Proposal for PAC24

Investigation of Exotic Baryon States in Photoproduction Reactions with CLAS

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Abstract

Recent theoretical work based on the chiral soliton model predicts the existence of a spin $\mathbf{s} = 1/2$ anti-decuplet of 5-quark states ($qqqq\bar{q}$). The lowest lying member, the Θ^+, is predicted to be an exotic isosinglet baryon state with strangeness $S = +1$ (originally named the Z^+). Its predicted mass is 1530 MeV and its width is ~ 10 MeV. Evidence for the existence of the Θ^+ has been reported by the LEPS/SPring-8 Collaboration and also by the ITEP (Moscow) group. Analyses of existing CLAS data suggest that the Θ^+ exists, but are still not conclusive due to the limited statistics.

In this proposal we are asking for 30 days of beam time to run a photoproduction experiment on a deuterium target using the CLAS detector and the Hall B bremsstrahlung tagged photon facility. Using a 3 GeV endpoint energy and a 2 charged particle trigger we will be able to increase the existing statistics by a factor of 20. This will allow us to clearly settle the question of the existence of the Θ^+ and also study its properties.

Executive Summary:

For more than 30 years, physicists have searched without success for the so-called pentaquark, a baryon made up of 4 quarks plus an antiquark. Such states are not prohibited by QCD, and definitive evidence of pentaquark states would be an important addition to our understanding of QCD. In fact, the question of which color singlet configurations exist in nature lies at the heart of non-perturbative QCD. A narrow baryon resonance with the exotic strangeness quantum number $S = +1$ is a natural candidate for a pentaquark state with a $(uudd\bar{s})$ configuration.

In October 2002, the LEPS/SPring-8 Collaboration presented evidence for a narrow resonance with strangeness $S = +1$, a mass of 1.54 GeV, and a statistical significance of 4.6 σ. Even more recently, the DIANA Collaboration at ITEP re-analyzed a decade-old experiment and found a sharp $S = +1$ peak with the same mass (and similar statistical significance). Both measurements are in good agreement with the predictions of the lowest mass pentaquark, called the Θ^+, based on symmetries of group theory and the chiral soliton model that predict a new anti-decuplet of baryons. In the past several months, the CLAS Collaboration has analyzed their data for the same basic photoproduction reaction as reported by SPring-8, but the statistical significance of the g2 data is too small to either confirm or deny their claim for this same spectator reaction. More promising results have been obtained from the g2 data for an exclusive reaction, for which several independent analyses have found evidence for a $S = +1$ baryon resonance at 1.55 GeV. Both inclusive and exclusive reactions would benefit significantly from more statistics.

In this proposal, we request beam time for a new measurement on a deuterium target with the CLAS detector that will increase current statistics by a factor of at least 20. This will be sufficient to provide a conclusive result on the existence of this resonance. If the Θ^+ exists, this new data set will provide valuable information regarding its mass, width, and decay angular distribution. CLAS is the appropriate detector to answer the credible claims, both theoretical and experimental, of a baryon with the exotic structure $(uudd\bar{s})$ at a mass of 1.54 GeV. In addition, studies of other baryon resonances expected to be members of the new anti-decuplet will be investigated to strengthen the theoretical understanding of the Θ^+ state.

1 Introduction

It is well established from high-energy neutrino and anti-neutrino scattering experiments [1] that sea-quarks ($q\bar{q}$ pairs) are part of the ground-state wave function of the nucleon. In addition, pion electroproduction experiments in the Δ-resonance region have shown [2] the presence of a pion "cloud" surrounding the valence quarks. In this sense, we know that 5-quark ($qqqq\bar{q}$) configurations are an admixture with the standard 3-quark valence configuration. It is natural to ask whether a 5-quark configuration, where the $\bar{q}$ has a different flavor than the other valence quarks, can exist. Such states are not forbidden by the rules of QCD.

One mystery of the strong interaction is why 5-quark valence configurations have not been observed definitively via experiment. In fact, the scientific bias against any configuration other than mesons and baryons has led some people to ask whether the rules of QCD should be modified to prohibit pentaquark resonances [3]. Of course, the question is not settled. Recently, the symmetries of the chiral soliton model have been used by Diakonov *et al.* [4] to predict a 5-quark resonance, with strangeness $S = +1$ and a narrow width, originally called the Z^+, but now renamed as the Θ^+. Here, we propose to search for this resonance with the CLAS detector.

The possible existence of the Θ^+ is not entirely theoretical. The LEPS/SPring-8 Collaboration in Japan announced, at the PANIC 2002 conference [5], the observation of a baryon resonance at 1.54 GeV with a narrow width of < 25 MeV and strangeness $S = +1$. This measurement had limited statistics, but accepting their estimate for the background under this peak, the statistical significance is $4.6 \pm 1.0\ \sigma$. The mass and width of this peak are consistent with the above prediction [4]. Also, recent unpublished ITEP results from re-analysis of older data for the reaction $K^+n \to K^0p$ show a narrow peak at the same mass, again with strangeness $S = +1$. These observations await confirmation or denial by other experimental facilities.

The CLAS detector is in a good position to investigate the claims of SPring-8 and ITEP. In 30 days of running on a liquid-deuterium target with a trigger set for 2 charged particles, CLAS will obtain sufficient statistics to clearly settle the question of the existence of the Θ^+. If it exists, angular distributions from CLAS will provide valuable information on the reaction mechanism to produce the Θ^+. Regardless of whether one believes in the theoretical prediction, it is important for Jefferson Lab to make a statement on claims of the existence of the Θ^+, because it will have *significant* implications for the N* spectrum and other non-perturbative aspects of QCD.

2 The Anti-decuplet

The spin-1/2 baryon octet and the spin-3/2 baryon decuplet are famous examples of group theory as applied to particle physics. The symmetries of QCD established these as the lowest-lying multiplets of 3-quark baryons. In the 1960's, the prediction by Gell-Mann of the Ω^- baryon, which was confirmed experimentally soon after, was a triumph for group theory and is a standard item in particle physics textbooks. Gell-Mann and Okubo went on to exploit the symmetries of SU(3) to predict the mass splittings within the decuplet, using the effective mass of the strange quark as a parameter. Once the mass splitting was determined, then the mass of the other members of the decuplet could be deduced.

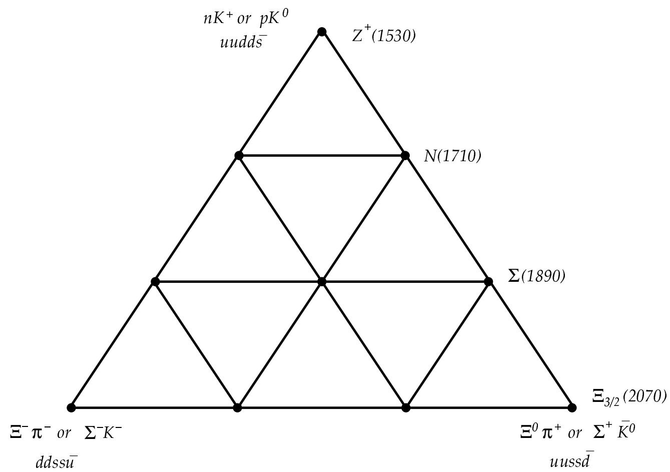

Figure 1: The antidecuplet as predicted by Diakonov *et al.*

The symmetries of the chiral soliton model can be similarly used to relate the mass splittings between the octet and decuplet [4]. Within this model, the members of the octet and decuplet appear simply as different rotations in the spin and isospin space of the same particle (the chiral soliton). These symmetry relations work surprisingly well, to an accuracy of 1-2%. The parameters of this model are the mass ratios of u, d, and s quarks (taken from lattice gauge theory) and the nucleon Σ-term (based on a combination of experimental measurements and theoretical extrapolations) along with 2 free parameters (the ratios of moments of inertia from rotations of the chiral soliton). Although the chiral soliton model is only an approximation of nature, the excellent agreement between the predicted and known mass splittings is sufficiently intriguing to explore other symmetries of this model.

An additional symmetry group, known as the anti-decuplet, is also predicted by the chiral soliton model [4]. This multiplet is a different rotation in the spin/isospin space of the chiral soliton, and hence the same parameters deduced from the octet and decuplet can be used to predict its mass splittings. This multiplet corresponds to 5-quark baryons having spin 1/2, and could have been constructed based on group theory alone. The advantage of the chiral soliton model is that the mass splittings are predicted from symmetries, so that if one member of the anti-decuplet can be identified then the masses of the other baryons in this multiplet are predicted.

The structure of the anti-decuplet is shown in Fig. 1. As with the other multiplets, the strangeness quantum number increases by one for each step down. One interesting feature of this multiplet is the exotic quantum numbers of the isosinglet member at the top, the Z^+ (now called the Θ^+), with quark configuration ($uudd\bar{s}$). The next rung down is a nucleon resonance, which is identified as the $P_{11}(1710)$. This resonance is given 3-star status by the Particle Data Group, and is the only P_{11} resonance between the Roper resonance and tentative (1-star) resonances at higher mass [6]. (Note: to be a member of the anti-decuplet, the N* baryon must have $J^\pi = \frac{1}{2}^+$ and isospin $I = \frac{1}{2}$ and hence must be a P_{11} resonance.) The $P_{11}(1710)$ serves as the "anchor" for the masses of the anti-decuplet and gives the predicted mass of 1530 MeV for the Θ^+ . The width of the Θ^+ comes from a combination of its decay coupling constant into $N\bar{K}$

and the available phase space for its decay. The coupling constant can be predicted from the symmetries of the model, and phase space constrains the width to be on the order of 10's of MeV (not 100's of MeV).

Even without the symmetries of the chiral soliton model, one could get a crude approximation of the mass of the Θ^+ just by the simple assumption of ~ 150 MeV for the mass of the strange quark. In the octet and the decuplet, each rung down has an additional strange quark and a corresponding increase in mass of about 150 MeV. The parallel situation is found with the 5-quark anti-decuplet. The key observation from the chiral soliton model is the identification of this group with spin 1/2, and that the symmetries allow for a more precise determination of the mass and width of the Θ^+.

We note that there is another interpretation for a narrow baryon resonance with strangeness $S = +1$. It is possible that a kaon-nucleon "molecular" state could exist. Indeed, there is some evidence that the $\Lambda(1405)$ could be a $K-N$ bound state [7, 8] from the measured non-symmetric decays of $\pi^-\Sigma^+$ and $\pi^+\Sigma^-$ channels. If this interpretation of the $\Lambda(1405)$ is correct, then it is possible that KN resonant states might also exist. One way to distinguish between the Θ^+ as given above and a possible KN molecular state is to see if the Θ^+ is an isosinglet or whether both K^+p and K^+n channels show sharp structures at similar masses. The proposed experiment will search for resonance states in both channels.

3 Previous Pentaquark Searches

Many searches for a 5-quark resonance with strangeness $S = +1$ (both an isosinglet called the Z_0 or an isotriplet called the Z_1) have been published, as summarized in the PDG listings [6]. None of these searches produced convincing evidence, and were given only 1-star status by the PDG. In fact, the evidence is so weak that the PDG has dropped the category of $S = +1$ baryon candidates from the PDG tables since 1986. More recently, a phase-shift analysis [9] of K^+ scattering data from proton and deuteron targets was completed, but only hints of poles in this analysis were found. The above prediction of Diakonov *et al.*, with the Θ^+ at 1530 MeV, is too low in mass to be seen in these searches (which focus in the mass range 1.55-2.65 GeV). The experimental problem is that low-momentum kaon beams are needed in order to reach lower mass, but the kaon lifetime is short, and most of the beam decays before reaching the target.

The SPring-8 experiment has been mentioned above briefly, and details are available in a preprint [5]. This experiment used the reaction $\gamma n \to K^- \ \Theta^+ \to K^-K^+n$. The source of neutrons was carbon nuclei in a scintillator (CH_2) just downstream of a liquid-hydrogen (LH_2) target. The vertex resolution from the detected K^+K^- pair was clean, and their analysis compared data from the LH_2 and CH_2 targets. If the Θ^+ is indeed an isosinglet (as predicted), then this reaction should be seen only from the neutron. The signal is seen in the missing mass spectrum of the K^-, after cutting out other sources of background such as ϕ-meson production or $\Lambda(1520)$ production that also have a K^+K^- pair in the final state. The final results are shown in Fig. 2, where the left panel is the K^+ missing mass, showing the $\Lambda(1520)$ from the CH_2 target before and after the proton veto, and the right panel is the K^- missing mass, showing the Θ^+ peak from the CH_2 and the normalized background from the LH_2 target overlaid.

We note that the Spring-8 result depends crucially on correcting the missing mass

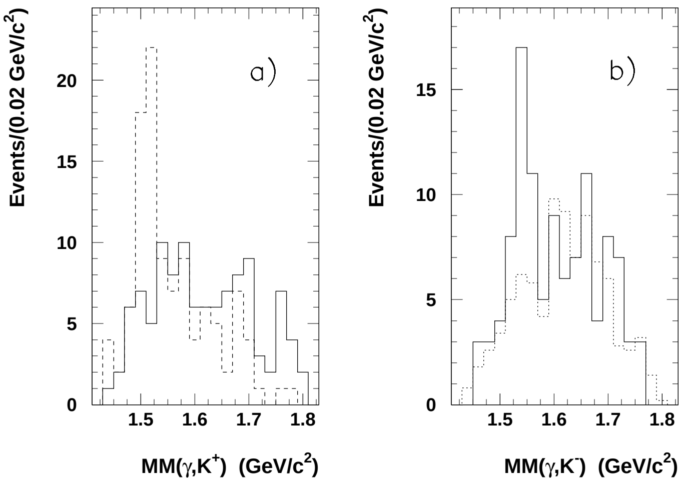

Figure 2: The final results of the SPring-8/LEPS experiment. On the left, the dashed line shows events with an associated proton, with a peak due to the $\Lambda(1520)$, and the solid line is for events without a proton. On the right, the solid line is for the same events without a proton, but for the K^- missing mass which shows a peak at 1540 MeV for the Θ^+. The dotted line shows the background shape as measured from the LH_2 target.

resolution for spreading due to Fermi motion of the target neutrons (in carbon). Although this method is shown in their preprint to work for a calibration reaction, $\gamma n \to K^+\Sigma^- \to K^+\pi^- n$, it is not above reproach. Other aspects of the data analysis are being examined for possible systematic errors, but at the present time the SPring-8 result should be taken seriously.

Preliminary analysis of the g2 data from CLAS were reported in a CAA (CLAS Approved Analysis) proposal approved by the CLAS Real Photons Working Group in November, 2002 [10]. (Note: A CAA is a proposal to the CLAS Collaboration to analyze *existing* data. This is a mechanism within the CLAS Collaboration to identify analysis efforts that are peer-reviewed within the collaboration at the same standard as proposals sent to the PAC.) These data showed a sharp peak in the K^- missing mass spectrum from the same reaction as the SPring-8 result, albeit at a mass of 1.51 GeV rather than 1.54 GeV. This led to a substantial analysis effort by several teams to quantify the background shape and the statistical significance of the possible Θ^+ peak. More details will be given in the next section.

Another result has been reported recently by the DIANA Collaboration from ITEP [11], where they observe a narrow ($<$ 10 MeV) peak at 1.54 GeV with a statistical significance of $> 4\ \sigma$. The reaction they studied was $K^+n \to (\bar{K}^0)\ \Theta^+ \to (\bar{K}^0)\pi^+\pi^-p$ from re-analysis of bubble-chamber data taken in the 1980's, where the neutron is part of a Xe nucleus. Their analysis procedure is not known at the time of this writing, but it appears that they have only a few cuts and none of them appear to constrain the kinematics in strange ways. Their results, which were announced after those from SPring-8, support the presence of a narrow Θ^+ resonance.

It is, of course, possible to search for the Θ^+ in photoproduction from a proton target. An obvious reaction to look at is $\gamma p \to \bar{K}^0\Theta^+ \to \pi^+\pi^-K^+(n)$. In this case, one might expect to find evidence of this reaction in old bubble-chamber data as well.

However, no clear evidence has been reported for a narrow peak in this reaction in older data. Preliminary analysis by the Italian group (from INFN) of the CLAS Collaboration using the g1c data to look for the above reaction also shows no evidence for a peak in the 1.5-1.6 GeV range. This has led to some speculation about whether production of the Θ^+ is suppressed from a proton target [12]. Of course, this reaction should also be examined more closely in future analysis by the CLAS Collaboration.

In contrast, analysis of CLAS data from the g6 run (with a proton target) have recently been done for the reaction $\gamma p \to \bar{K}^{0*}\,\Theta^+ \to K^-\pi^+K^+(n)$ by V. Koubarovski [14]. Although these preliminary results are not presented here, the spectra are encouraging and show a narrow peak at about 1.54 GeV with fair statistical significance. (Results might be available at the time of the oral presentation.)

We also note that searches for other pentaquark configurations, such as bound states with open charm, have not been successful [15]. These studies are beyond the scope of the current proposal, but so far no higher-mass pentaquark states have been found.

4 Preliminary Results from CLAS

Two types of preliminary analyses have been performed: the first for the spectator reaction, where a K^+K^- pair was detected, and the second for the exclusive reaction, where three coincident particles (K^+K^-p) were required. The advantage of the latter reaction is that it is kinematically complete, and free from the assumption in the former of a non-interacting spectator nucleon. Both analyses used the same data set, which is described next.

The CLAS database has been searched for runs with a beam energy and a nuclear target similar to that reported by SPring-8. The only photon data set that meets this requirement is the g2 run. The g2 run was taken at two electron beam energies, 2.474 and 3.115 GeV, and the photon beam (from the 10^{-4} tagger radiator) was incident on a 10 cm long liquid-deuterium target.

The total number of events in the g2 data set with a K^+ candidate (in the mass range 0.3-0.7 GeV) and a negative track in the same event is about 2.5 million. The number of events in the SPring-8 energy range (1.5-2.3 GeV) with only one photon in the beam bucket of the K^+ is about 1.4 million. Further cuts to throw out "bad" TOF paddles and a loose requirement of particle ID for a coincident K^+ and K^- results in only a few thousand events over the entire acceptance of CLAS. Many of these events are associated with known strangeness-production channels, which are a background when looking for a Θ^+ peak, resulting in a rather meager event sample (by CLAS standards) for the reaction of interest.

One difference between CLAS and the LEPS detector (at SPring-8) is the region of kinematic acceptance. The LEPS detector was designed to study ϕ-meson photoproduction, and so has a forward-angle design that is limited to polar angles θ less than $\sim 30^\circ$. On the other hand, CLAS has very little acceptance for photoproduction at angles forward of $\sim 20^\circ$. In this sense, the detectors are complementary. The CLAS detector has almost no acceptance for detecting K^+K^- pairs from ϕ decay, whereas the LEPS detector is dominated by K^+K^- pairs from this reaction. If the Θ^+ is produced by a diffractive reaction mechanism, similar to $\Lambda(1520)$ production, then the CLAS acceptance would result in less sensitivity to the Θ^+ than for the LEPS detector.

4.1 The Spectator Reaction

Several reactions can lead to the final K^+K^- state: 1) $\gamma N \rightarrow \phi N$, 2) $\gamma p \rightarrow K^+\Lambda^*$, 3) $\gamma n \rightarrow K^-\Theta^+$, 4) Non-resonant (Born diagram) production. In the first three cases, the particles in the final state are expected to have a narrow width, and can be detected by either the invariant mass of the K^+K^- pair or the missing mass of one of the kaons. For a deuterium target, the latter two reactions are blurred by the Fermi momentum of the bound nucleons. Techniques to handle the Fermi spreading will be discussed below.

The reaction measured by SPring-8 assumed that a photon hits a neutron in a carbon nucleus, and the rest of the nucleus is a spectator. For the g2 data, we can make the same assumption, where the proton in deuterium is a spectator. One advantage for the g2 data is that the Fermi momentum in deuterium is nicely described by the Bonn or Paris potential, unlike the approximate Fermi gas model typically used for carbon, and hence can be modeled in computer simulations (GSIM).

The approach of our group was to perform several independent analyses to search for the Θ^+ following the general method reported by the SPring-8 experiment. We then compared our results at various stages, and soon found that a clean method of particle identification is essential to this analysis. After much work and lots of discussion, our group converged to a method for particle ID based on the consistency between timing and momentum measurements for a given mass of each detected hadron. We have applied 2.5-σ cuts on the kaon particle ID peak in the analysis presented below. Note that good particle ID is essential to a successful search, because spurious peaks could be formed from false identification of pions or protons as kaons. In our analysis, we have been careful to guard against this potential problem.

The next step in the analysis is to apply kinematic cuts to the data. For this, we used the GEANT-based CLAS Monte Carlo known as GSIM for guidance. The g2 data spectra were compared with GSIM, and there is generally good agreement for the basic cuts. Of course, the real data contain many reactions, whereas GSIM has only a few isolated reaction mechanisms. In order to get a reasonable description of the data, it is necessary to mix together the different event generators in order to model the background under the $\Lambda(1520)$ and possible Θ^+ peaks. For the plots below, we have taken 100K events from the $\Lambda(1520)$ channel, 200K events from the ϕ channel, and 50K events from the Θ^+ channel with a mass of 1.54 GeV and a width of 15 MeV. (At present, no events from a non-resonant production are included).

The acceptance in CLAS for ϕ-meson production going to a K^+K^- final state is quite small. According to GSIM, which does not include final-state interactions (FSI), essentially all of the ϕ events form a peak below 1.05 GeV in the $K\bar{K}$ invariant mass and have a $K\bar{K}$ missing mass in the range of 0.80-1.0 GeV. In the g2 data, we see a sharp peak at 1.02 GeV, which is easily cut out of the analysis.

For $\Lambda(1520)$ and Θ^+ production, where both a K^+ and a K^- was detected in CLAS, the momenta of the kaons in GSIM are limited to the range of 0.3-1.2 GeV for the K^+ and 0.3-0.9 GeV for the K^- as shown in Fig. 3. Here, the kaon momentum is plotted as a function of its calculated mass for the data (top) and GSIM (bottom). We note that the agreement between data and GSIM is quite good, indicating that the particle ID cuts are working well, and that GSIM can be used to guide the kinematic cuts. Based on these results, we used the above momentum cuts on the g2 data analysis.

The simulations can also be examined for the expected range of $K\bar{K}$ missing mass

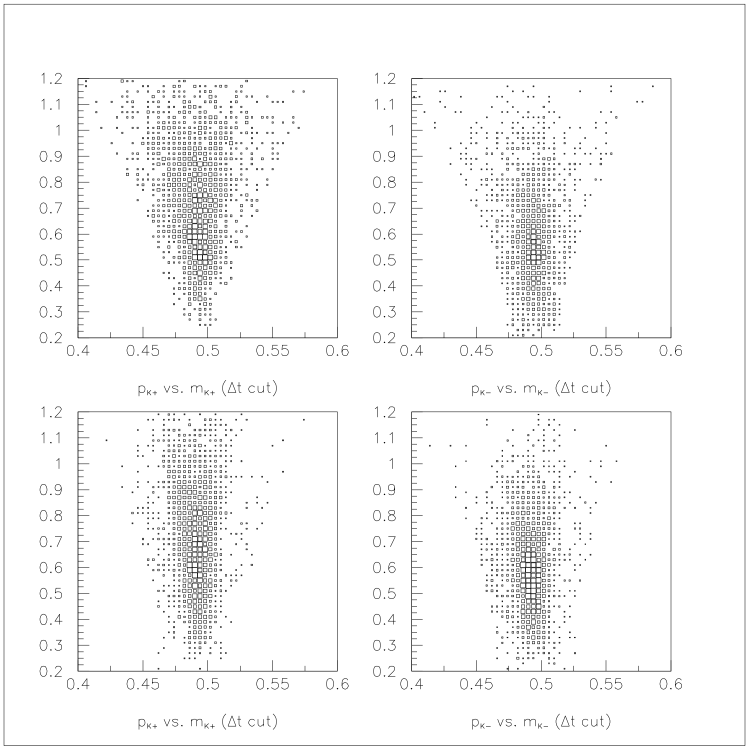

Figure 3: Plot of momentum versus mass for the K^+ and K^- for data (top) and GSIM (bottom). The GSIM spectrum is a mixture of several reactions (see text). Both data and GSIM are limited to the photon energy range $E_\gamma = 1.5$-2.3 GeV.

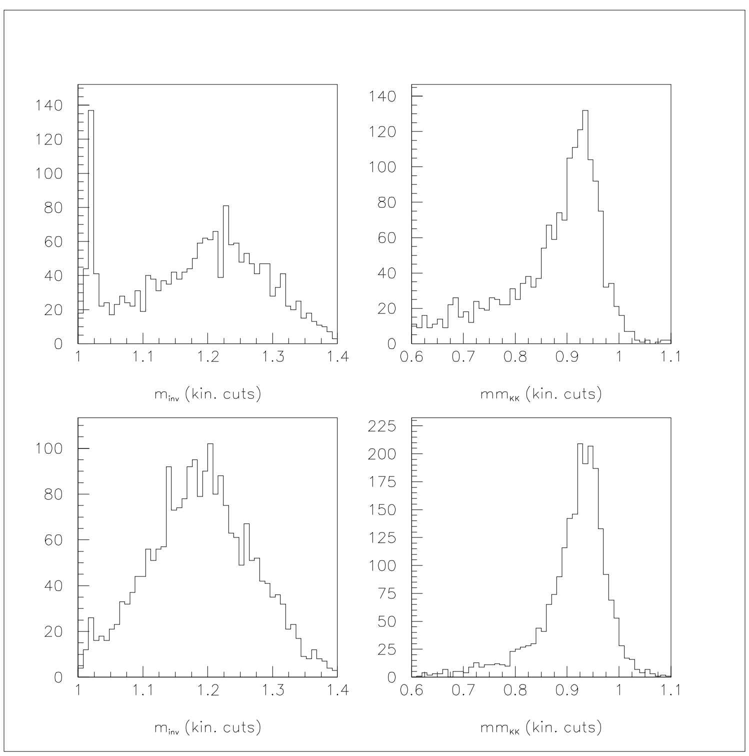

Figure 4: Invariant mass and missing mass of the $K\bar{K}$ pair for data (top) and GSIM (bottom).

and invariant mass. These spectra are shown in Fig. 4, where again the data are shown in the top panels and GSIM in the bottom panels. The peak corresponding to the missing mass of the nucleon is clearly seen in both cases, which is spread by the Fermi motion of the struck nucleon. Here, one sees a difference between data and GSIM, in particular below 0.8 GeV where the data show substantially more strength than GSIM. This is most likely due to FSI, which are not present in the GSIM event generators. Based on these results, we placed a cut from 0.8-1.0 GeV on the $K\bar{K}$ missing mass in the analysis of the spectator reaction.

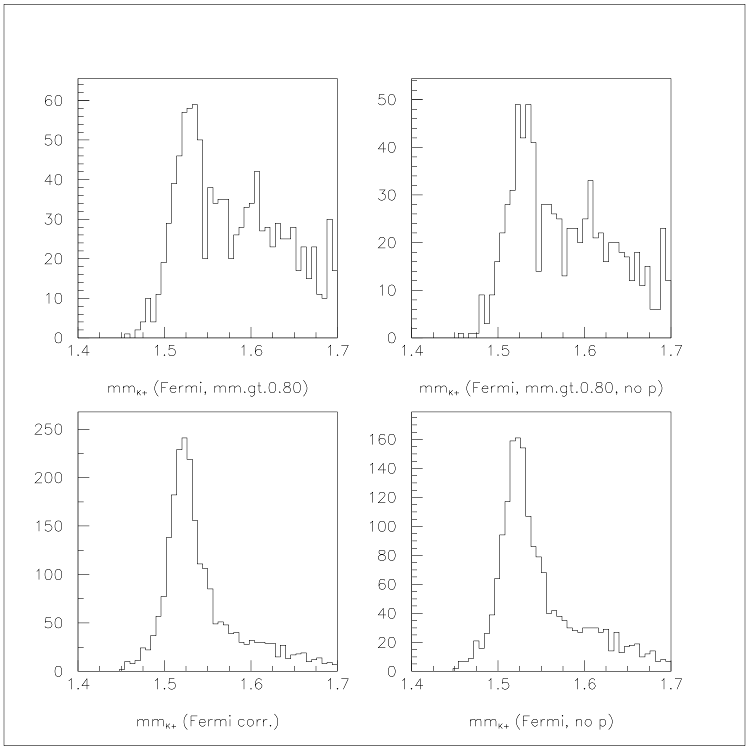

Figure 5: Plot of the K^+ missing mass with and without a proton for data (top) and GSIM (bottom).

The K^+ missing mass for the data (top) and GSIM (bottom) is shown in Fig. 5 for events with and without a proton in the event. In both cases, a Fermi momentum correction has been applied (according to the prescription given in Ref. [13]). The $\Lambda(1520)$ peak position and width is similar for both GSIM and data. As shown in Section 5, almost all of the $\Lambda(1520)$ can be cut by requiring the K^+ missing mass to be above 1.55 GeV. Although this cut does not eliminate all of the possible Λ^* production, it is the optimal cut position. Of course, we expect to have an energetic proton associated with each Λ^* event, but the "holes" in the CLAS acceptance reduce the proton detection efficiency (as quantified in Section 5).

Finally, the Fermi-corrected K^- missing mass, after applying the above cuts, is shown in Fig. 6 for events with and without a proton. In the latter case, we expect a reduction in the background due to Λ^* resonances. Again, the top panels are data, and the lower panels are from GSIM. Although there is no prominent peak in the data, there is an interesting structure near 1.51 GeV that should be investigated further. In particular, we will vary the cuts to see if the signal to noise ratio can be enhanced in a rational way. In all cases, we should be careful to make statistically sound judgements.

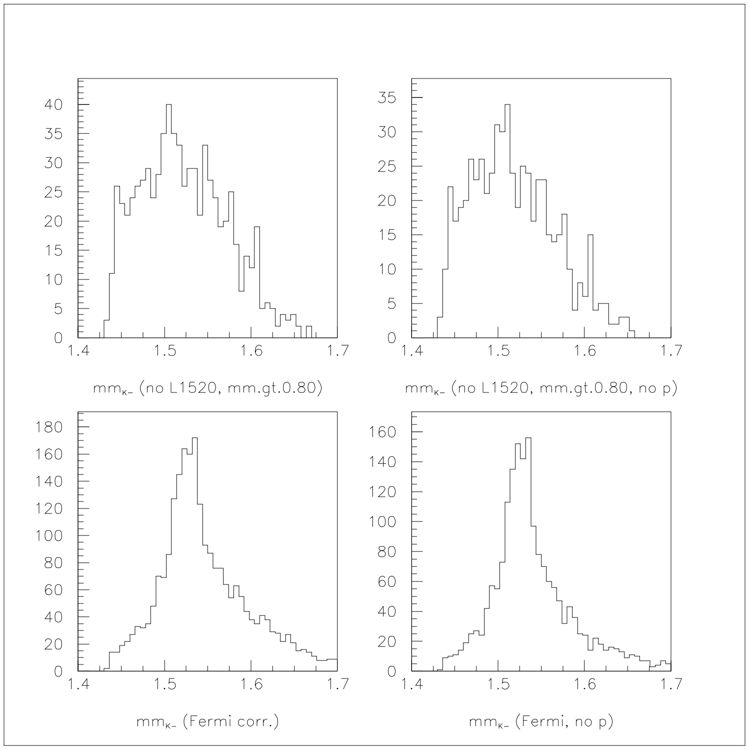

Figure 6: Plot of the K^- missing mass with and without a proton for data (top) and GSIM (bottom).

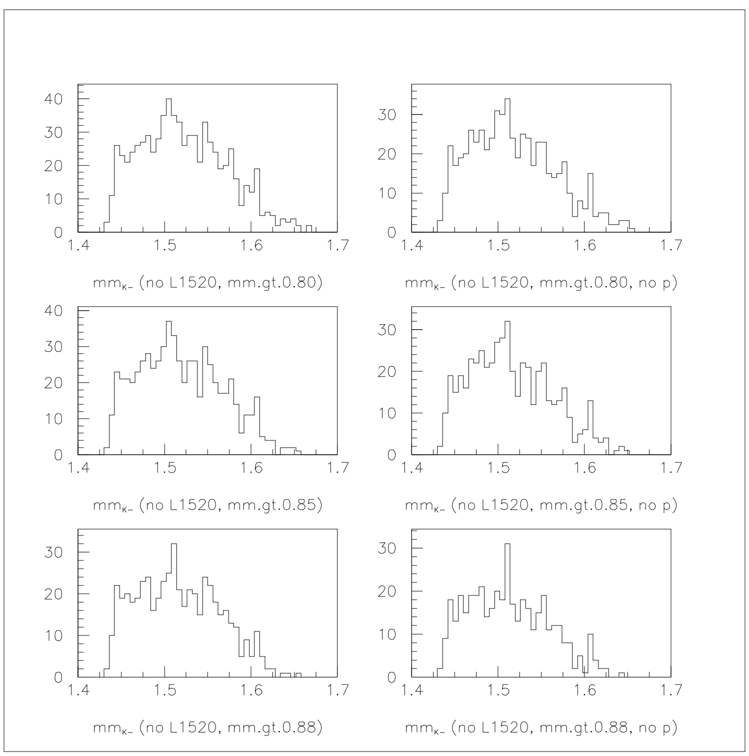

Figure 7: Plot of the K^- missing mass with and without a proton for various cuts (shown) on the $K\bar{K}$ missing mass.

In Fig. 7 we have varied the range of the $K\bar{K}$ missing mass cut. The "standard" cut is shown at the top, and narrower cuts of 0.85-1.0 and 0.88-0.98 GeV are used in the middle and lower plots, respectively. The idea behind narrower cuts is two-fold. First, we know that the Fermi-correction is only an approximation, and this has been shown (in GSIM) to have less ambiguity for data closer to the nucleon mass (0.94) in the $K\bar{K}$ missing mass peak. Second, the FSI "noise" at lower $K\bar{K}$ missing mass is likely to decrease relative to the "signal" for a tighter cut here. In Fig. 7, the tighter cuts seem to take away events everywhere in the spectrum, yet the enhancement near 1.51 GeV does not go away. We note that the statistical significance of the "spike" at 1.51 GeV does not change substantially with application of these cuts, and it is questionable (in these low-statistics) whether there is any signal of the Θ^+ .

One possible explanation of the lack of a strong peak in the CLAS data, when compared with the SPring-8/LEPS results, is the kinematical acceptance. If the Θ^+ is produced with a forward-angle reaction mechanism, such as a diffractive t-channel diagram, then the LEPS acceptance would be favored over the CLAS acceptance. Clearly, the current analysis needs a substantial increase in events before a clear (statistically significant) result can be rendered. The proposed experiment, if approved, will solve this problem.

4.2 The Exclusive Reaction

The reaction mechanism for the exclusive channel could proceed through a two-step process, and there are many possible diagrams that could be drawn. One possible diagram is shown in Fig. 8a, where the Θ^+ is created, and the K^- the re-interacts with the proton (which is close by). In another possible diagram, Fig. 8b, the photon strikes the proton creating a K^+K^- pair, and the K^+ re-interacts with the residual neutron to form a Θ^+ resonance. In either case, the missing mass of the K^-p system, which is identical to the invariant mass of the K^+n system, is calculated and a sharp peak in this spectrum would indicate a possible Θ^+ resonance. Note that this two-step reaction mechanism allows CLAS to detect kinematic regions that might otherwise be excluded from the acceptance, such as very forward-peaked t-channel processes.

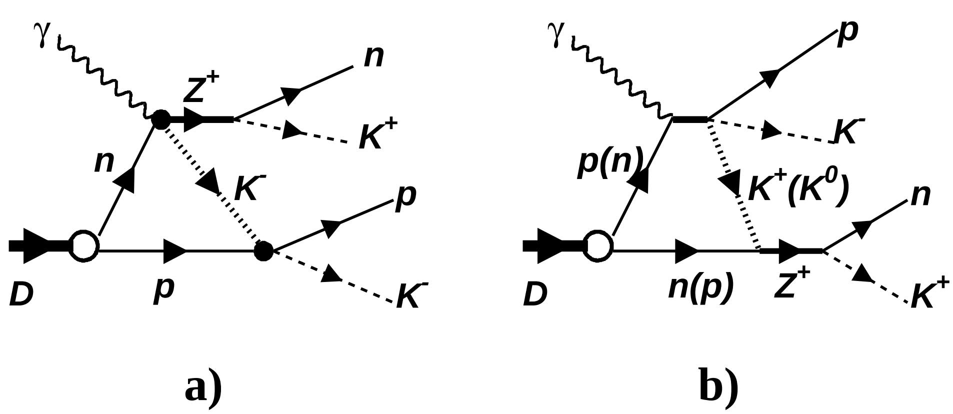

Figure 8: Two possible diagram for the production of the Θ^+ (labelled the Z^+) through re-interaction of the kaon with the spectator nucleon.

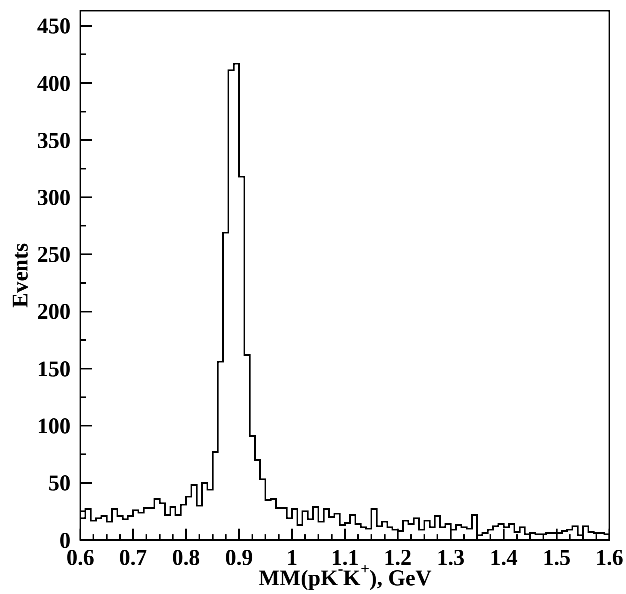

Figure 9: Missing mass squared of the $K\bar{K}p$ system. The sharp peak is at the location of the nucleon mass squared.

The analysis procedure for the exclusive channel is done in a slightly different way. First, contamination from pions is easily removed because of the tight kinematic constraint on the $K\bar{K}p$ missing mass (which must equal the mass of the unobserved nucleon). A plot of the missing mass is shown in Fig. 9 that shows a very narrow peak at the mass squared of the nucleon, with very little background. Note that this plot also requires the vertex time of the proton to be within 1.5 ns of that for each kaon to ensure that all hadrons originate from the same tagged photon.

Several additional cuts are applied. The first is to eliminate events with a $K\bar{K}$ invariant mass less than 1.07 GeV (to remove the ϕ-meson). The second cut limits the K^+ momentum to be less than 1.0 GeV. This cut is based in part on Monte Carlo simulations, which show that the K^+ momentum from the decay kinematics of the Θ^+ is $<$ 1.0 GeV (within the CLAS acceptance). A third cut is applied to the K^-p invariant mass to remove the Λ^* events (the $\Lambda(1520)$, the $\Lambda(1670)$, and $\Lambda(1690)$ regions). The last cut removes low $K\bar{K}p$ missing momenta, which are events where the neutron was just a spectator. The ability to separate events with and without an energetic neutron is a critical step in testing whether a two-step process took place or not. Events with an energetic proton *and* a spectator neutron are likely associated with Λ^* production. In order to produce Θ^+ events as in Fig. 8, both a proton and an energetic neutron are desired. With these cuts, the K^-p missing mass is shown in Fig. 10. This plot shows a clear peak at 1.55 GeV with a width of 10 MeV, with a statistical significance of more than 5 σ.

Although the above data are highly suggestive that the Θ^+ exists, they are still not conclusive. In particular, more data would allow us to quantify the background shape better, and would also increase the statistical significance of the peak. The current data are not sufficient to investigate systematic effects of the detector acceptance nor is it possible to extract an angular distribution. The proposed experiment will provide the data necessary to "nail down" the questions raised by the analysis of the g2 data set.

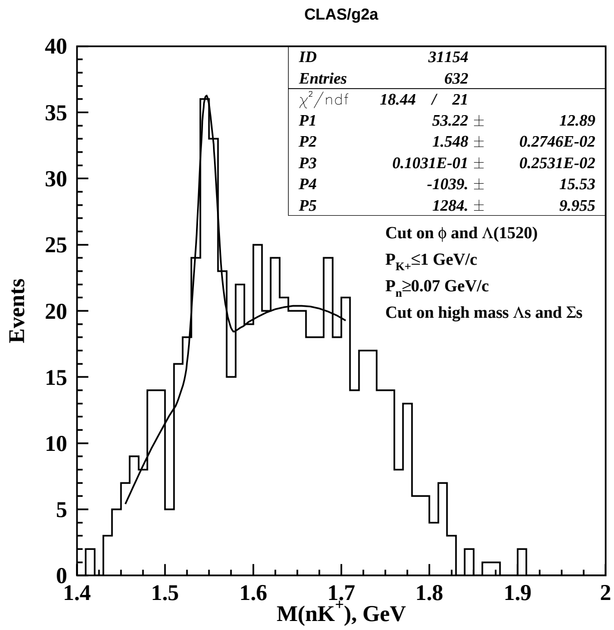

Figure 10: Invariant mass of the (nK^+) system for exclusive events on the deuteron in which K^+, K^-, and p particles were detected. Backgrounds from ϕ and Λ^* production were cut away, as were events with low recoil momentum "spectator" neutrons.

5 Estimates from Monte Carlo Studies

The $\Lambda(1520)$ is a background process for investigations of a possible $\Theta^+(1540)$ resonance when the detected particles are the K^+ and K^-. The reactions are:

$$\gamma + p \to K^+ + \Lambda^* \to K^+ + K^- + p$$

and

$$\gamma + n \to K^- + \Theta^+ \to K^- + K^+ + n$$

and the final state nucleon is not detected. Another competing reaction is ϕ-meson production, which will be discussed later. The goal of this section is to estimate the acceptance for the $\Lambda(1520)$ and the predicted $\Theta^+(1540)$ resonance in the CLAS detector, and the distribution of these events in the kinematic variables used when searching for signatures of the Θ^+ .

5.1 GSIM event simulation

Event generators used for the $\Lambda(1520)$ and the Θ^+ are uniform in phase space. Although the cross section for $\Lambda(1520)$ production has been measured, it is not known with precision, and the phase space generator should suffice to observe kinematic distributions of the reaction. Also, a Fermi momentum was given to the struck nucleon with a distribution as given by the Bonn potential for a nucleon in deuterium.

The GSIM code, which is a version of the GEANT simulation software configured for the CLAS detector, was set up for the same conditions as for the g2 data set, with an electron beam energy of 2.478 GeV and a B-field setting of 3377 Amps (88% of the maximum torus coil setting). After the events were run through GSIM, the CLAS-standard software GPP package was used to knock out dead wires, bad TOF paddles, and bad tagger counters using maps from the g2 run.

The output of GSIM/GPP was cooked using the same track reconstruction software (the a1c code) as was used for the g2 data. Then ntuples were created for use with the CERN software package PAW. The ntuples were run through the same analysis code as was used in the search for the Θ^+.

5.2 $\Lambda(1520)$ simulations

The results shown below are from the GSIM files for the study of $\gamma p \to K^+\Lambda(1520) \to K^+K^-p$ reaction. The simulation was run for 100,000 events at photon energies up to a 2.3 GeV electron endpoint energy.

The cuts on the data are briefly described:

- Events with more than 1 photon within 1.0 ns of the vertex time are thrown away.
- Photon energies below threshold (1.5 GeV) are thrown away.
- A match between the time-of-flight and momentum of a particle is required for both kaons.
- The kaons must both track back to the target volume.
- A cut on the kaon momentum is used to "clean up" kaon decays.
- The missing mass of the $K\bar{K}$ pair was constrained to be close to the nucleon mass.
- $K\bar{K}$ pairs with an invariant mass near the $\phi(1020)$ are removed.
- Events from the peak of the $\Lambda(1520)$ are removed in the K^- missing mass spectra (for consistency with the Θ^+ analysis procedure).
- A correction for the Fermi momentum is applied.

The results in Fig. 11 have been integrated over the entire acceptance of CLAS. The top panels are for the K^+ missing mass, and the bottom panels are for the K^- missing mass (after cutting out the $\Lambda(1520)$ peak). A sharp peak in the K^- missing mass could mimic the effect of a Θ^+ signal. Events in the right panels also require that CLAS did not detect a proton from $\Lambda(1520)$ decay. From these plots, we can see that acceptance for events is about 1.2% of the initial 100,000 events thrown, and events with a detected proton are about 65% of the total. After cutting events in the $\Lambda(1520)$ peak, only about 10% of these events remain, and these events fill the phase space of the K^- missing mass spectra.

5.3 $\Theta^+(1540)$ simulations

The same analysis procedure was applied to the simulated Θ^+ events. The results are shown in Fig. 12. The arrangement of the panels here is the same as for the previous figure. After the cut that is always applied to remove events with a K^+ missing mass

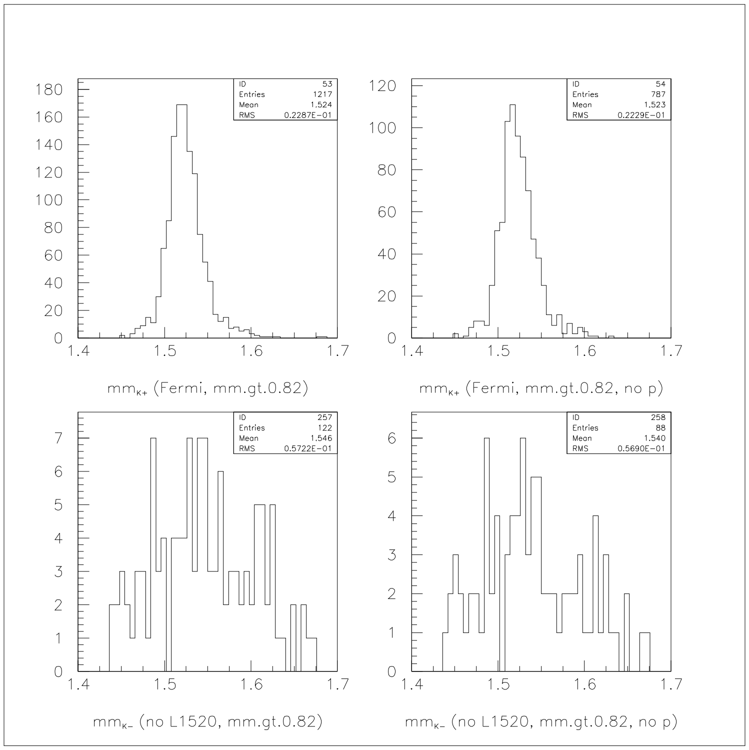

Figure 11: Monte Carlo with a phase-space $\Lambda(1520)$ event generator. (Top) $\Lambda(1520)$ peak in the K^+ missing mass; (Bottom) K^- missing mass, after analysis cuts, which shows the calculated background to the Θ^+ search due to $\Lambda(1520)$ production.

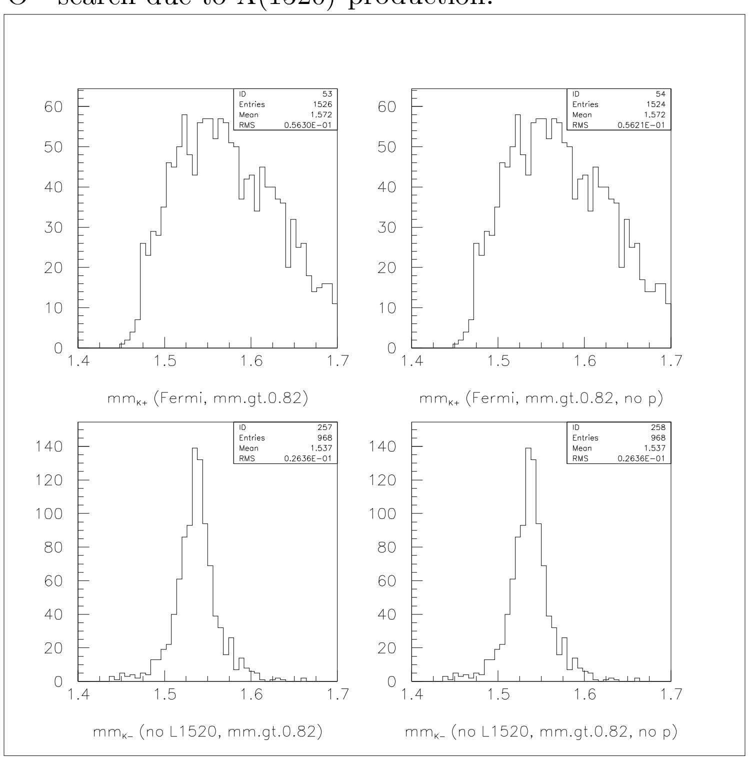

Figure 12: Monte Carlo with a phase-space $\Theta^+(1540)$ event generator, for the same analysis cuts as in the previous figure. (Top) K^+ missing mass, which is background for $\Lambda(1520)$ production; (Bottom) K^- missing mass showing the generated Θ^+ peak.

below 1.55 GeV (the $\Lambda(1520)$ cut), the acceptance for Θ^+ events is about 1.0% (based on 100,000 generated events). The extra requirement of a proton veto has almost no effect on these events, since there is no proton from the $\Theta^+ \rightarrow K^+n$ decay branch. Hence, the right panels have the same number of counts as the left panels, unlike the case for the $\Lambda(1520)$.

We note that the width of the Θ^+ peak is slightly narrower than for the $\Lambda(1520)$ case, but is still significant at about 25-30 MeV (FWHM). Here, the intrinsic width of the Θ^+ was assumed to be 15 MeV.

5.4 Sensitivity to the Production Mechanism

The assumption of an isotropic angular distribution is perhaps too naive. The $\Lambda(1520)$ and Θ^+ acceptances are roughly the same under the assumption that both are produced with isotropic angular distributions. However, previous studies of $\Lambda(1520)$ production [18, 19] show that the reaction mechanism is strongly forward-peaked. *Preliminary* simulation studies show that the acceptance for the $\Lambda(1520)$ under the assumption of an exponential t-dependent production mechanism is quite different than the acceptance an isotropic angular distribution. If the Θ^+ production mechanism is also non-isotropic, then its acceptance may also be affected.

One explanation of why the SPring-8 experiment sees statistically significance peaks for both the $\Lambda(1520)$ and the Θ^+ whereas the CLAS spectator reaction data does not, is that the acceptance ratio (Λ^*/Θ^+) for SPring-8 is likely to be different from CLAS. We do not yet have definitive data on the angular distribution for these reactions, and a significant increase in statistics at CLAS would allow angular binning of the data. Iteration between measured angular data and simulations with empirical angular distributions would allow a more precise estimate of the acceptances for these reactions. This could be the key to understanding the results hinted at by the g2 data.

6 Decay Angular Distributions

Measuring the angular distribution of the K^+n in the center-of-mass (CM) system is very important to establish the quantum numbers of the Θ^+ [16]. If the Θ^+ is indeed a $J^\pi = \frac{1}{2}^+$ resonance, then the K^+n must be in a relative p-wave. Assuming that the Θ^+ exists, we now proceed to examine assumptions about its decay angular distribution.

In the simplest case, where the Θ^+ has $J = 1/2$, the angular distribution of the K^+ is isotropic in the K^+n CM system. This is different from the case of the $\Lambda(1520)$, which has $J = 3/2$. In this case, the angular distribution has been measured [18, 19], and depends on the M-substate of the produced Λ^*. In general, for any $J = 3/2$ decay, the angular distribution for pure $M_J = 3/2$ is $0.75(1 - \cos^2\theta_K)$ where θ_K is the K^+ CM angle. However, if the decay proceeds via pure $M_J = 1/2$, then the angular distribution is given by $0.25(1 + 3\cos^2\theta_K)$.

If the beam ($J = 1$) and a target nucleon ($J = 1/2$) couple to $J = 3/2$ or $J = 1/2$ with equal probability, then simple angular momentum algebra gives the relative population of the M_J substates: the $M_J = 1/2$ substate is populated at 1/3 compared with the $M_J = 3/2$ state. Of course, the production mechanism complicates the picture, and for t-channel diagrams with K and K^* exchange, the relative populations of M_J substates can be different from the simple case given above. In general, see Ref.

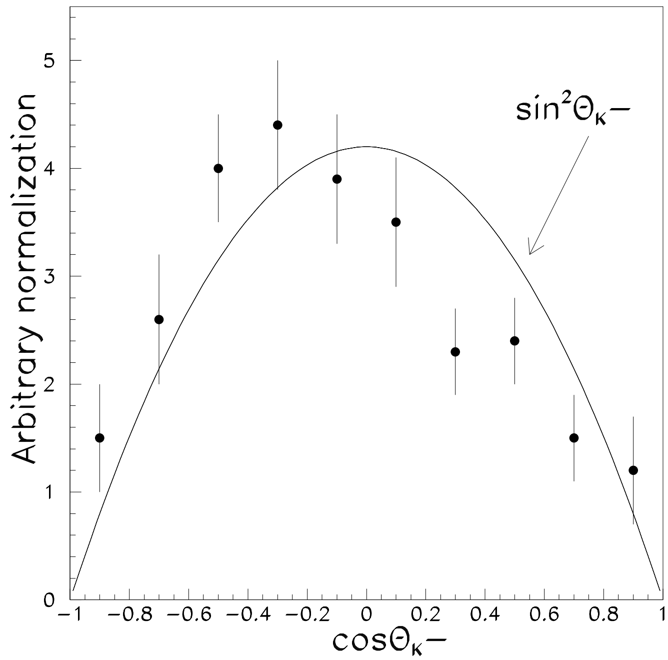

Figure 13: Decay angular distribution in the CM frame of the $\Lambda(1520)$ resonance from Daresbury. The general functional expected for a spin 3/2 resonance is given in the text.

[17], the CM decay angular distribution of a $J = 3/2$ particle will be given by:

$$A(1 - \cos^2\theta_K) + B(1 + 3\cos^2\theta_K),$$

where A and B are determined from the data.

While the decay angular distribution does not, by itself, determine the spin and parity of the Θ^+ resonance, it provides a valuable first step. If the angular distribution is isotropic, then this suggests that the Θ^+ would be $J = 1/2$, as predicted by the anti-decuplet [4]. The decay of the $\Lambda(1520)$, on the other hand, could be analyzed in the same way (using the K^- angle) and this non-isotropic decay could be compared with that for the Θ^+ decay. As an example, photoproduction data from the Daresbury Laboratory [18] is shown in Fig. 13. In this experiment, a total of 653 $\Lambda(1520)$ events were produced, integrated over all photon energies (2.8-4.8 GeV) and all angles, and these data are plotted in 10 angular bins. The evidence for the assignment of spin 3/2 to the $\Lambda(1520)$ is based on this decay angular distribution.

Of course, a substantial increase in the g2 statistics is necessary to carry out this kind of study for the Θ^+. For 8 angular bins, with a statistical accuracy on the order of 10%, then about 800 counts are needed. This amounts to over a factor of 20 increase in counts over that from the g2 data set.

7 Energy Distribution and Systematics

In addition to decay angular distribution, an increase in the statistics by a factor of 20 will enable many other investigations. In this section, we explore a few ways that increased statistics could help if clear evidence for the Θ^+ is found.

The energy distribution of the Θ^+ production could give valuable tests of theoretical predictions. Although these predictions are not yet available, theorists [16] are currently working on various reaction dynamics. If the Θ^+ production is flat or decreasing with photon energy (from threshold) and the background from non-resonant K^+K^- production increases with energy (as expected from phase space), then taking bins in the photon energy will help to reduce the background. On the other hand, preliminary results from the g2 data suggest that the exclusive channel cross section increases with photon energy. In any case, more statistics are necessary before we can deduce any possible energy dependence of the Θ^+ reaction mechanism.

Other systematic effects that are often investigated in CLAS are the sector dependence (azimuthal angle) and variations on cuts for the particle ID, fiducial volume, vertex position, and other angle/momentum regions of the detected particles. We have looked at these distributions briefly with the g2 data, but the limited statistics makes it difficult to conclude anything (except to say that there is no "hot spot" of Θ^+ production, *e.g.*, due to instrumental problems). A concerted effort to study the systematics uncertainties will require a large factor of increase in the statistics.

8 The N*(1710) Resonance

If the Θ^+ exists, then the other members of the anti-decuplet should also be present in nature, and predictions of their decays could be tested experimentally. Unfortunately, the width of the Σ and Ξ members of the anti-decuplet are expected to be large, and may be difficult to measure. On the other hand, the $N^*(1710)$, which serves to anchor the anti-decuplet masses, is still quite uncertain and further measurements from the neutron (in a deuterium target) would be helpful.

There have been many papers about extracting the N^* spectrum from partial-wave analysis, and many references are given in the PDG listing [6]. The primary reference used by the PDG is from Manley [20], which gives the $P_{11}(1710)$ with a total width of about 250 MeV, due in part to a large partial width into the $\pi\Delta$ decay channel. This contrasts sharply with the analysis of Cutkosky [21], who found a total width of about 90 MeV. In a more recent analysis by Manley, using better πN partial waves and also including γN reactions, the partial width to the $\pi\Delta$ channel has changed substantially from his 1992 paper [20, 23] (from $\sim$50% to $\sim$10% branching ratio).

It is safe to say that the $N^*(1710)$ is not clearly defined, and all analyses show that this resonance does not couple strongly to πN [24]. Since the database is dominated by πN final states, the resonance parameters are not easily extracted. However, the decay into the ηN and $K\Lambda$ channels is now thought to dominate the decay width, and measurements in these channels have recently been carried out at CLAS. Preliminary analysis of these data suggest [23, 24] that the role of the $N^*(1710)$ in the total cross section is not dominant.

In order to demonstrate this point, calculations from the KAON-MAID program with and without the $N^*(1710)$ are shown in Fig. 14 for both proton and neutron targets. In either case, there is little effect on the total cross section when the $N^*(1710)$ is removed from the calculation. This is due, in part, because the t-channel is known to dominate the total cross section for Λ production. However, when calculations are done for the differential cross section at $\theta^*_K = 90°$, far away from t-channel dominance, then removal of the $N^*(1710)$ has a large effect. We note that these calculations have been

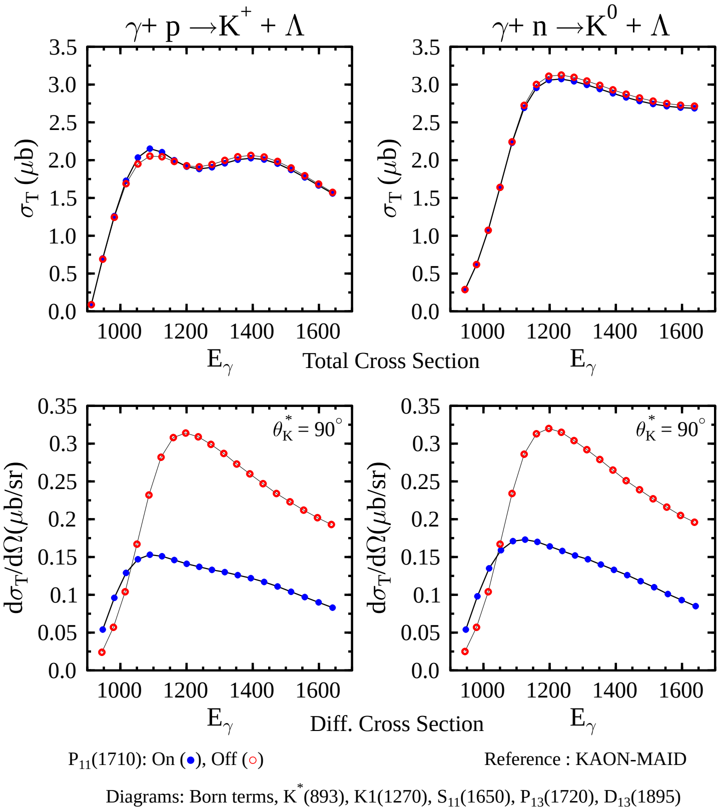

Figure 14: Calculations from the KAON-MAID program showing the effect of removing the $N^*(1710)$ from the reaction mechanism for $K\Lambda$ photoproduction. Total cross sections are shown on the top, and differential cross sections at 90° are shown on the bottom.

fit to the available data, and so the curves with the $N^*(1710)$ "On" represent the proton target data. (There is almost no data for Λ production from a deuteron target.) While this exercise only hints at the necessity of the $N^*(1710)$ in $K\Lambda$ photoproduction, it does suggest that further measurements in this channel (particularly from the neutron) would be helpful to improve our understanding of the $N^*(1710)$ resonance.

Other channels, such as $\gamma p \to \pi N$ and $\gamma p \to \eta p$ show weak coupling to the $N^*(1710)$. The coupled channel analysis of Dytman *et al.* [25] gives a branching ratio of the $N^*(1710)$ to ηN of only 6% ± 1%. On the other hand, a coupled channels analysis [22] of $\pi N \to \eta N$ and $\eta N \to \eta N$ suggests that the $N^*(1710)$ may have a large branching ratio to ηN (up to 89% ± 7%). A separate coupled channel analysis [23] of $\pi N \to \pi N$ and $\pi N \to \pi\pi N$ also found a strong ηN branching ratio (73% ± 16%). It is an interesting question why the photoproduction data [27] do not show strong coupling to the $N^*(1710)$.

The lack of a strong signal for $\gamma p \to N^*(1710) \to \eta p$ might be explained by a recent paper by Polyakov and Rathke [12] on photoexcitation of the anti-decuplet. Using symmetries from the chiral soliton model, they find that, to first order, the magnetic transition from the octet nucleon to the anti-decuplet $N^*(1710)$ is:

$$\mu_{NN*} = -(2T_3 - 1)\frac{1}{12\sqrt{5}}(v_1 + v_2 + 0.5v_3),$$

where the v_i are parameters of the theory. From this expression we see that reactions from the proton are suppressed (in fact, forbidden to first order) whereas the transition from the neutron is allowed. If this model is correct, then we need to analyze data from the neutron in order to test this prediction. If the symmetries that predict the Θ^+ from the anti-decuplet are correct, then the suppression of photoproduction to the $N^*(1710)$ from the proton should also be tested.

Possible evidence that photoproduction from the neutron is enhanced in the region of the $N^*(1710)$ comes from new η production data from GRAAL [28]. The ratio of total cross sections for η photoproduction are measured exclusively from protons or neutrons (in a deuterium target, with detection of the recoil nucleon). The preliminary results show a rising neutron/proton cross section ratio in the region of the $N^*(1710)$. Subsequent analysis with higher-energy photons indicate the cross section ratio falls again after the $N^*(1710)$ region. Again, this is only tentative evidence for the transition proposed by Polyakov and Rathke, but it suggests that more data at CLAS from a deuterium target could give valuable information on the role of the $N^*(1710)$ in photoproduction reactions from the proton compared with the neutron.

9 Count Rate Estimates

The g2a data set is used to estimate the expected statistics for this proposal. The online run data base provides the total integrated electron beam charge for all runs to be 9.5 mC over a data acquisition time of 9.4 days. During the run, the average beam current was approximately 10-12 nA. The target length was 10 cm, and the tagger radiator had a thickness of 10^{-4} radiation lengths.

From the analysis of the exclusive channel from the g2a data, a total of about 50 Θ^+ candidates were found by fitting the mass spectrum (see Fig. 10). Under these conditions, about 5.25 events of interest are produced for each mC of electron beam.

Since the proposed experiment will focus on the reconstruction of K^+K^- and K^+K^-p particles from a deuterium target, it is desired to have a 2-charged-particle trigger, such as the one used for the g6c run. In that run, a thicker radiator (3×10^{-4}) and a thicker target (18 cm long) were used, yet the DAQ trigger rate was only 2 kHz. The trigger efficiency, based on the number of reconstructed 2-track events, was close to 90%. We propose to use the same configuration as g6c, but with a 3 GeV beam. By extrapolating the DAQ rate and the number of reconstructed 2-track events (about 32% of the 1-track triggers have 2-tracks) in the g2a run, we estimate that with 15 nA of current, the DAQ rate will be a manageable 2.7 kHz. The expected total number of Θ^+ events under these new conditions would be:

$$N_{\Theta^+} = 50 \left(\frac{L}{10 \text{ cm}}\right) \left(\frac{RL}{10^{-4}}\right) \left(\frac{T}{9.4 \text{ days}}\right) \left(\frac{I}{11\text{nA}}\right),$$

where for our proposal we take $L = 18$ cm is the target thickness, $RL = 3 \times 10^{-4}$ is the radiator length, $T = 30$ is the time in days, and $I = 15$ nA is the beam current.

One important aspect of the experiment is to analyze the CM angular distribution of the K^+ from the Θ^+ decay, which will allow one to deduce the spin of the resonance. As shown in section 6, it will require at least 800 counts to get sufficient statistics to show whether the decay angular distribution is isotropic (spin 1/2) or non-isotropic (higher spin). In addition, these data will provide information on $K\Lambda$ production from the neutron in the region of the $N^*(1710)$. While measurements of the cross section alone will not be sufficient to do a partial wave analysis and hence separate the P_{11} channel from the other N^* resonances, these data from the neutron will provide new information and perhaps test the prediction of the chiral soliton model that $N^*(1710)$ production is suppressed from proton targets.

This proposal requests 30 days of beam time to run with a 3 GeV electron beam in the tagged photon configuration of CLAS, with an 18 cm liquid-deuterium target. The torus magnet would run in the standard full-field setting. The expected number of counts in the same energy range as for the g2a data for the full energy region is about 1200 events. This would be sufficient to conclusively demonstrate (or refute) the existence of the Θ^+.

10 Summary

The Θ^+ resonance, if it exists, has important consequences for QCD. First, it hints at a richer spectrum of N^* resonances in general, and second it would be the first candidate for the pentaquark that is not just a trivial 3-quark plus $q\bar{q}$ sea-quark wavefunction. If it is actually the object predicted by Diakonov *et al.*, then it is important to gather sufficient statistics to measure its properties and guide the theoretical understanding of the reaction dynamics that could produce it. The evidence so far from SPring-8, ITEP and the exclusive analysis of the g2 data set at CLAS suggest that a narrow resonance with strangeness $S = +1$ exists and has a mass close to that predicted for the Θ^+. It is important that CLAS pursue this topic and make a conclusive measurement that either confirms or denies the existence of this $S = +1$ resonance. Assuming the count rates from the g2 data are correct, then the proposed experiment could also measure the decay angular distribution and energy dependence of this resonance. There measurements will test the prediction that the Θ^+ has spin 1/2 and determine its production cross section. We request **30 days of beam high priority** for this experiment so that it can be done in a timely fashion and, with the analysis machinery already in place, can be rapidly communicated to the physics community.

References

[1] F. Halzen and A. Martin, *Quarks & Leptons*, John Wiley & Sons, New York, 1985, Chapter 9.

[2] K. Joo *et al.*, Phys. Rev. Lett. **88**, 122001 (2002).

[3] Harry J. Lipkin, in *Intersections Between Particle and Nuclear Physics*, AIP Conf. Proc. **150**, p. 657, 1986.

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

[5] T. Nakano *et al.*, e-print arXiv: hep-ex/0301020.

[6] The Particle Data Group, Phys. Rev. D **45**, No. 11 (1992) p. VIII.58.

[7] J.K. Ahn, *et al.*, PANIC contributed talk, in press.

[8] J.C. Nacher, E. Oset, H. Toki and A. Ramos, Phys. Lett. B **455**, 55 (1999).

[9] J.S. Hyslop, R.A. Arndt, L.D. Roper and R.L. Workman, Phys. Rev. D **46**, 961 (1992).

[10] K. Hicks *et al.*, *Search for a $S = +1$ Z^+(1530) Resonance at CLAS*, October 24, 2002.

[11] A.G. Dolgolenko, private communication; V.V. Barmin *et al.*, talk at the Russian Academy of Sciences, Dec. 3, 2002 (to appear in Yad. Fiz.).

[12] M.V. Polyakov and A. Rathke, eprint arXiv: hep-ph/0303138.

[13] E. Smith, *Fermi Momentum Correction in Deuterium*, CLAS note 03-003 (2003).

[14] V. Koubarovski, CLAS analysis note 2003-102.

[15] E.M. Aitala *et al.*, FERMILAB-Pub-97/118-E; see also hep-ph/9407319.

[16] Dmitri Diakonov, private communication.

[17] S. Gasiorowicz, *Elementary Particle Physics*, Wiley, New York, 1966, Chapter 19, p. 289-312.

[18] D. Barber *et al.*, Z. Phys. C **7**, 17 (1980).

[19] S.P. Barrow *et al.*, Phys. Rev. C **64**, 044601 (2001) and references therein.

[20] D.M. Manley and E.M. Saleski, Phys. Rev. D **45**, 4002 (1992).

[21] R.F. Cutkosky and S. Wong, Phys. Rev. D **42**, 235 (1990).

[22] Batinic *et al.* Phys. Rev. C **51**, 2310 (1995).

[23] M. Manley, private communication.

[24] R.A. Arndt, I.I. Strakovsky, R.L. Workman, and M.M. Pavan, in preparation, to be submitted to Phys. Rev. C.

[25] T.P. Vrana, S.A. Dytman and T.-S.H. Lee, Phys. Rep. **328**, 181 (2000).

[26] F.X. Lee *et al.*, Nucl. Phys. A **695** 237 (2001); see *www.kph.uni-mainz.de/MAID/kaon/kaondmaid.html*.

[27] M. Dugger *et al.*, Phys. Rev. Lett. **89** 222002 (2002).

[28] V. Kousznetsov, "First results on eta photoproduction on the neutron at GRAAL", Proceedings of the N* 2002 Conference, Pittsburgh, October 2002.