

An Experimental Review of the Θ^+ Pentaquark

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Abstract. Evidence for the Θ^+ pentaquark is still sketchy at the present time. This state, if it exists, has a small width and consequently a small production cross section. No single experiment has overwhelming evidence for the Θ^+ and some non-observations of the Θ^+ are difficult to understand unless this exotic baryon also has an exotic production mechanism. However, new data from the LEPS and CLAS collaborations with higher statistics are on the way, which will likely resolve the question of whether the Θ^+ exists.

1. Introduction

The history of physics has many examples of experimental results that were controversial at first and later confirmed by better experiments [1, 2]. Of course, there are also many examples of results that were later shown to be wrong with higher statistics [3, 4]. The question of when a result is real (or when it is a mistake) is a tricky one, and the situation is exacerbated when people make strong statements based on scant data. A better approach is to be patient and let science take its course. If the results are real, then they will be borne out in time by better experiments. In the meantime, it is best to be cautious when drawing conclusions.

It is interesting to look at papers from the 1960's when new resonances were being discovered at a rather fast pace. For example, the first evidence for the ω meson [5] showed a narrow peak on top of a broad phase space that had only 83 ± 16 counts (about $5\text{-}\sigma$) on top of a background of about 98 counts (see Fig. 1). In this measurement, the width of the peak is about 30 MeV, which is close to the experimental resolution of 24 MeV. Within two years, there were many papers [6] confirming this result with higher statistical significance and better resolution.

The situation with the Θ^+ (an exotic baryon with a 4-quark plus one anti-quark $udud\bar{s}$ valence structure) is not so unlike the experimental evidence of the ω meson, except that the statistics are a bit lower (see Fig. 2). The first papers (reviewed in Ref. [7]) reported a narrow peak [8, 9, 10] with about 4-5 σ statistical significance on top of a broad background. At the time of writing, it has been a year plus a few months since the first publication of the LEPS collaboration, and there have been 10 experimental papers confirming the Θ^+ (see Table 1) with statistical significance ranging from 3 to 7 σ . What is different from the case of the ω meson is that the Θ^+ baryon is not seen in some experiments (high-energy, where production by fragmentation is dominant, nor is it seen in e^+e^- collisions at B-factory energies where other baryon-antibaryon resonances are seen). These non-observations are worrisome, and suggest that if the Θ^+ exists, its production mechanism is somehow suppressed (in an unexpected or “exotic” way). This leads to theoretical speculations and creates doubt that the Θ^+ exists.

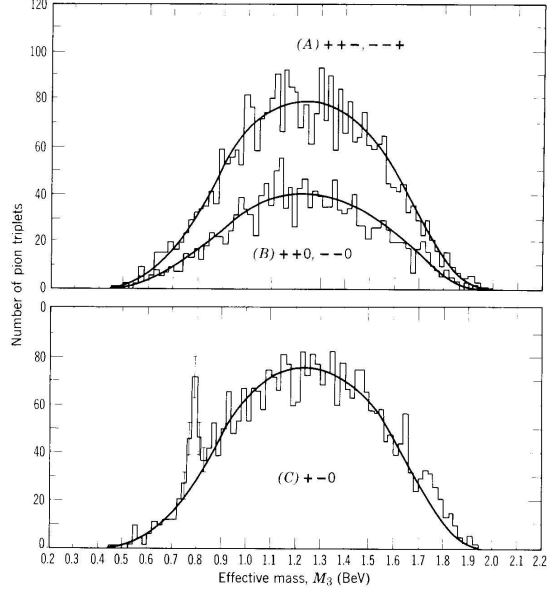


Figure 1. First evidence for the discovery of the ω vector meson [5]. The plots show the invariant mass distribution for 3 pions with two having the same charge (top) or one of each type (+, - or 0 charge), showing that the ω is an isoscalar particle.

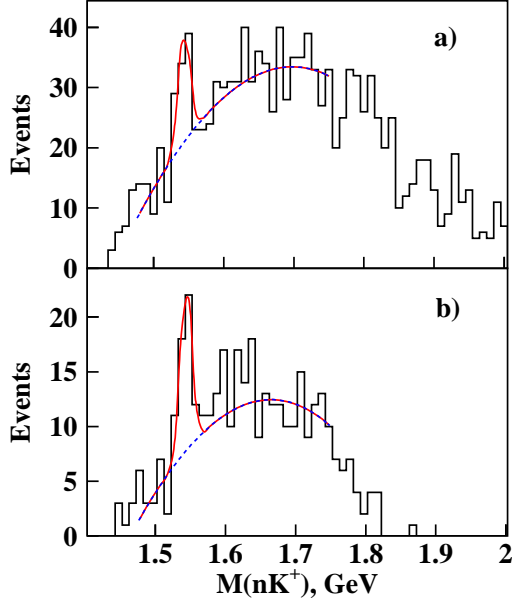


Figure 2. Evidence for the Θ^+ pentaquark from CLAS data on deuterium [10] with loose (top) and tight (bottom) analysis cuts.

In fact, if the Θ^+ does not exist, it will be an interesting case for the history of physics. Did the experimental reports underestimate the statistical significance? Is there some kind of kinematic reflection, combined with statistical fluctuations, that could create this effect? If so, could such an effect explain all of the Θ^+ experimental results? In the next two sections, some of these questions will be examined. In the last section, an outlook for future experiments with better statistics will be presented.

2. Experimental Evidence

Experiments with positive evidence for the Θ^+ are shown in Table 1. The mass spectra for these experiments have been shown at many conferences [7], and so are not repeated here. There are several points to make regarding these positive results:

- There are many different reaction mechanisms that are listed in the table. While it is possible to construe a kinematic reflection [18] or a cusp effect that might affect one reaction channel, it is very difficult to find a mechanism that would create a false peak in all cases.
- Each of these experiments has some weakness [19]. For example, some experiments require harsh cuts that, combined with detector acceptance, could possibly create unexpected structures in the mass spectra. In other cases, the shape of the background under the peak is not well known, which could affect the statistical significance.
- The statistical significance in the table is calculated as a fluctuation of the background. This is *not* the same procedure as used to calculate the area under a peak. Since the shape of the background is not known perfectly, the σ 's shown in the last column are likely an overestimate of the statistical significance [14].

- The masses are a bit inconsistent. Taken as a whole, almost all measurements are within 1-2 standard deviations of the average value, 1535 MeV. However, some measurements are clearly inconsistent with others, such as the DIANA and ZEUS results. Either the experimentalists have underestimated their systematic errors, or there is a serious problem to be faced (suggesting that the Θ^+ might not exist, or some other explanation such as a weak, yet-unknown Σ^+ resonance near 1525 MeV).
- No single experiment makes a really convincing case that the Θ^+ exists. What is needed is a really good experiment with high statistics that shows a strong peak over a smooth background. Until this happens, we must take a cautious view on the existence of the Θ^+ .

Table 1. Published experiments with evidence for the Θ^+ baryon.

Reference	Group	Reaction	Mass (MeV)	Width (MeV)	σ 's*
[8]	LEPS	$\gamma C \rightarrow K^+ K^- X$	1540 ± 10	< 25	4.6
[9]	DIANA	$K^+ X e \rightarrow K^0 p X$	1539 ± 2	< 9	4.4
[10]	CLAS	$\gamma d \rightarrow K^+ K^- p(n)$	1542 ± 5	< 21	$5.2 \pm 0.6^\dagger$
[11]	SAPHIR	$\gamma d \rightarrow K^+ K^0(n)$	1540 ± 6	< 25	4.8
[12]	ITEP	$\nu A \rightarrow K^0 p X$	1533 ± 5	< 20	6.7
[13]	CLAS	$\gamma p \rightarrow \pi^+ K^+ K^-(n)$	1555 ± 10	< 26	7.8
[14]	HERMES	$e^+ d \rightarrow K^0 p X$	1526 ± 3	13 ± 9	~ 5
[15]	ZEUS	$e^+ p \rightarrow e^+ K^0 p X$	1522 ± 3	8 ± 4	~ 5
[16]	COSY-TOF	$pp \rightarrow K^0 p \Sigma^+$	1530 ± 5	< 18	4-6
[17]	SVD	$pA \rightarrow K^0 p X$	1526 ± 5	< 24	5.6

* Gaussian fluctuation of the background, as $N_{peak}/\sqrt{N_{BG}}$. This “naive” significance may underestimate the real probability of a fluctuation by about 1-2 σ .

† Further analysis of the CLAS deuterium data suggest that the significance of the observed peak may not be as large as indicated.

What is not shown in the table are the beam energies used. Many of these experiments are done near (within a few GeV) to the threshold for Θ^+ production. This provides an advantage, because it limits the number of possible reactions that can contribute to the background. For example, the LEPS data has a maximum beam energy of 2.4 GeV, which is too low for production of higher-mass mesons (such as the $a_2(1320)$ followed by decay to a $K^+ K^-$ pair with enough energy to be detected). At higher energies, many more particles with high masses are produced and follow decay paths that are not well known. Determining the background shape is easier for near-threshold experiments, such as COSY-TOF, where a limited number of calculable cross sections contribute to the background shape under the Θ^+ peak.

In any measurement, there is a chance that the production of other particles can “reflect” into the mass spectrum of interest. A possible mechanism has been described by Dzierba *et al* [18]. However, such reflections are more likely to create broad peaks (widths of 50-100 MeV) rather than narrow peaks (widths of 20 MeV or so). Still, broad peaks coupled with low statistics can cause fluctuations that might result in narrow peaks. Simulations of these processes, coupled with the detector acceptance and the analysis cuts used are an essential step in a good experiment. For example, the CLAS experiment [13], as well as others shown in the table, did these necessary simulation studies. The specific model used by Dzierba *et al* has been

refuted [20], and is no longer of concern for the CLAS analysis, but in general one must be careful to consider the effect of kinematic reflections.

Assuming for the moment that the Θ^+ is real, then a theoretical model is needed to explain its structure. The Θ^+ was predicted by Diakonov, Petrov and Polyakov (DPP) [21] at a mass of about 1530 MeV with a width of < 15 MeV. One prediction of the DPP model is that the Θ^+ is part of a group structure (a $\overline{10}$) and other exotic baryons, such as the Ξ^{--} should also exist. One experiment [22] has claimed to see the Ξ^{--} at a mass of about 1860 MeV, but there has been no confirmation of this result by other experiments. If the other members of the $\overline{10}$ group are not found, then this brings into doubt the interpretation of the Θ^+ within this model. Again, we must be cautious about depending too heavily on one model, and ask whether the Θ^+ could have some other interpretation, such as a bound πKN state [23, 24] or some other theory. The important thing is to continue experimental searches for the Θ^+ and for other members of the $\overline{10}$ group.

3. Published Non-observations

Experiments having a null result in searches for the Θ^+ are listed in Table 2. Again, these mass plots have been shown before, and will not be repeated here. In the positive results of the previous section, some criticisms were listed. In fairness, we should also be critical of the non-observations:

- These experiments break down into two categories: e^+e^- production, where there are no quarks in the initial state, and high-energy proton collisions, where the multiplicity of particles in the final state is typically large.
- The production mechanism of the Θ^+ (if it exists) is not known. In the case of e^+e^- annihilation, baryon-antibaryon production has a lower probability than meson pair production (see below). No reasonable theoretical prediction exists for the probability of $\Theta\bar{\Theta}$ production. Comparisons with, say, $\Lambda(1520)$ production are of limited use without theory to guide us.
- Similarly, the production mechanism of the Θ^+ from high-energy proton scattering, which proceeds mainly through fragmentation of the projectile or the target, is unclear. One theoretical estimate [32] shows that the Θ^+ production in the fragmentation model of quark counting rules calculates that the ratio of Θ^+ production is suppressed by more than 10^3 as compared with $\Lambda(1520)$ production. (The limits shown in the table are typically a few percent of Λ^* production rates.)
- When the particle multiplicities are high, the method to determine which particle is produced at the same vertex as the detected K_s^0 becomes difficult. For example, if there are 5 protons in the same event as the K_s^0 , then all five combinations must be used for the invariant mass of the pK^0 spectrum, unless some of these protons can be identified with another particle in the event. This combinatorial background can be significant, and one should look carefully at how these backgrounds are handled in the non-observation experiments.

The detection of the complete final state in exclusive reactions holds an advantage over the inclusive production presented in the non-observation publications. This is especially true for experiments at near-threshold production, where the number of particles in the final state are limited. In the high-energy experiments, the production of hadrons is thought to go via a complicated “hadronization” process of string-breaking and statistical energy sharing [33]. When a high-mass baryon is produced, it will go through subsequent decays that may preferentially populate one state, such as the $\Lambda(1520)$ as opposed to, say, the $\Sigma^0(1660)$. Without theory to

Table 2. Published experiments with non-observation of the Θ^+ baryon.

Reference	Group	Reaction	Limit	Sensitivity?
[25]	BES	$e^+e^- \rightarrow J/\Psi \rightarrow \Theta\bar{\Theta}$	$< 1.1 \times 10^{-5}$ B.R.	No*
[26]	Belle	$e^+e^- \rightarrow \bar{B}^0 B^0 \rightarrow \bar{p}p K^0$	$< 2.3 \times 10^{-7}$ B.R.	Θ^{++}
[27]	BaBar	$e^+e^- \rightarrow \Upsilon(4S) \rightarrow p K^0 X$	$< 1.0 \times 10^{-4}$ B.R.	??
[28]	HERA-B	$pA \rightarrow K^0 p X$	$< 0.02 \times \Lambda^*$	No?
[29]	CDF	$p\bar{p} \rightarrow K^0 p X$	$< 0.03 \times \Lambda^*$	No?
[30]	PHENIX	$Au + Au \rightarrow K^- \bar{n} X$	(not given)	??

* see Ref. [31] for calculations.

guide us, systematics of various baryon final states need to be studied with the goal to estimate the uncertainties in baryon production mechanisms.

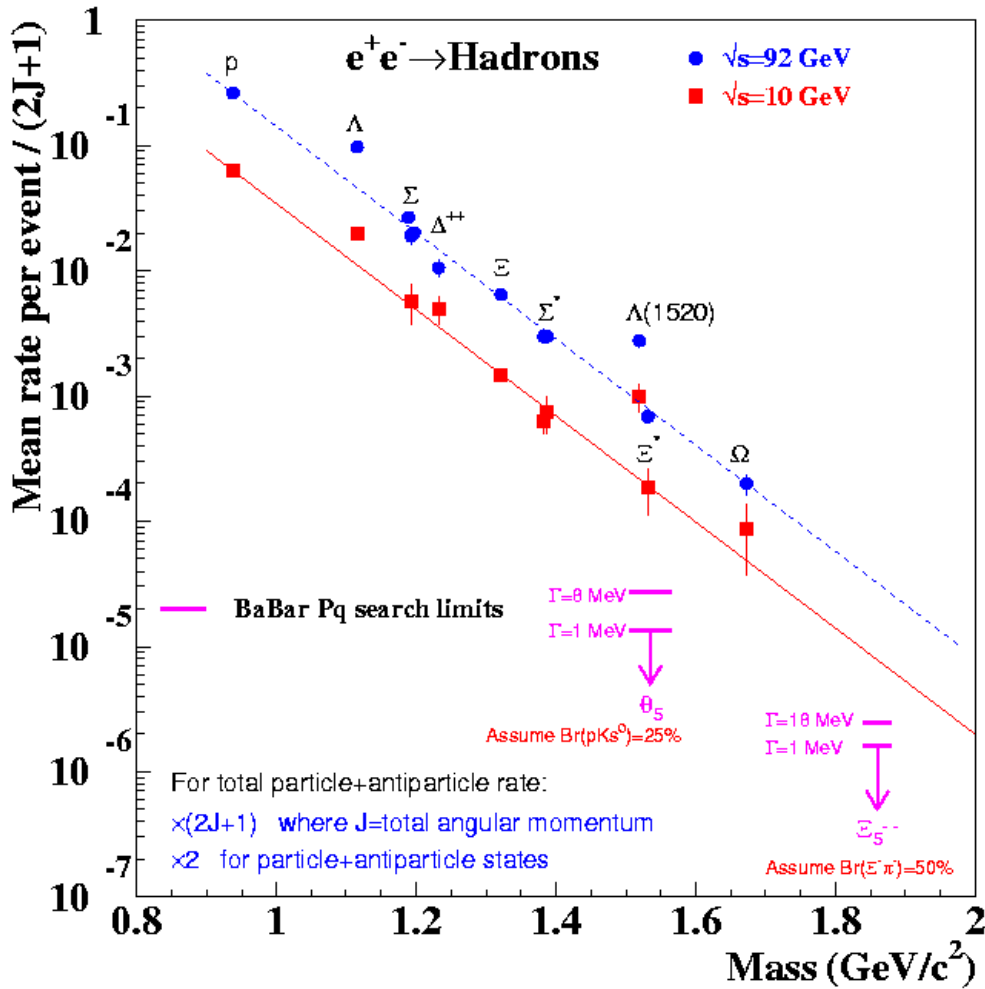


Figure 3. Phenomenology of the rate hadron production from e^+e^- collisions the BaBar experiment [27].

The BaBar experiment [27] has investigated some of the systematics of meson and baryon production from e^+e^- collisions, as shown in Fig. 3. There are several interesting points regarding this plot. First, there is a different slope (by a factor of two) for mesons and baryons [34]. Of course, mesons have a quark-antiquark pair and baryons have 3-quarks, so it is easy to believe that their respective production rates should be different. An extension of this line of reasoning suggests that *pentaquark particles should also have yet a different slope*. Again, theoretical models are needed to calculate the slope for pentaquark production. Until this is done, we do not know if the Θ^+ should have been seen in these experiments. Second, it is interesting to see that some baryons fall significantly above or below the average of the lines in Fig. 3. For example, the $\Lambda(1520)$ production rate is about 3-4 times higher than one would expect based on the systematics. Similarly, the Λ ground state rate is about 2 times higher. So far, no theory can explain this. Clearly, there is a lot of theoretical work necessary before the expected rate of Θ^+ production in e^+e^- collisions can be calculated.

An essential ingredient to the argument that the non-observations imply a non-existence of the Θ^+ is that the production probability of pentaquark particles is similar to the production probability of 3-quark baryon resonances. As just discussed, there is good reason to doubt this assumption. Hence, we are left with a situation where the non-observations of the Θ^+ are not convincing negative evidence, and the low-statistics experiments of the previous section are not convincing positive evidence. Obviously, the next step is to get higher statistics in an experiment where positive results were already seen.

4. Experimental Outlook

Several collaborations are pursuing higher-statistics experiments with the goal to determine the existence (or not) of the Θ^+ . At HERMES, by the end of 2004 they will collect twice the data as used in their publication [14]. At COSY-TOF, an upgrade will allow better vertex resolution and overall they expect about 5 times the data under similar conditions to Ref. [16]. At KEK, a new high-resolution experiment to measure $K^+p \rightarrow \Theta^+\pi^+$ has been approved [35] and will run in early 2005. At LEPS, data from a deuterium target (with more statistics by a factor of a few) was taken in 2003 and has already been shown at various conferences and is being readied for publication. At CLAS, new high-statistics data [36] similar to conditions of Ref. [10] (and also data on a proton target [37]) were completed in mid-2004, and are currently under analysis. An outlook of the latter two experiments will be given below.

At SPring-8, data on a 15 cm liquid deuterium target were taken during a few months in 2003 at a photon intensity of about $10^6/\text{sec}$. The reaction of interest is $\gamma d \rightarrow K^+K^-X$ and under the assumption of a spectator proton, the missing mass of the K^+ gives Y^* resonances with strangeness $S = -1$, such as $\Lambda(1520)$, and the missing mass of the K^- gives possible Θ^+ resonances with strangeness $S = +1$. The LEPS detector covers only the forward angles [8] and is symmetric in acceptance for K^+ and K^- particles. Because of Fermi momentum, a kinematic correction is necessary [38] which is applied in the same way for both Y^* and Θ^+ mass spectra. These data have been shown at other conferences [39] and preliminary analysis indicates a peak with more statistical significance than the previous publication [8] but refinements of the analysis are still in progress. Final results are expected to be submitted for publication in early 2005.

Jefferson Lab experiment 03-113 [36] was run during March to May of 2004 at an electron beam energy of 3.776 GeV. Two separate magnetic field settings of the CLAS spectrometer [40] were taken, one at 80% of the maximum (same as Ref. [10]) and one at 60%. The latter field setting was done to reduce the loss of forward-angle K^- particles, which are bent into the “hole” of the CLAS acceptance (at the exit of the beam pipe). The two magnetic field settings also provide a consistency check because particles of the same momentum will traverse different paths for different B-field settings. The integrated luminosity at each B-field setting was approximately 10 times greater than that of the earlier publication [10], although about

half of the photon flux is at higher energy than used earlier.

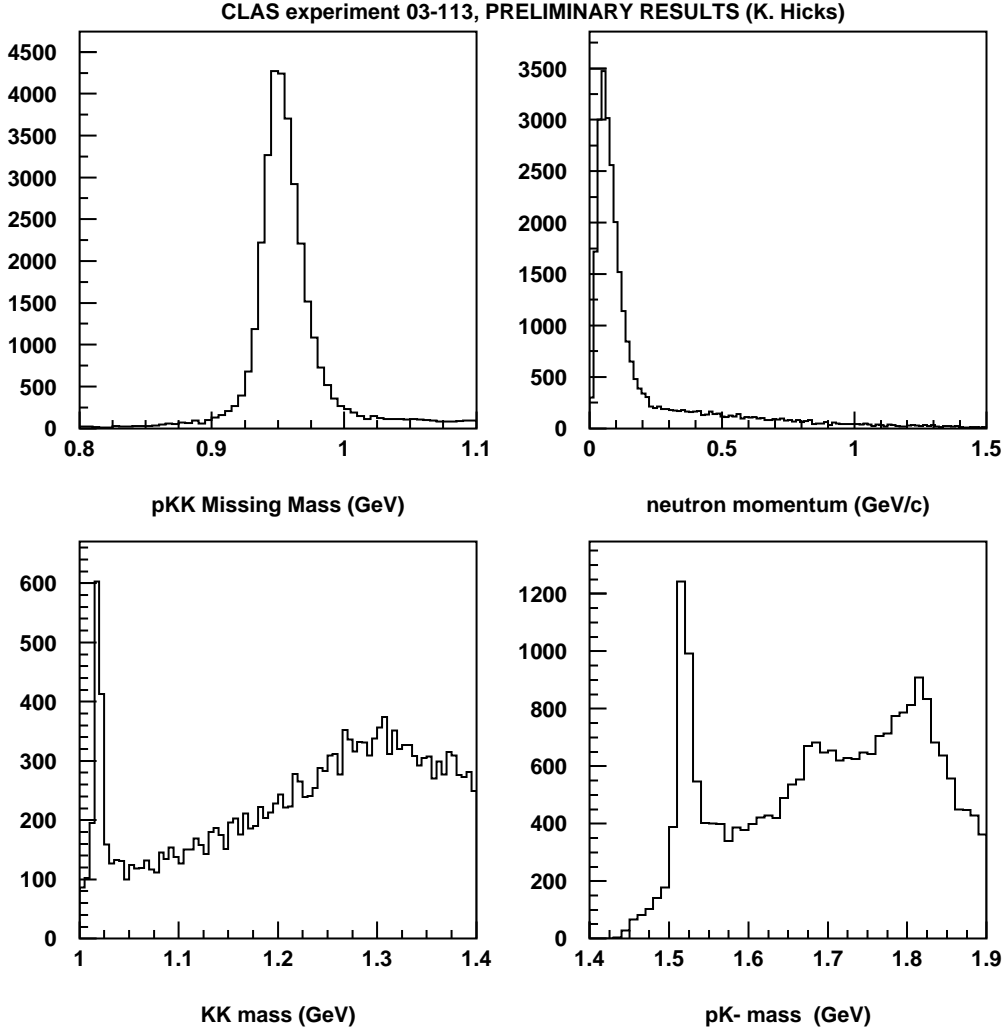


Figure 4. Mass spectra from about half of the high B-field data from CLAS for the high-statistics experiment 03-113 on a deuterium target.

Mass spectra from about 50% of the high-field data from the CLAS experiment are shown in Fig. 4 for the reaction $\gamma d \rightarrow K^+ K^- p(n)$. The neutron is deduced by the missing mass of the $K^+ K^- p$ final state, as shown in the top left plot. These spectra are *still preliminary* and are integrated over all photon energies and all particle angles (see Ref. [41]). The resolution in these plots will be improved, and refinements of calibrations and rejection of background (such as mis-identified particles) are still in progress. The distribution of neutron momenta are shown by the top right plot, for a cut on the $MM(K^+ K^- p)$ from 0.90 to 0.98 GeV, and shows a peak at the Fermi momentum corresponding to reactions where the neutron is a spectator. In the final analysis for Θ^+ production, the neutron from Θ^+ decay is expected to have momentum above 0.2 GeV/c and this event selection will reduce the background from neutron spectator reactions. Invariant mass spectra for the detected $K^+ K^-$ and $p K^-$ pairs are shown in the lower

two plots. The $\phi(1020)$ peak is clearly seen, along with a broad background that rises and falls in part due to the detector acceptance (these raw spectra are uncorrected for the acceptance). In the pK^- mass, the $\Lambda(1520)$ shows a strong peak, along with broader peaks at about 1.68 and 1.81 GeV due to higher-mass Λ^* states. We note that these higher-mass states were not seen in our previous analysis [10] due to a lower photon beam energy. Also, these states are not seen in the non-observation experiments given in Table 2, which suggests that there are important differences in reaction mechanisms between these experiments and those done at CLAS.

5. Summary

There will continue to be critics of the evidence for the Θ^+ pentaquark, as long as the real statistical significance (as opposed to the naive one) is relatively low, or if severe angle cuts have been applied to the data. The situation is complicated by the fact that high-energy experiments have not observed the Θ^+ . However it is not clear if the Θ^+ can be seen in fragmentation, where constituent counting rules suggest a substantial suppression of its production rate [32]. Because of the uncertainty in the production mechanism, the non-observation experiments do not rule out the existence of the Θ^+ any more than they rule out the existence of the $\Sigma(1660)$ which is also not seen in the pK^0 spectra of these experiments.

Kinematic reflections [18] have been refuted in the case of the CLAS data [20] and seem unlikely to explain the Θ^+ peaks in the 10 experiments with positive evidence, which use many different reactions. However, sources of background in all experiments (both those with observations of the Θ^+ and those without) should continue to be investigated. Some experiments have already done careful simulations, but more theoretical input for these simulations is desired.

High-statistics experiments using medium-energy probes at near-threshold production are the key to solving this dilemma. Several experiments have been done and are under analysis. It is likely that the question of whether the Θ^+ exists or not will be answered by mid-2005.

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