Cavendish-HEP-04/15
TAUP 2769-04
WIS/11/04-May-DPP
ANL-HEP-PR-04-45

Why the Θ^+ is seen in some experiments and not in others – a possible explanation

Marek Karliner [a,b*]
and
Harry J. Lipkin [b,c†]

[a] *Cavendish Laboratory*
Cambridge University, England;
and
[b] *School of Physics and Astronomy*
Raymond and Beverly Sackler Faculty of Exact Sciences
Tel Aviv University, Tel Aviv, Israel

[c] *Department of Particle Physics*
Weizmann Institute of Science, Rehovot 76100, Israel
and
High Energy Physics Division, Argonne National Laboratory
Argonne, IL 60439-4815, USA

Abstract

The contradiction between evidence for and against the existence of the Θ^+ pentaquark might be resolved if it only appears as a result of a particular production mechanism which is present in some experiments and absent in others. We examine the implications of Θ^+ production via decay of a cryptoexotic N^* resonance with a mass of about 2.4 GeV corresponding to a peak in the experimental data for the invariant mass of the (Θ^+, K^-) system. Further experimental checks are suggested.

*e-mail: `marek@proton.tau.ac.il`

†e-mail: `ftlipkin@clever.weizmann.ac.il`

The recent experimental discovery [1] and subsequent confirmation [2]-[14] of an exotic 5-quark KN resonance Θ^+ with $S = +1$, a mass of ∼1540 MeV, a very small width $\lesssim 20$ MeV (possibly as little as 1÷2 MeV [15]), and a presumed quark configuration $uudd\bar{s}$ has given rise to a number of experiments with contrary results. Some experiments see the Θ^+ [1]-[14], others definitely do not [16]-[20] and give upper limits on its production.

This contradiction is expected to become even sharper as the experiments which see the Θ^+ have better statistics and rule out the explanation that it is a statistical fluctuation. At this point it seems crucial to analyze and extend both the positive and negative experiments to either establish the Θ^+ as a real particle and understand this contradiction or to find good credible reasons against its existence.

Many detailed theoretical pentaquark models have been proposed, but none address the problem of why certain experiments see it and others do not. We therefore do not consider them here and refer the reader to the comprehensive review by Jennings and Maltman [21].

Our purpose here is to analyze the puzzle, suggest one possible explanation and suggest experimental checks.

One possible resolution of this contradiction is that a specific production mechanism is present in the experiments that see the Θ^+ and is absent in those that do not see it. The data presented in the CLAS paper on the reaction $\gamma p \to \pi^+ K^- K^+ n$ [6], and in particular the $(K^+ K^- n)$ mass distribution in Fig. 5 which shows a peak at the mass of 2.4 GeV suggest [22] that there might be a cryptoexotic N^* resonance with hidden strangeness. Searches for such baryon resonances with hidden strangeness [23] have indicated possible candidates. Further evidence for this resonance is hinted at in the preliminary results from NA49 [24].

A cryptoexotic $N^*(2400)$ with hidden strangeness has a mass too high to be the N^* in the same $SU(3)$ multiplet as the Θ^+. It fits naturally into the P-wave (ud) diquark-$ud\bar{s}$ triquark model [25,26] for the Θ^+, as an orbital excitation of the $udd\bar{s}s$ N^* in the same $\overline{\mathbf{10}}$. It contains a (ds) diquark in the same flavor $SU(3)$ multiplet as the (ud) diquark in the Θ^+. Such a (ds) diquark in a D-wave with the $ud\bar{s}$ triquark would have a dominant decay into $K^-\Theta^+$ via the diquark transition $ds \to ud + K^-$. Decays into a kaon and a hyperon would be suppressed by the centrifugal barrier forbidding a quark in the triquark from joining the diquark.

We wish to point out some experimental implications of this possibility and suggest ways of using experimental data to check whether this can indeed solve the puzzle of the contradiction between positive and negative evidence for the Θ^+.

1. All experiments which see the Θ^+ and have sufficient energy for producing the $N^*(2400)$ should look for an accompanying K^- or K_s and examine the mass spectrum of the $K^-\Theta^+$ and $K_s\Theta^+$ systems.[1]

[1] In some photoproduction experiments, e.g. SPRING-8 and the lower-energy CLAS-I, the photon energy is too low for this. We thank Danny Ashery for pointing this out. Excitation at such lower energies may be possible at the lower energy tail of a Breit-Wigner resonance 200 MeV wide or using Fermi momentum in experiments on nuclear targets; e.g. $\gamma^{12}C$ at SPRING-8, where $E_{CM}(\gamma N)$=2.3 GeV.

2. There are many rumors and conference presentations [19]-[20] about experiments that searched for pentaquarks and did not find them. These experiments should not be left in the rumor/slides stage but put on the record with a careful analysis showing whether they should have been seen with given specific production mechanisms.

   All experiments which did not see the Θ^+ should check whether their experiment would produce a $K^-\Theta^+$ or $K_s\Theta^+$ resonance in the 2.4 GeV region and whether their analysis would emphasize this region in their search for the Θ^+. For example, the B-decay modes that have been suggested for pentaquark searches [27,28] would not produce this 2.4 GeV N^*. Similar considerations should be applied to searches in e^+e^- and $\gamma\gamma$ like those proposed in Ref. [29].

3. The angular distribution of the kaon emitted with the Θ^+ in the photoproduction reaction $\gamma p \to \bar{K}^o\Theta^+$ for which preliminary data have recently been presented by CLAS [30] carries interesting information. If it is produced from a cryptoexotic N^*, there should be no forward-backward asymmetry in the kaon angular distribution. If it is peaked forward, this is meson exchange. It it is peaked backward, it is baryon exchange (see related discussion in Ref. [31]). In this case the same baryon exchange should be seen in $\gamma n \to K^-\Theta^+$. The Θ^+ should be produced equally by photons on protons and neutrons.

4. The angular distributions in the photoproduction reaction $\gamma p \to \pi^+K^-K^+n$ [6] are more complicated, but may still carry interesting information. We consider two possible production mechanisms for the additional pion.

   If the π^+K^- system comes from a $\bar{K}^*$ resonance, all the above discussion for the photoproduction reaction $\gamma p \to \bar{K}^o\Theta^+$ applies to the angular distribution of the $\bar{K}^*$. Models like Ref. [31]) which explain the narrow width of the Θ^+ by a suppressed $NK\Theta^+$ coupling relative to $NK^*\Theta^+$ can be tested here via their prediction that Θ^+ production with a backward K^* should be stronger than the production with a backward kaon. Unfortunately measurement of forward-backward asymmetry is complicated by the presence of a strong forward-peaked background due to t-channel exchange that is most simply treated by cutting out all forward-peaked events including the signal.

   If the reaction goes via the cryptoexotic N^* and is described by the diagram 3a of Ref. [6], the pion goes forward and everything else is in the target fragmentation region. The latter possibility is strengthened by the fact that the π^-p cross section data have a gap in the mass range $2.3 - 2.43$ GeV [22].

5. The production of Θ^+ by baryon exchange is related to reactions between normal nonexotic hadrons that can go by exchange of an exotic positive-strangeness baryon. The baryon exchange diagram proposed in [30] for Θ^+ photoproduction with an outgoing kaon is simply related to the backward K^-p charge-exchange diagram shown in Fig. 1 of [31]. The lower $KN\Theta^+$ vertices are the same; the upper vertex is also $KN\Theta^+$ for K^-p charge-exchange but is $\gamma\Theta^+\Theta^+$ for Θ^+ photoproduction.

   If this diagram contributes appreciably to Θ^+ photoproduction, it indicates that the contribution of the $KN\Theta^+$ vertex is appreciable and should also contribute appreciably to backward K^-p charge-exchange. There may even be some backward K^-p charge-exchange data available previously ignored, because everyone knew that there were no positive strangeness baryons to produce this baryon exchange.

6. The Θ^+ is a baryon containing a strange antiquark. In the low-energy photoproduction experiments these constituents are already present in the initial state, the baryon in the target and the strange antiquark in the strange component of the photon, which is known. In other experiments where baryon number and strangeness must be created from gluons, the cost of baryon antibaryon and strangeness-antistrangeness production by gluons must be used to normalize the production cross section in comparison with the photoproduction cross sections. This can be done experimentally by measuring the baryon-antibaryon production and strange pair production in the same experiment that does not see the Θ^+.

   One can also tune this kind of estimates by comparing the rate of anti deuteron and antiproton production in a given experiment. Such an analysis has been carried out by H1 [32], yielding antideuteron/antiproton ratio $\bar{d}/\bar{p} = 5.0 \pm 1.0 \pm 0.5 \times 10^{-4}$.

   On the other hand, although LEP experiments produce roughly one proton per Z^0 decay [33] and have accumulated millions of Z^0 decays on tape, very little is known about antideuteron production at LEP. The one theoretical prediction we are aware of is Ref. [34], which uses the Lund string fragmentation model to predict 5×10^{-5} deuterons per Z^0 decay. The only relevant experimental publication we are aware of is from OPAL [35], which reports exactly *one* antideuteron candiate event which was eventually dismissed because it did not pass through the primary vertex. From this OPAL infers at 90% confidence level an upper limit on antideuteron production of 0.8×10^{-5} anti-deuterons per Z^0 in the momentum range $0.35 < p < 1.1$ GeV.

   A recent estimate [36] based on this data concludes that $\bar{d}/\bar{p} < 1.6 \times 10^{-4}$ which is significantly less than the ratio reported by H1 [32].[2] The reason for this presumed difference is unknown at present. It would be very valuable to have more information on antideuterons from the LEP experiments.

7. ZEUS has observed both Θ^+ and its antiparticle, $\bar{\Theta}^-$ [12]. It is important for ZEUS to provide information about the relative number of anti-Θ-s and the number of antiprotons. This would give the probability of creating a Θ^+ when the baryon is already present. This probability has to be folded into any experiment (e.g. at LEP) which does not have an initial baryon, does not see the Θ^+, and wants to interpret their upper limit as significant evidence against it. We note in passing that a statement from H1 regarding the Θ^+ is expected in near future.

8. The cryptoexotic N^* would be expected to have other decay modes. In the diquark-triquark model the dominant other decay mode is the SU(3) partner of the $K^-\Theta^+$ decay giving a pion and a P-wave nonstrange pentaquark with hidden strangeness. Decays into a strange meson carrying the strange antiquark and a normal baryon;

[2]We thank T. Sloan for discussion of this point.

e.g. $K\Lambda$, $K\Sigma$, $K\Sigma^*$, ϕN, are suppressed by the centrifugal barrier in the D-wave diquark-triquark model but may be appreciable in other models. Searching for these other decay modes would would give further evidence for this cryptoexotic resonance and this model for pentaquark production. The relative branching ratios would also provide information about the structure of this N^*. The N^* is an isospin doublet and both charge states N^{*+} and N^{*o} should be observed.

9. The cryptoexotic N^* with hidden strangeness could have a partner $N^*_{\bar{c}c}$ with hidden charm, obtained by replacing the $s\bar{s}$ pair by a $c\bar{c}$ pair. This would then be observable as a $D\Theta_c$ or $D^*\Theta_c$ resonance seen as a $D\bar{D}N$, $D^*\bar{D}^*N$, $D^*\bar{D}N$ or $\bar{D}^*DN$ narrow resonance near the mass of $2.4 + 2[M(\Lambda_c) - M(\Lambda)] \sim 4.7$ GeV.[3] In any model with orbital excitation the higher mass of the $c\bar{c}$ pair will reduce the kinetic energy. A quantitative estimate of this reduction is highly model dependent.

If the Θ^+ is a positive parity pentaquark, as suggested e.g. in correlated quark models [25,26], [37], [21], there must be a P-wave orbital excitation that leads to two states having $J = 1/2$ and $J = 3/2$ with a small spin-orbit splitting [38] of the order of 50 MeV. Both states would be expected to be produced roughly equally in the $K\Theta^+$ decay of a higher N^* resonance with the same orbital partial wave, except for the case where the N^* has $J^P = (1/2)^-$. The more complicated angular distributions from the production and decay of the $J = 3/2$ state can provide additional information.

The discussion of possible $J = 3/2$ partners is especially relevant in view of a recent preliminary report from CLAS [30] indicating a possible existence of two peaks in the K^+n invariant mass – at 1523 ± 5 and 1573 ± 5 MeV, with estimated statistical significance of 4σ and 6σ, respectively. It is very important that other experiments check this observation.

The preceding discussion focused on the Θ^+, but some of the above comments apply also to the searches for the Ξ^{--}, Θ_c, Θ_b^+ and other pentaquarks.

If the Θ^+ is confirmed, the likelihood that other members of the antidecuplet exists is quite high [39], [25,26], [37] and possibly there are additional exotic multiplets whose properties can be inferred from those of the Θ^+, see e.g. [40]-[42].

So far, one published experiment reported observing the Ξ^{--}, i.e. the $ddss\bar{u}$ pentaquark [44] at 1.862 ± 0.002 GeV and width below the detector resolution of about 18 MeV, as well as a candidate at the same mass for the $\Xi^o_{3/2}$ member of the corresponding $I = 3/2$ isomultiplet, with quark content $uss\bar{q}q$, where $q = u, d$. A critical discussion of the NA49 results appears in Ref. [45]. There are conference talks from WA89 [46], CDF [47] and ZEUS [48], reporting null search results, but again no papers.

The mass of the Ξ^{--} as reported by NA49 [44] seems rather high compared with the theoretical expectations [25,26], [37] based on the Θ^+ mass. Moreover, recently we derived an upper bound on the mass difference between the Ξ^{--} and Θ^+ [49]. This bound is more than 20 MeV below the experimentally reported $\Xi^{--} - \Theta^+$ mass difference.

The existence of Θ^+ would also make it very likely that its anti-charmed and anti-bottom relatives Θ_c and Θ_b^+ exist. Theoretical predictions based on the presumed quark structure

---

[3]We thank Uri Karshon for discussion on the interplay of $N^*_{\bar{c}c}$ mass estimate vs. the relevant thresholds.

of the Θ^+ place the Θ_c mass between 3 GeV [50] and 2.7 GeV [37] and the Θ_b^+ mass between 6.40 GeV [50] and 6.05 GeV [37], where the lower values are below threshold for strong decays.

Recently the H1 Collaboration reported evidence for a narrow anti-charmed baryon state, a resonance in $D^{*-}p$ and $D^{*+}\bar{p}$ with a mass of $3099 \pm 3 \pm 5$ MeV and a measured Gaussian width of 12 ± 3 MeV [51] A parallel analysis by ZEUS sees no signal [52]. ALEPH has also reported a null result at a conference [19] and FOCUS announced null search results on a Web page [53]. Again, we can only stress again the importance of having these results written up.

NOTE ADDED

After this work appeared in the arXiv, Ref. [54] pointed out additonal tentative evidence for N^* with hidden strangeness and a mass around 2400 MeV [23].

ACKNOWLEDGEMENTS

The research of one of us (M.K.) was supported in part by a grant from the United States-Israel Binational Science Foundation (BSF), Jerusalem. The research of one of us (H.J.L.) was supported in part by the U.S. Department of Energy, Division of High Energy Physics, Contract W-31-109-ENG-38.

We thank Danny Ashery, Daniel Barna, Stan Brodsky, Volker Burkert, Frank Close, Karin Daum, Sergei Chekanov, Leonid Gladilin, Ken Hicks, Kreso Kadija, Uri Karshon, Terry Sloan, Igor Strakovsky and Bryan Webber for discussions.

REFERENCES

[1] T. Nakano *et al.* [LEPS Coll.], Phys. Rev. Lett. **91**, 012002 (2003), hep-ex/0301020.
[2] V. V. Barmin *et al.* [DIANA Coll.], Phys. Atom. Nucl. **66**, 1715 (2003) [Yad. Fiz. **66**, 1763 (2003)], hep-ex/0304040.
[3] S. Stepanyan *et al.* [CLAS Coll.], Phys. Rev. Lett. **91**, 252001 (2003), hep-ex/0307018.
[4] J. Barth *et al.* [SAPHIR Coll.], hep-ex/0307083.
[5] A. E. Asratyan, A. G. Dolgolenko and M. A. Kubantsev, hep-ex/0309042.
[6] V. Kubarovsky *et al.* [CLAS Coll.], [Phys. Rev. Lett. **92**, 032001 (2004)] Erratum – ibid. **92**, 049902 (2004), hep-ex/0311046.
[7] R. Togoo *et al.*, Proc. Mongolian Acad. Sci., **4** (2003) 2.
[8] A. Airapetian *et al.* [HERMES Coll.], Phys. Lett. B **585**, 213 (2004) hep-ex/0312044.
[9] A. Aleev *et al.* [SVD Coll.], hep-ex/0401024.
[10] M. Abdel-Bary *et al.* [COSY-TOF Coll.], hep-ex/0403011.
[11] P. Z. Aslanyan, V. N. Emelyanenko and G. G. Rikhkvitzkaya, hep-ex/0403044.
[12] S. Chekanov *et al.* [ZEUS Coll.], hep-ex/0403051.

[13] T. Nakano, talk at NSTAR 2004, March 24-27, Grenoble, France,
http://lpsc.in2p3.fr/congres/nstar2004/talks/nakano.pdf .
[14] Y. A. Troyan *et al.*, hep-ex/0404003.
[15] S. Nussinov, hep-ph/0307357; R. W. Gothe and S. Nussinov, hep-ph/0308230; R. A. Arndt, I. I. Strakovsky and R. L. Workman, Phys. Rev. C **68** (2003) 042201, nucl-th/0308012 and nucl-th/0311030; J. Haidenbauer and G. Krein, hep-ph/0309243; R. N. Cahn and G. H. Trilling, hep-ph/0311245; A. Casher and S. Nussinov, Phys. Lett. B **578** (2004) 124, hep-ph/0309208.
[16] J. Z. Bai *et al.* [BES Collaboration], hep-ex/0402012.
[17] K. T. Knopfle, M. Zavertyaev and T. Zivko [HERA-B Coll.], hep-ex/0403020.
[18] C. Pinkenburg [for the PHENIX Coll.], nucl-ex/0404001.
[19] P. Hansen [for ALEPH Coll.], talk at DIS 2004,
http://www.saske.sk/dis04/talks/C/hansen.pdf
[20] Throsten Wengler [reporting DELPHI Coll. results], talk at Moriond '04 QCD,
http://moriond.in2p3.fr/QCD/2004/WednesdayAfternoon/Wengler.pdf
[21] For a review of the considerable theoretical literature on pentaquark models and an in-depth discussion, see Byron K. Jennings and Kim Maltman, hep-ph/0308286.
[22] V. Burkert, talk at NSTAR 2004, March 24-27, Grenoble, France,
http://lpsc.in2p3.fr/congres/nstar2004/talks/burkert_2.pdf .
[23] L. G. Landsberg, Phys.Rept.320(1999) 223; hep-ex/9910048.
[24] D. Barna [presenting NA49 Coll. data], lecture at 3rd Budapest Winter School on Heavy Ion Physics, Dec. 8-11,
http://www.hef.kun.nl/~novakt/school03/agenda/Barnatalk.pdf
[25] M. Karliner and H. J. Lipkin, hep-ph/0307243.
[26] M. Karliner and H.J. Lipkin, Phys. Lett. B **575** (2003) 249.
[27] Jonathan L. Rosner, hep-ph/0312269.
[28] T. E. Browder, I. R. Klebanov and D. R. Marlow, hep-ph/0401115.
[29] S. Armstrong, B. Mellado and S. L. Wu, hep-ph/0312344.
[30] M. Battaglieri [presenting CLAS Coll. data], talk at Pentaquark Workshop, Feb. 10-12, 2004, Trento, Italy,
http://www.tp2.ruhr-uni-bochum.de/talks/trento04/battaglieri.pdf .
[31] M. Karliner and H. J. Lipkin, Phys. Lett. B **586**, 303 (2004) hep-ph/0401072.
[32] A. Aktas *et al.* [H1 Collaboration], hep-ex/0403056.
[33] I. G. Knowles and G. D. Lafferty, J. Phys. G **23**, 731 (1997) hep-ph/9705217.
[34] G. Gustafson and J. Hakkinen, Z. Phys. C **61**, 683 (1994).
[35] R. Akers *et al.* [OPAL Collaboration], Z. Phys. C **67**, 203 (1995).
[36] T. Sloan, private communication.
[37] R. L. Jaffe and F. Wilczek, Phys. Rev. Lett. **91**, 232003 (2003), hep-ph/0307341.
[38] J. J. Dudek and F. E. Close, Phys. Lett. B **583**, 278 (2004), hep-ph/0311258.
[39] D. Diakonov, V. Petrov and M. V. Polyakov, Z. Phys. A **359** (1997) 305, hep-ph/9703373.
[40] H. Walliser and V. B. Kopeliovich, J. Exp. Theor. Phys. **97** (2003) 433 [Zh. Eksp. Teor. Fiz. **124** (2003) 483] hep-ph/0304058.
[41] D. Borisyuk, M. Faber and A. Kobushkin, hep-ph/0307370 and hep-ph/0312213; B. Wu and B. Q. Ma, hep-ph/0312041 and hep-ph/0312326.

[42] J. R. Ellis, M. Karliner and M. Praszałowicz, hep-ph/0401127.
[43] R. Jaffe and F. Wilczek, hep-ph/0312369.
[44] C. Alt *et al.* [NA49 Collaboration], hep-ex/0310014.
[45] H. G. Fischer and S. Wenig, hep-ex/0401014.
[46] J. Pochodzalla [presenting WA89 Coll. data], talk at the 2nd Panda Workshop, Frascati, 3/18-19,2004,
www.lnf.infn.it/conference/2004/Panda/Frascati2004_final_pochodzalla.pdf .
[47] I. Gorelov [presenting CDF Coll. data], talk at DIS-2004, Štrbské Pleso, Slovakia, 14-18 April 2004, http://www.saske.sk/dis04/talks/C/gorelov.pdf .
[48] S. Chekanov [presenting ZEUS Coll. data], talk at DIS-2004, Štrbské Pleso, Slovakia, 14-18 April 2004, http://www.saske.sk/dis04/talks/C/chekanov.pdf .
[49] M. Karliner and H. J. Lipkin, hep-ph/0402008.
[50] M. Karliner and H. J. Lipkin, hep-ph/0307343.
[51] A. Aktas *et al.* [H1 Collaboration], hep-ex/0403017.
[52] L. Gladilin [on behalf of ZEUS Coll.], DESY seminar 12/3/04,
http://webcast.desy.de/Pentaquark120304.htm ;
U. Karshon [on behalf of ZEUS Coll.], talk at DIS 2004, Štrbské Pleso, Slovakia, 14-18 April, http://www.saske.sk/dis04/talks/D/karshon.ps.gz .
[53] *"A Search for a State which Decays to a Charged* D^* *and Proton at FOCUS"*, http://www-focus.fnal.gov/penta/penta_charm.html .
[54] Ya.I. Azimov and I.I. Strakovsky, hep-ph/0406312.