathrm{Xe}' \to K^0 p\mathrm{Xe}'$ with mass 1539 ± 2 MeV and width less than 9 MeV [2]. Preliminary results from an experiment by the CLAS Collaboration in Hall B at Jefferson Lab confirm the existence of a narrow Θ^+ in the reactions $\gamma d \to \Theta^+ K^- p \to K^+(n) K^- p$ at a mass of 1542 ± 5 MeV and width less than 22 MeV, and $\gamma p \to \Theta^+ \pi^+ K^- \to K^+(n)\pi^+ K^-$, at around the same mass [3].

The Θ^+ is interpreted as a state containing a dominant pentaquark Fock-state component $uudd\bar{s}$ decaying to $K^+ n$, in contrast to its interpretation as a chiral soliton [4,5]. The pentaquark should have isospin $I = 0, 1$ or 2. Here we hypothesize a certain isospin assignment for this state based on two precepts:

- The Θ^+ seen experimentally exists, and is resonant;

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doi:10.1016/j.physletb.2003.08.010

- A pentaquark 110 MeV above threshold should have a decay width of the order of 500 MeV unless its decays are suppressed by phase space, symmetry, or special dynamics.

As will be clear from the discussion of the second precept below, the expected width for the decay $\Theta^+ \to K^+ n$ is greater than the experimental widths unless the decay proceeds in F-wave or higher, i.e., the total angular momentum J of Θ^+ is $\geqslant 5/2$ for a parity $P = + \ \Theta^+$, or $J \geqslant 7/2$ for $P = -$. We consider such a high J assignment for the Θ^+ unlikely for such a light resonance (see the discussion of the J^P assignments of the Θ^+ below). Hence the two precepts indicate that the decay of the Θ^+ is suppressed either by special dynamics unknown to us, or by symmetry. It is hypothesized that the latter possibility ensues, and specifically that Θ^+ is $I = 2$. For this isospin, the decay $\Theta^+ \to K^+ n$ is isospin-symmetry violating. This is not the case if the Θ^+ is isoscalar or isovector. It is shown below that isospin symmetry violating decay widths are typically 0.1% of isospin conserving widths.

The reasons for the second precept are as follows. Any state with the structure $qqqq\bar{q}$, for any flavors, has as a possible color configuration a set of three quarks in a colorless (baryon) state, plus a quark and anti-quark in a colorless (meson) state. This means that by a simple rearrangement of the color configuration, the state can “fall apart” into a baryon and meson, with only weak forces between the two colorless hadrons. Multi-quark states which are above threshold for such fall-apart decays can be expected to be immeasurably broad, as no such states have been observed to date. The WA102 Collaboration [6] sees roughly 15 000 events in $f_2(1270)\pi\pi$ that are well described by a Breit–Wigner at 1950 MeV with a width of 450 MeV, associated with the state $f_2(1950)$. This is likely the broadest well established resonance. This would suggest that multi-quark states that fall-apart should have decay widths of at least 500 MeV.

The largest phase space for the fall apart decay of an isoscalar or isovector $\Theta^+ \to nK^+$ will be when the Θ^+ has $J^P = 1/2^-$, and so decays in an S-wave. This is the lowest angular momentum possible for the Θ if its four quarks and anti-quark are in a spatial ground state. If the width of such a state is 500 MeV, then other spin-parity assignments for the Θ^+ will allow decay widths suppressed by phase-space factors $(p/\beta)^{2L}/(2J+1)$, where $\beta \simeq 400$ MeV is a typical energy scale associated with the size of hadrons, and $p = 270$ MeV is the center of mass decay momentum.

If the Θ^+ is isoscalar or isovector with spin-parity $3/2^-$ or $5/2^-$, also possible in a spatial ground state, the decay is D-wave, with a width significantly larger than the observed limit.[1] If the Θ^+ has spin-parity $1/2^+$ or $3/2^+$, which require one unit of orbital angular momentum, the decay is P-wave with larger widths. If the Θ^+ has $J^P = 5/2^+, 7/2^-, \ldots$ then it decays in F-wave or higher, and it is possible that is an isoscalar or isovector state and phase space suppression accounts for the small observed width. However, it is unlikely that such a state would be a ground state, as the addition of orbital angular momentum will significantly increase its energy.

In what follows, an estimate is made of the width of the isotensor $\Theta^+ \to nK^+$ decay. Isospin-violating strong decays in mesons have widths which are typically fractions of MeV. The P-wave decay $\omega \to \pi^+\pi^-$ is a G-parity and so isospin-violating strong decay, with a partial width of 0.14 MeV, which is roughly 0.1% of the isospin conserving $\rho \to \pi\pi$ width.

An upper bound on the width of an isotensor Θ^+ can be estimated as follows. The $m_d - m_u$ mass difference and electromagnetic interactions cause the wave functions of the Θ^+ and final-state nucleon to contain small isospin impurities

$$\begin{aligned} \left|\Theta^+\right\rangle &= |I = 2, I_z = 0\rangle + \alpha|1, 0\rangle + \beta|0, 0\rangle, \\ |n\rangle &= |1/2, -1/2\rangle + \gamma|3/2, -1/2\rangle. \end{aligned}$$

Assuming a strong decay operator $\mathcal{O}$ which conserves isospin, the isospin violating $\Theta^+ \to nK^+$ decay width will be

$$\begin{aligned} \left\langle\Theta^+\middle|\mathcal{O}\middle|nK^+\right\rangle \simeq{}& \gamma\langle 2|\mathcal{O}|3/2, 1/2\rangle + \alpha\langle 1|\mathcal{O}|1/2, 1/2\rangle \\ &+ \beta\langle 0|\mathcal{O}|1/2, 1/2\rangle, \end{aligned}$$

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[1] The state $\Lambda(1520)$ decays to $\overline{K}N$ in D-wave, has a mass similar to the Θ^+, but has a small width of 15.6 ± 1.0 MeV. However, its decay requires the creation of a light $q\bar{q}$ pair through a non-trivial decay operator. It is, therefore, necessarily narrower than a similar state with a fall-apart decay, where the final state configuration exists in the initial state and so the decay operator is trivial (unity).

ignoring terms second order in the small coefficients and suppressing I_z values. Isospin-violating effects in the nucleon wave function are known to be very small [7,8], so γ is negligible. A larger mixing occurs in the Λ^0–Σ^0 system, where the physical Λ is a mixture $\Lambda_8^0 + \epsilon \Sigma_8^0$ of states of definite isospin with a mixing coefficient [9] of $\epsilon = -0.015$, and similarly for the physical Σ^0. Assuming that α and β are both of this size, and that the isospin-conserving decays widths (of our state well above its fall-apart decay threshold) are all of the order of 500 MeV, a rough upper bound for the Θ^+ width is $4(0.015)^2(500\text{ MeV}) = 0.45$ MeV. This is of the same order of magnitude as that of the isospin-violating $\omega \to \pi^+\pi^-$ decay width, and is much smaller than the experimental upper bounds on the Θ^+ width.

2. Prediction of strongly decaying Θ^{++} and Θ^0 and weakly decaying Θ^{+++} and Θ^-

If the Θ^+ is an $I = 2$ pentaquark, it is the isospin projection $I_z = 0$ member of the multiplet depicted in Table 1. If discovered, the Θ^{+++} would be the first triply charged hadron. Typical splittings in $I = 1/2, 1$ or $3/2$ multiplets are $n - p = 1.3$ MeV, $\pi^\pm - \pi^0 = 4.6$ MeV and $\Delta^0 - \Delta^{++} = 2.3$–$2.7$ MeV, respectively, [10]. From model expectations and data [11], the $\Delta^- - \Delta^{++}$ splitting is likely close to 4.5 MeV. Based on this, the largest mass splitting in the Θ multiplet is expected to be less than 10 MeV. The relevant threshold for strong decay of the Θ is NK. Since the Θ^+ is below $NK\pi$ threshold by about 30 MeV, its isospin partners are also.[2] This precludes the strong decays $\Theta \to NK\pi$, specifically $\Theta^- \nrightarrow n\pi^-K^0$ and $\Theta^{+++} \nrightarrow p\pi^+K^+$, and so these states must[3] decay weakly as indicated in Table 2. A multiplet where the central members (Θ^0, Θ^+ and Θ^{++}) decay strongly, while the outlying members (Θ^{+++} and Θ^-) decay weakly, has no analogue for known mesons and baryons.

Table 1
Quark content, I_z, and strong decay modes of Θ states

State	Quarks	I_z	Decay modes
Θ^-	$dddd\bar{s}$	-2	
Θ^0	$uddd\bar{s}$	-1	nK^0
Θ^+	$uudd\bar{s}$	0	nK^+, pK^0
Θ^{++}	$uuud\bar{s}$	1	pK^+
Θ^{+++}	$uuuu\bar{s}$	2	

Table 2
Semi-leptonic and non-leptonic weak decay modes of the Θ^{+++} and Θ^- in order of increasing phase space. Here $l = e, \mu$. All decay modes listed are Cabibbo suppressed. Also indicated is whether the decay proceeds by single W annihilation (A), exchange (E), or production (P), as well as the number of $q\bar{q}$ pairs that are created by the strong interaction. Decays involving final states $\Delta\pi\pi(l^+\nu_l)$, $N\pi\pi\pi(l^+\nu_l)$ and $N\pi\pi\pi\pi(l^+\nu_l)$ are not listed. Only two-body decays involving the $f_0(600)$ are indicated. Genuine three-body decays, e.g., $p\pi^+\pi^+$, are distinguished from those that proceed through an intermediate resonance, e.g., $\Delta^{++}\pi^+ \to p\pi^+\pi^+$, even though they lead to the same final state. Because the Δ is broad, a final state $\Delta X l^+\nu_l$ would be experimentally indistinguishable from $N\pi X l^+\nu_l$, if ν_l is undetected

State	Decay mode		Pairs	State	Decay mode		Pairs
Θ^{+++}	$p\pi^+l^+\nu_l$	A	1	Θ^-	$n\pi^-$	E	0
	$p\pi^+\pi^+$	A	1		$n\pi^-\pi^0$	E	1
	$p\pi^+\pi^0l^+\nu_l$	P	1		$n\pi^-\pi^-l^+\nu_l$	P	1
	$\Delta^{++}l^+\nu_l$	A	0		$\Delta^-\pi^0$	E	0
	$\Delta^{++}\pi^+$	A	0		$\Delta^-\pi^-l^+\nu_l$	P	0
	$\Delta^{++}\pi^0l^+\nu_l$	P	0		$\Delta^- f_0(600)$	E	0

3. Explanation of CLAS and DIANA data

The isotensor Θ^+ is produced via isospin conserving reactions of the form $\gamma N \to \Theta^+ K$ or $\gamma d \to \Theta^+ K^- p$, through the isovector component of the photon, at LEPS and CLAS.[4]

In the CLAS Collaboration's photo-production experiment with a deuteron target, the Θ^+ is reconstructed from the invariant mass spectrum of K^+n in the reaction $\gamma d \to pK^-K^+(n)$. The four momenta of all reaction products are specified, as the three charged particles in the final state are detected, and the neutron is then identified by missing mass. Note that a detailed study of this reaction was unable to explain the events interpreted as the Θ^+ by non-resonant rescattering processes [12]. Similarly, in the photo-

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[2] The lowest threshold is $p\pi^0K^\pm$ at 1567 MeV. Only the $p\pi^0K^+$ decay can come from a pentaquark with the structure of the Θ^+.

[3] The electromagnetic decay $\Theta \to X\gamma$ is kinematically forbidden if there is no pentaquark X with the charge of the Θ, but at a lower mass.

[4] The d has $I = 0$.

production experiment with a proton target, the neutron in $\gamma p \to \pi^+ K^- K^+(n)$ is identified by missing mass after detection of the charged particles.

In the deuteron target experiment, it should be possible to produce the isospin partner Θ^{++} of the Θ^+ by the reaction $\gamma d \to \Theta^{++} K^- n \to p K^+ K^-(n)$, and detect it by examining the invariant mass of the $K^+ p$ system [13]. It may be the case that production of the Θ^{++} is suppressed relative to that of the Θ^+. If, as is common in kaon photo-production experiments at these photon energies, the reactions $\gamma n \to K^- \Theta^+$ and $\gamma p \to K^- \Theta^{++}$ result in forward peaked K^- distributions, these negatively charged particles will be bent into the beam direction by the magnetic field and will go largely undetected, unless they scatter off the spectator nucleon. Scattering cross sections for $K^- n$ are considerably smaller than those of $K^- p$ where they are measured, at kaon beam energies of 600 MeV or higher [10]. So if the K^- particles are forward peaked and the $K^- n$ cross section remains small down to low energies, it is likely that the Θ^{++} will remain undetected without a larger data sample.

Under ideal circumstances a formation reaction of the form $K^+ n \to \Theta^+ \to K^0 p$, with a K^+ momentum of 440 MeV incident on a Xe target at rest and with the Xe$'$ at rest in its ground state (quasi-free production), could account for the ITEP data. However, such a formation process is isospin violating for an isotensor Θ^+. It is hence predicted that ITEP should not see the Θ^+ through this formation process. In the ITEP experiment the kinematics are not completely reconstructed for the reaction K^+ Xe $\to K^0 p$Xe$'$, as the energy and momentum of the Xe$'$ is unknown, and so it is not possible to know whether this quasi-free production process happens. If ITEP is indeed seeing the isotensor Θ^+, this is expected to be through isospin allowed $K^+[pn]_{I=1} \to \Theta^+[p]$ or $K^+[nn]_{I=1} \to \Theta^+[n]$ processes.

4. Mechanisms for the production of Θ^{+++} and Θ^-

Here we focus on likely production mechanisms for the weakly decaying pentaquark states Θ, as opposed to anti-pentaquark states $\overline{\Theta}$, because of the availability of nuclear targets. The figure of merit is whether the production cross section for Θ times the branching ratio of Θ into its final state is substantial.

On face value the most promising process for the production of the Θ^{+++} is $pp \to \Theta^{+++} \Sigma^-$, which involves one $s\bar{s}$ pair creation. The search may be feasible at ITEP, JHF or COSY. The reaction $pp \to \Theta^+ \Sigma^+$ was previously suggested [14] in order to search for the Θ^+. Another promising process is $K^+ p \to \Theta^{+++} \pi^-$, involving the creation of one light quark pair. A search at JHF and ITEP is feasible. In these experiments the weakly-decaying Θ^{+++} could be either long-lived and produce a track in the detector, or relatively short-lived, and so should be observed in $p\pi^+\pi^+$ (see Table 2).

Production of the Θ^- in pp or $K^+ p$ collision would require more simultaneous quark pair creations, and so is strongly suppressed. The most promising production mechanism for Θ^- appears to be $nn \to \Theta^- \Sigma^+$, although this would require a neutron beam more energetic than the maximum 800 MeV beam at LANSCE at LANL.

There is a secondary production mechanism for the Θ^{+++} and Θ^- in photo- or electro-production at JLab, SPring-8, Mainz, SAPHIR or HERA, following production of a K^+ or K^0. The production of the Θ^{+++} would proceed as follows. In the reaction $\gamma d \to \Sigma^- \pi^- \Theta^{+++}$ a K^+ can be produced off the neutron ($\gamma n \to \Sigma^- K^+$), which then interacts with the proton, $K^+ p \to \Theta^{+++} \pi^-$. The final state $\Sigma^- \pi^- \Theta^{+++}$ consists entirely of weakly decaying particles. The process $\gamma d \to \Sigma^- \pi^- \Theta^{+++}$ involves in total two $q\bar{q}$ pair creations, and scattering of the K^+ with the proton, qualitatively similar to the possible production mechanisms at CLAS discussed in the previous section. The production mechanism for the Θ^- is closely related, and occurs at a similar level in $\gamma d \to \Sigma^+ \pi^+ \Theta^-$. Here the effect is to produce a K^0 off the proton ($\gamma p \to \Sigma^+ K^0$), which then interacts with the neutron, $K^0 n \to \Theta^- \pi^+$.

5. Simple pentaquark model and J^P assignments

It is conceivable to interpret the isotensor Θ^+ as a ΔK molecule below threshold. However, this interpretation faces two problems:

- The Δ is short-lived (115–125 MeV wide [10]), making a simple molecular picture unlikely.
- The Θ^+ is ~ 190 MeV below the ΔK threshold, which is an atypically large binding energy compared to molecular candidates like the $f_0(980)$ and $a_0(980)$, which are ~ 10 MeV below threshold. Furthermore, relating the binding energy of a molecule $1/E_b \sim 2\mu r^2_{\text{r.m.s.}}$ to the root mean square separation between the Δ and K, yields $r_{\text{r.m.s.}} \sim 0.5$ fm. This distance is smaller or similar to the sizes of the constituents, so that the picture of a molecule built from undeformed hadrons is not reasonable.

The Θ^+ is hence best modeled as a pentaquark, as opposed to a loosely bound molecular state. An isotensor pentaquark can only be constructed when each of the quark-pairs are isovector, which means that each of the quark-pairs ij and kl must be symmetric under exchange $i \to j$, $k \to l$, so that the flavor wave function is also totally symmetric. Assuming that the Θ^+ is the ground-state pentaquark, and that the ground-state has all the quarks and anti-quark in relative S-waves (which would give the lowest energy if there is no strong repulsive core), the spatial wave function is totally symmetric. The Pauli principle and isospin symmetry require the overall fermion wave function to be totally anti-symmetric under exchange of the four light quarks, so that the color-quark-spin wave function of the four quarks must be totally anti-symmetric.

This implies that the four quarks must be in an anti-symmetric representation of the color-spin symmetry group SU(6). This is[5] the $\overline{\mathbf{15}}$ representation of SU(6), which is made up of a color $\bar{\mathbf{6}}$ with spin zero, and a color triplet of spin 1. When combined with the color $\bar{\mathbf{3}}$ anti-quark, a color singlet pentaquark can only have the four quarks combined to a color-triplet with spin 1. This restricts the isotensor pentaquark to $J^P = 1/2^-$ or $3/2^-$. These J^P would only allow S- or D-wave decays $\Theta^+ \to nK^+$, which, when compared with experiment, indicates that Θ^+ is anomalously narrow. Even though the observation of Θ^+ in nK^+ allows for any J^P assignment, and an angular analysis must yet be performed to determine the parity of the Θ^+, it is expected that $J^P = 1/2^-$ or $3/2^-$.

In Ref. [16] the Θ^+ is interpreted as an isoscalar or isovector pentaquark in a constituent quark model with a flavor-spin interaction that arises from Goldstone boson exchange between the quarks. This flavor-spin interaction provides an attractive interaction between the quarks, which can lower the energy of the state with the four light quarks in an P-wave state below that of the corresponding S-wave state, so that the ground state pentaquark has positive parity [17].

6. Discussion

The chiral-soliton model prediction [5] of a narrow isoscalar state Z^+ at 1530 MeV, situated at the top of an $\mathrm{SU}(3)_f$ anti-decuplet of $J^P = 1/2^+$ states, partially motivated the searches for the experimental Θ^+ state described above. In Ref. [5], the width of the Z^+ is predicted to be 15 MeV. The mass of the Z^+ is found by “anchoring” the anti-decuplet to a non-exotic member of the anti-decuplet, which has nucleon flavor. This is identified with the established state $N(1710)$ seen in $N\pi$ elastic scattering, as well as in other channels. If the anti-decuplet P_{11} is chosen to be $N(1440)$, the Z^+ state would be stable against strong decays, and if it is chosen to be $N(2100)$ the Z^+ would be very broad. The $N(1710)$ state is described in the constituent quark model as a radial excitation of the nucleon, and its strong decays, photocouplings, and mass [18] are well understood in that model.

The total width of the $N_{\overline{10}}(1710)$ state is predicted in the chiral soliton model to be 43 MeV, which is below the 50 to 250 MeV range quoted by the Particle Data Group (PDG) [10], and significantly below the PDG’s “estimate” of 100 MeV. Similarly, the width of the $\Sigma_{\overline{10}}$, associated with the two-star P_{11} state $\Sigma(1880)$, is predicted to be about 70 MeV, which is again smaller than the 80–260 MeV range of widths quoted by the PDG. In the chiral soliton model, the widths of all members of the anti-decuplet are proportional to a calculated constant $G^2_{\overline{10}}$. If this was adjusted upward to accommodate the PDG estimate of the width of the $N(1710)$, the predicted width of the Z^+ would increase, and would exceed the bounds set by the experimental data.

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[5] We thank H.J. Lipkin for pointing this out; see also [15].

The essential mechanism for the narrow width of the Θ^+, which is well above its strong nK^+ and pK^0 thresholds, is that its decay to nK^+ or pK^0 is isospin violating if it is isotensor. It is as though the strong decay threshold has been "raised". It is intriguing to note that such raised thresholds will occur for all isotensor $qqqq\overline{Q}$ states, with q an up or down quark, and Q a heavy quark, since their decay to $N(q\overline{Q})$ also violates isospin conservation. A related phenomenon happens for the $dddQ\bar{u}$ and $uuuQ\bar{d}$ pentaquarks. The decays $dddQ\bar{u} \to \Delta^-(Q\bar{u})$ or $\Sigma_Q\pi^-$ are allowed, while $dddQ\bar{u} \to N(Q\bar{u})$ or $\Lambda_Q\pi$ are not. Also, the decays $uuuQ\bar{d} \to \Delta^{++}(Q\bar{d})$ or $\Sigma_Q\pi^+$ are allowed, while $uuuQ\bar{d} \to N(Q\bar{d})$ or $\Lambda_Q\pi$ are not.

Acknowledgements

Helpful discussions with T. Barnes, T. Goldman, R.C. Haight, K. Hicks, V. Koubarovski, H.J. Lipkin, C.A. Meyer, R. Schumacher, and S. Stepanyan are gratefully acknowledged. This research is supported by the US Department of Energy under contracts DE-FG02-86ER40273 (S.C.), W-7405-ENG-36 (P.R.P.), DE-AC05-84ER40150 (W.R.) and DE-FG05-94ER40832 (W.R.).

References

[1] T. Nakano, et al., LEPS Collaboration, Phys. Rev. Lett. 91 (2003) 012002;
K. Hicks (for the LEPS Collaboration), in: Proceedings of Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2003), 19–24 May, New York, NY.

[2] V.V. Barmin, et al., DIANA Collaboration, hep-ex/0304040, Phys. At. Nucl., in press.

[3] S. Stepanyan (for the CLAS Collaboration), in: Proceedings of Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2003), 19–24 May, New York, NY;
R. Schumacher (for the CLAS Collaboration), in: Jefferson Lab User's Group Meeting Workshop, 11–13 June, Newport News, VA;
S. Stepanyan, et al., CLAS Collaboration, hep-ex/0303018.

[4] M. Chemtob, Nucl. Phys. B 256 (1985) 600;
L.C. Biedenhahn, Y. Dothan, in: From $SU(3)$ to Gravity, Festschrift in Honor of Yuval Ne'eman, Cambridge Univ. Press, Cambridge, 1986;
H. Walliser, Nucl. Phys. A 548 (1992) 649;
H. Weigel, Eur. Phys. J. A 2 (1998) 391;
H. Walliser, V.B. Kopeliovich, hep-ph/0304058.

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

[6] D. Barberis, et al., WA102 Collaboration, Phys. Lett. B 471 (2000) 440.

[7] N. Isgur, Phys. Rev. D 21 (1980) 779;
N. Isgur, Phys. Rev. D 23 (1981) 817, Erratum.

[8] G.A. Miller, Phys. Rev. C 57 (1998) 1492.

[9] G. Karl, Phys. Lett. B 328 (1994) 149;
G. Karl, Phys. Lett. B 341 (1995) 449, Erratum.

[10] K. Hagiwara, et al., Particle Data Group, Phys. Rev. D 66 (2002) 1.

[11] S. Capstick, R. Workman, Phys. Rev. D 59 (1999) 014032.

[12] C. Meyer, CLAS Note 03-009, Jefferson Lab (2003).

[13] Electromagnetic production of the $uuud\bar{s}$ pentaquark was first considered by H.Y. Gao, B.Q. Ma, Mod. Phys. Lett. A 14 (1999) 2313.

[14] M.V. Polyakov, A. Sibirtsev, K. Tsushima, W. Cassing, K. Goeke, Eur. Phys. J. A 9 (2000) 115.

[15] H. Högaasen, P. Sorba, Nucl. Phys. B 145 (1978) 119.

[16] F. Stancu, D.O. Riska, hep-ph/0307010.

[17] F. Stancu, Phys. Rev. D 58 (1998) 111501.

[18] See S. Capstick, N. Isgur, Phys. Rev. D 34 (1986) 2809;
S. Capstick, W. Roberts, Phys. Rev. D 49 (1994) 4570;
S. Capstick, Phys. Rev. D 46 (1992) 1965, and references therein.