# Search for the $\Xi_5^{--}$ pentaquark

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## Abstract

We propose to search for the $\Xi_5^{--}$ pentaquark in the reaction $\gamma d \to K^+K^+p\,\Xi_5^{--}$. The $\Xi_5^{--}$ is identified by the $(K^+K^+p)$ missing mass in the $\gamma d \to K^+K^+pX$ process. The detector is the CLAS spectrometer surrounding an 18cm liquid $D_2$ target. The missing mass technique has been proven to be successful in our measurements of the $\Xi^-$ and its excited states in $\gamma p \to K^+K^+\Xi^-$, also with the CLAS detector. For $E_e = 5.7\,\mathrm{GeV}$, we expect approximately 180 $\Xi_5^{--}$ events in a ten-day run if its mass is 1862 MeV as claimed by NA49. This will enable us to determine the mass of the $\Xi_5^{--}$ to an accuracy of 2 MeV or better, set an upper limit on the width of $15-20$ MeV, and make the first measurement of the energy dependence and angular distribution for $\Xi_5^{--}$ photoproduction for comparison with $\Xi^-$ photoproduction data.

If a beam energy of 5.7 GeV is not available in a timely manner (as suggested by the JLab management), an interesting alternative to the preferred conditions will enable us to determine whether a deuterium target is substantially better than a proton target for $\Xi$ measurements, as indicated by theory. By raising the beam energy to 5.0 GeV, the *g10* run of the approved experiment E03-113 scheduled to run in Spring 2004 is compatible with $\Xi_5^{--}$ photoproduction. To compensate for the expected reduction in yield at higher $E_e$, we ask that this run be extended by ten days. In this combined run, we expect a total of $35-40$ $\Xi_5^{--}$ events, which would be enough to confirm the status of the $\Xi_5^{--}$.



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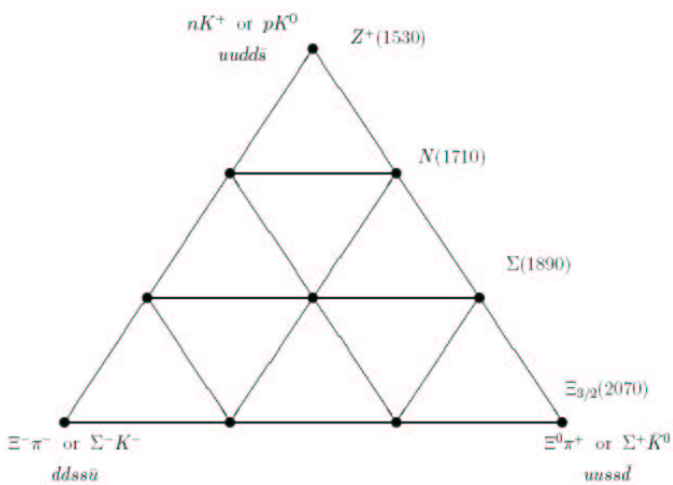


Figure 1: The antidecuplet predicted by Ref. [7]. The $Z^+(1530)$ is today identified as the $\Theta^+(1540)$. NA49 [8] claims to have seen the $\Xi_5^{--}$ and the $\Xi_5^0$ with a mass of 1862 MeV.

## I. INTRODUCTION

The recent discovery of the $\Theta^+$ [1–6] has caught the imagination of the nuclear physics community. This particle, part of an antidecuplet predicted by Diakonov et al. [7], has exotic quantum numbers, and cannot be a three-quark state. The minimal quark configuration for this state is $uudd\bar{s}$. Fig. 1 shows the structure of the antidecuplet. The $Z^+(1530)$ state at the apex of the antidecuplet is today identified as the $\Theta^+(1540)$. Among the other nine members of the antidecuplet, seven look like three-quark states and can mix strongly with them; only the $\Xi_5^{--}$ and the $\Xi_5^+$ have exotic quantum numbers which preclude their existence as $qqq$ states. It is important to find these manifestly exotic states and to measure their properties, such as mass, width, $J^P$, decay modes, angular distribution, and excitation function, to help understand the nature of their structure. Following the suggestion of [9], we will use the notation "$\Xi_5$" to refer to cascade pentaquarks. The subscript "5" refers to the five quarks in the pentaquark. A recent measurement from CERN [8] reports the observation of two states at 1862 MeV with the quantum numbers of the $\Xi_5^{--}$ and $\Xi_5^0$ in a $4-6\sigma$ peak. They have been tentatively identified as the $\Xi_5^{--}$ and $\Xi_5^0$ members of the antidecuplet. The investigation of this signal is high priority research.

Table I: The CLAS data sets used to study $\Xi$ photoproduction. The normalization of the *g6b* data set is poorly known. Note that the electron endpoint energy $E_e$ is approximately 5% higher than the highest photon energy in the data set.

| Set | $E_\gamma$(GeV) | $I_e$ (nA) | Radiator | $z_{tgt}$(cm) | $\int \mathcal{L}dt$ ($pb^{-1}$) |
|---|---|---|---|---|---|
| *g6a* | $3.2 - 3.9$ | $45 - 50$ | $10^{-4}$ | 0 | 1.1 |
| *g6b* | $3.0 - 5.2$ | $35 - 45$ | $10^{-4}$ | 0 | |
| *g6c* | $4.8 - 5.4$ | $40 - 50$ | $3 \times 10^{-4}$ | $-100$ | 2.7 |

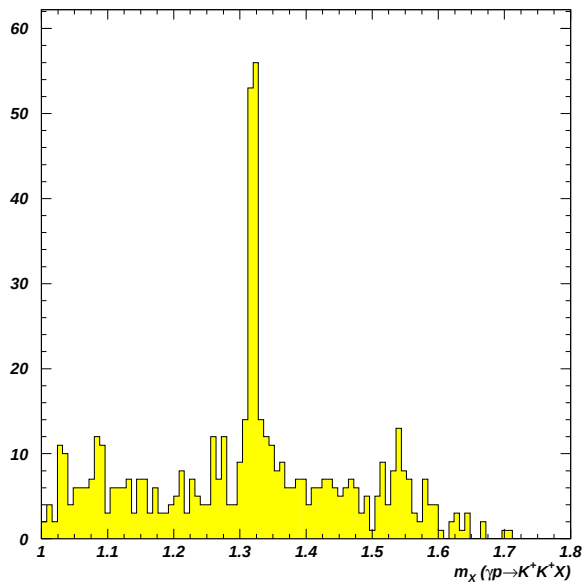


Figure 2: The $(K^+K^+)$ missing mass in the reaction $\gamma p \to K^+K^+X$ from the *g6a* data set (see Table I for the run parameters). The ground state $\Xi^-(1321)$ is clearly seen over a small background, and another enhancement at 1530 MeV marks the position of the first excited cascade state.

## II. ANALYSIS METHOD

We plan to look for the cascade pentaquarks in the $K^+K^+p$ missing mass spectrum of the $\gamma d \to K^+K^+p(\Xi_5^{--})$ reaction. We have successfully used the missing mass technique to measure the process $\gamma p \to K^+K^+\Xi^-$ [10]. We will quote results of our investigations in several places in this proposal using three CLAS data sets: *g6a*, *g6b*, and *g6c*. The run parameters are given in Table I. Fig. 2 shows the quality we can obtain with this method. An important question is whether this technique can also be used on a neutron target. For this measurement, we wish to use a deuterium target. We want to detect the two $K^+$'s and

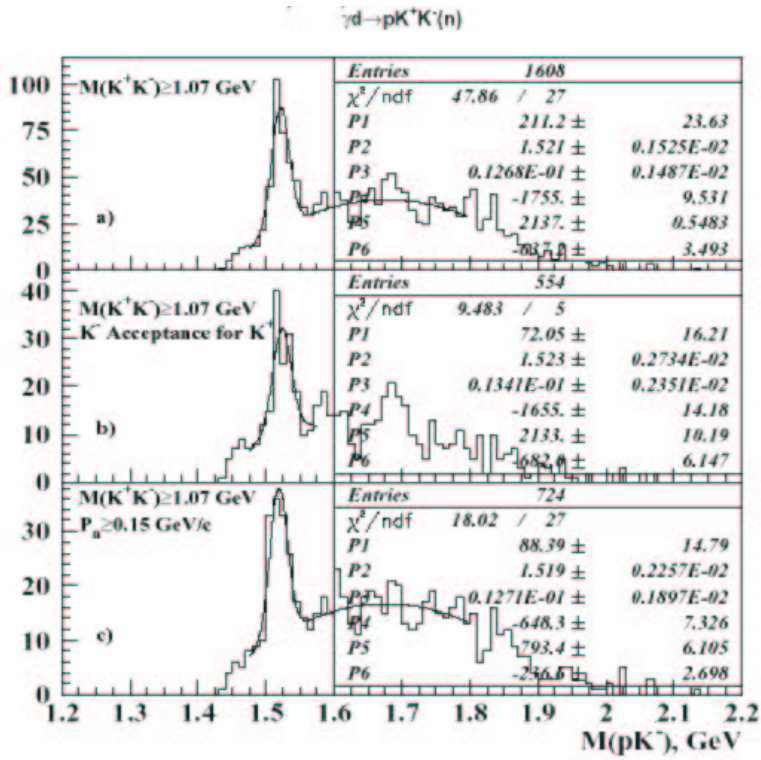


Figure 3: The invariant mass of the $K^-p$ system in the process $\gamma d \to K^-K^+pn$, as measured by CLAS. (a) Events are selected by removing events consistent with $\phi \to K^+K^-$. (b) The same distribution for events in which the $K^+$ is within the measured acceptance for $K^-$, showing the expected reduction in yield for the $\Theta^+$ due to geometric acceptance. (c) The same distribution for events in which the neutron momentum is larger than the expected tail from Fermi momentum in the deuteron.

the spectator proton and look at the missing mass of the $K^+K^+p$ system. The acceptance is boosted by the $K^+p$ final-state interaction to give the proton enough momentum to be detected in CLAS.

The idea of detecting a rescattered spectator nucleon in CLAS has been successfully used in the $\Theta^+$ photoproduction process $\gamma d \to K^-p\Theta^+ \to K^-pK^+n$. In this case, the neutron was identified by missing mass. Having detected all particles in the event either directly or indirectly, the $\Theta^+$ was inferred by the missing mass of the $K^-p$ system. To study the efficiency for detecting a rescattered nucleon, Stepanyan *et al.* [11] looked at the photoproduction of the $\Lambda(1520)$ on the deuteron. Fig. 3 from [11] shows the $K^-p$ invariant mass distribution before (a) and after (c) requiring that the spectator nucleon (the neutron

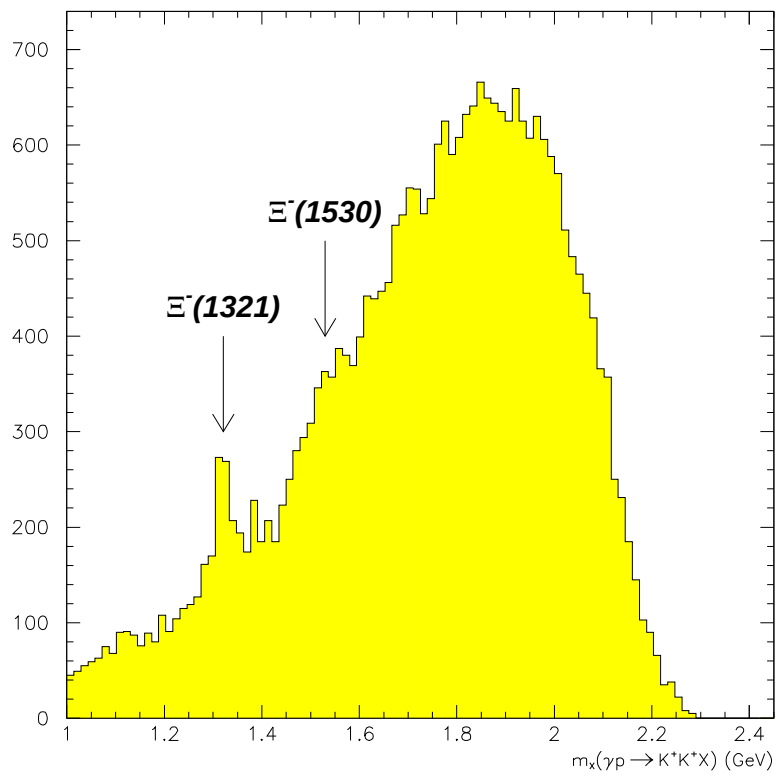


Figure 4: The missing mass in the process $\gamma p \to K^+K^+X$ for the *g6c* data set (see Table I for the run parameters). The large background is due in part to the large $\pi/K$ misidentification. The ground state $\Xi^-$ is clearly seen in the plot, but the $\Xi^-(1530)$ appears only as a shoulder.

in this case) have a momentum larger than that expected by a Fermi distribution. As seen in the figure, the yield is approximately 40% of the total yield.

The main physics background to this process is $\gamma d \to K^+\phi p\Sigma^-$, followed by $\phi \to K^+K^-$. The $K^+K^+$ missing mass in this case will be the invariant mass of the $K^-\Sigma^-$ system. This spectrum is not expected to peak.

The non-physics background comes in part from $\pi/K$ misidentification. It was studied in our analysis of $\gamma p \to K^+K^+\Xi^-$ in the *g6c* data set [12]. Fig. 4 shows the raw $K^+K^+$ missing mass. The large background due to $\pi/K$ misidentification washes out most of the features in the plot. The misidentification of a single $\pi^+$ as a $K^+$ results in the final state $K^+\pi^+\Sigma^- \to K^+\pi^+\pi^-n$. Misidentifying two $\pi^+$ as $K^+$ results in a $\pi^+\pi^+\Delta^- \to \pi^+\pi^+\pi^-n$ final state. The effect of one misidentification may be seen in Fig. 5, which shows the missing mass plot from the *g6b* data run. Since both the $\Sigma^-$ and the $\Delta^-$ decay exclusively to $n\pi^-$, we can remove these backgrounds entirely by requiring a proton in the final state from the

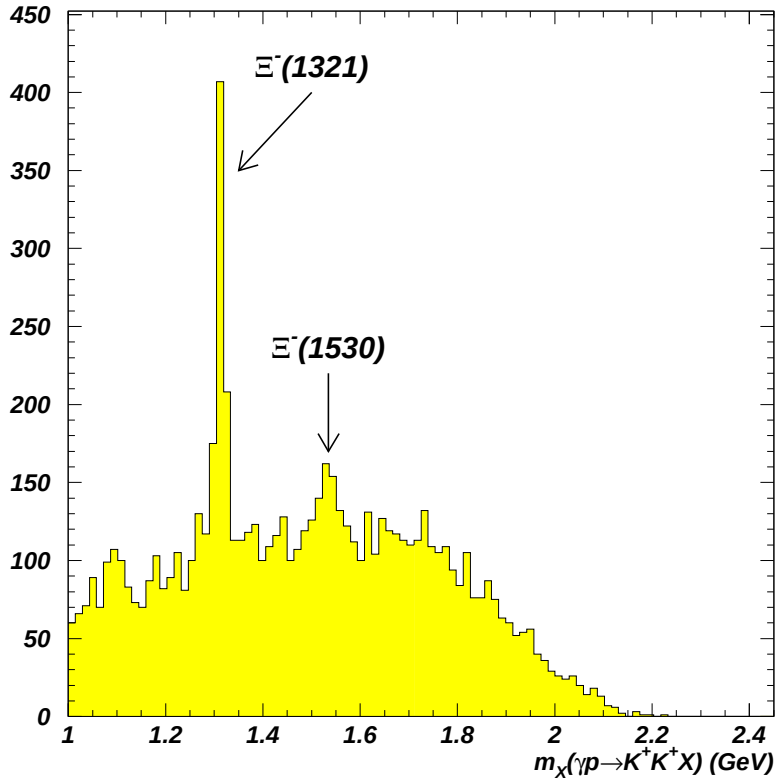


Figure 5: The $K^+K^+$ missing mass in $\gamma p \to K^+K^+X$ from the *g6b* data set (see Table I for the run parameters). Both the ground state $\Xi^-(1321)$ and the first excited state $\Xi^-(1530)$ are clearly seen. The structure at 1.1 GeV is due to the process $\gamma p \to K^+\pi^+\Sigma^-$, where the $\pi^+$ is misidentified as a $K^+$.

decay chain $\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$. Fig. 6 shows the result of such a cut. The background due to $\pi/K$ misidentification has been removed, and a great deal of structure is revealed at the price of fewer events. Another source of background is the misidentification of the beam photon associated with the event. This is in part responsible for the large background in Fig. 4. It will be much reduced by a new start counter, which will determine the vertex time much more precisely than the current detector allows.

## III. KINEMATICS

Although CLAS, with a maximum photon energy of approximately 5.4 GeV (based on an electron energy of 5.7 GeV) can produce a $\Xi_5^{--}$ as heavy as 2.3 GeV in the process $\gamma d \to K^+K^+p\,\Xi_5^{--}$ (assuming zero Fermi momentum), such a state is not detectable with

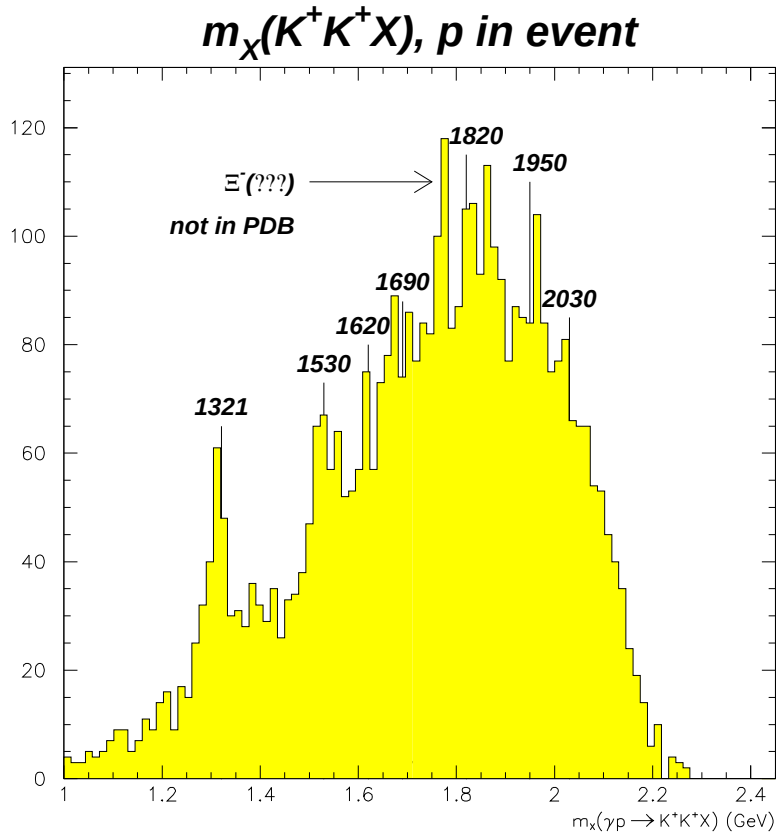


Figure 6: The same plot as in Fig. 4, with the requirement that the final state includes a decay proton. This cut reveals a large amount of structure in the plot, and has an enhancement at every Ξ state listed in the Particle Data Book up to 2030 MeV. There are two additional structures, at 1770 and 1860 MeV, that are still under study.

this method. To understand this, recall Fig. 2, which shows the $(K^+K^+)$ missing mass for $\gamma p \to K^+K^+X$ from the *g6a* data set, which had a maximum photon energy of 3.9 GeV. Based solely on kinematics, the maximum possible missing mass for these conditions is approximately 1880 MeV. However, the phase space of the plot dies out much earlier, at around 1700 MeV. The reason for this difference is that in order to be detected by the CLAS toroidal spectrometer, the two $K^+$'s have to have enough perpendicular momentum to be within the CLAS acceptance. From our experience with the cascade program, we have developed a rule of thumb, namely one needs roughly an extra 250 MeV in the c.m. in order to see a particle; note that a hint of the $\Xi^-(1530)$ appears to be showing in Fig. 2. Thus, in the process $\gamma d \to K^+K^+p\,\Xi_5^{--}$, we would expect to have good sensitivity to a mass as high as 2.0 GeV for the $\Xi_5^{--}$ for the highest energies available at JLab.

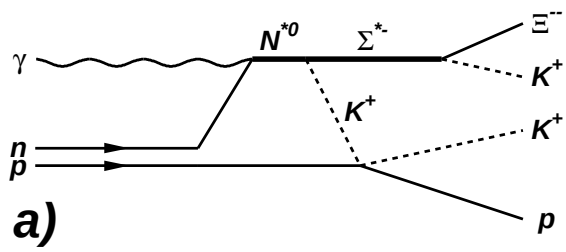


Figure 7: A possible Feynman diagram for $\Xi_5^{--}$ photoproduction on the neutron. The proton rescatters and is subsequently detected.

## IV. PRODUCTION REACTIONS

If $\Xi_5$ pentaquarks exist, they may be seen in a number of reactions. We propose to look at as many of these as possible, although the most promising is the process $\gamma d \to K^+K^+p\,\Xi_5^{--}$. Experimentally, we will detect the two $K^+$ and the spectator proton, much the same as in [3]. We will look for the $\Xi_5^{--}$ in the missing mass of the $K^+K^+p$ system. If the NA49 claim of 1862 MeV for the mass of the $\Xi_5^{--}$ is correct, the threshold photon energy $E_\gamma^{th}$ for this process is 3.9 GeV. Fig. 7 shows a possible Feynman diagram for this process.

## V. EXPERIMENTAL POSSIBILITIES

We envision a series of measurements of the cascade pentaquark. Initially, the most important question to be answered is whether or not it actually exists; thus far, only the NA49 collaboration has claimed to have seen it. What is needed as soon as possible is a confirming measurement. We would like to use our proven method with the missing mass technique to perform such a search.

Ideally, we would use the highest photon energy available with the highest electron current the detector can handle. However, since the urgency of this measurement is great, we must also consider the possibility of using a lower beam energy if it will allow us to run earlier, even if it means that we must take beam at less than optimal conditions. A successful run would encourage us to consider a later run to study the properties of the $\Xi_5$ using a deuterium target. We see the following options for this experiment:

1. A high-energy, high-current run on a deuterium target. Ideal running conditions would be a 50nA beam with an endpoint energy of 5.7 GeV on a $3 \times 10^{-4}$ radiator. In ten

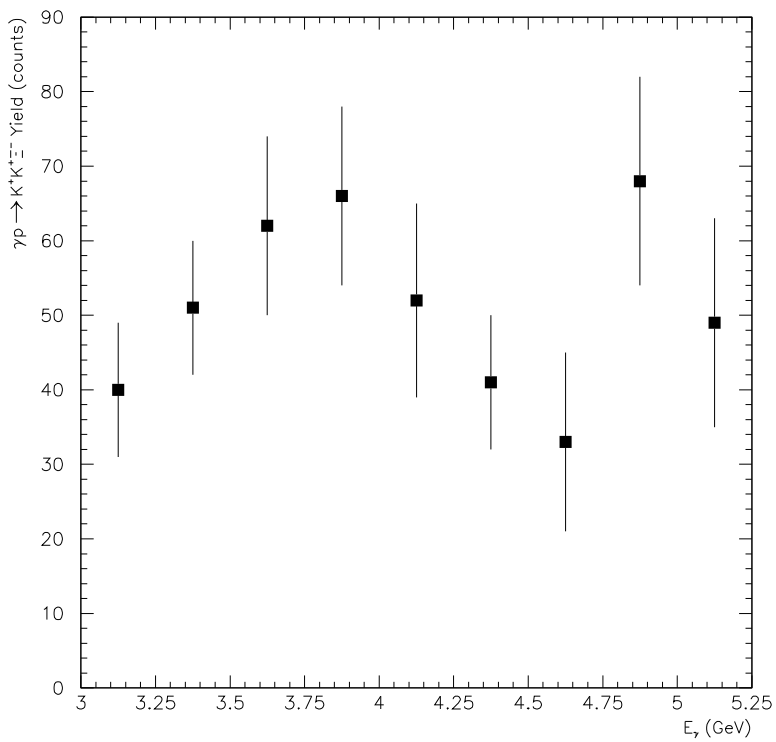


Figure 8: The total yield for $\gamma p \rightarrow K^+K^+\Xi^-$ as a function of photon energy $E_\gamma$ for the *g6b* data set (see Table I for the run parameters). The points reflect the actual number of detected events in each 250 MeV bin, and have not been corrected for either acceptance or photon normalization.

days, such a run could obtain as many as 180 detected $\gamma d \rightarrow K^+K^+p\,\Xi_5^{--}$ events (see below for a discussion of the counting rate). For such a run, we would need to modify the CLAS start counter in order to improve the $\pi/K$ separation. Such a modification is already being planned for the "super-g" run. With these statistics, we could make a coarse measurement of the energy dependence and angular dependence for $\Xi_5$ photoproduction, which will help in understanding the production mechanism for $\Xi_5$ photoproduction. Fig. 8 shows the yield plot for the *g6b* data set; Fig. 9 shows the angular distributions for the *g6a* and *g6b* data sets. Note that Fig. 8 was created by binning Fig. 5 into nine new histograms. Each of these new histograms represents an independent measurement of the mass of the $\Xi^-$; by fitting the position of the peak for each plot, we may make a more precise statement about the mass of the $\Xi$. Fig. 10 shows the measured centroid of the missing mass peak in the *g6b* data set after splitting the data into nine 250 MeV-wide bins. There are known energy loss and momentum corrections which have not yet been applied to the data, which leads to a

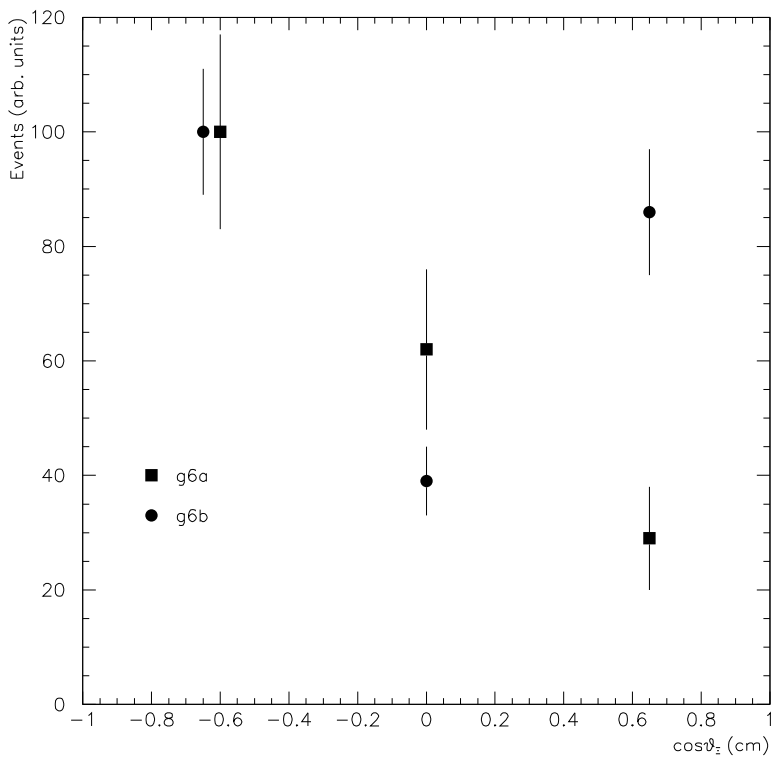


Figure 9: The angular distribution for the *g6a* (squares) and *g6b* (circles) data sets. See Table I for the run parameters. The event numbers are arbitrarily normalized.

slightly lower value of the mass. However, the fact that the mass is very stable over a 2.2 GeV range indicates that this is not a kinematic reflection, and also indicates that once all the corrections are made, that our final mass should be good to within 2 MeV.

2. As it is likely that a high energy beam and an improved start counter will not be available soon, we may also consider a longer run at lower energy with the existing detector. We will obtain fewer events, but we should still be able to make a conclusion on the status of the $\Xi_5^{--}(1862)$. We estimate that with the present detector, we will be limited to 15nA. Under these conditions, with a 5.0 GeV electron beam, we would expect to see nearly 40 events in a 40-day run.

There is an approved experiment, *g2c*, scheduled to take 30 days of beam at 4.0 GeV for E03-113, a study of the $\Theta^+$ pentaquark. As an alternative to option #2 above, we could use this beam time as well, but in order to be compatible with a search for cascade pentaquarks, we must raise the accelerator energy to 5.0 GeV.

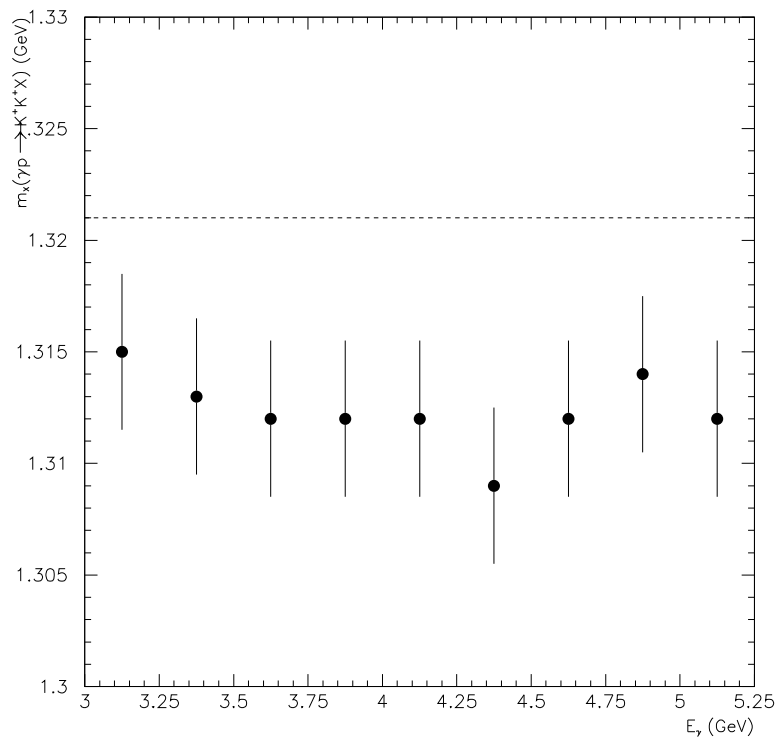


Figure 10: The dependence of the uncorrected mass of the $\Xi^-$ ground state missing mass peak with photon enregy. The y-values of the points are the centroids of the peaks in the missing mass plots for $\gamma p \rightarrow K^+K^+X$, for $E_\gamma$ in 250 MeV-wide bins. The uncertainty in the y-axis is set to 25% of the bin width of the missing mass plot. Energy loss and momentum corrections have not yet been applied to the data, which leads to a slightly lower (about 9 MeV) value of the mass. The dashed line shows the accepted value of the mass of the $\Xi^-$ ground state of 1.321 GeV.

The spokesmen of E03-113, Ken Hicks and Stepan Stepanyan, agree that the importance of this measurement justifies running it with their experiment. However, if they run at 5.0 GeV instead of 4.0 GeV, they anticipate having a lower counting rate due to a smaller cross section at high energy. To compensate for this, we ask for an additional ten days of running time to compensate for the lower $\Theta^+$ yield. Their agreement to run at higher energy is contingent upon receiving the extra beam time.

## VI. COUNT RATES

To estimate the number of detected events $N_e$ for this experiment, we use the following formula:

$$N_e = \int_{E_\gamma^{lo}}^{E_\gamma^{hi}} N_t N_b(E_\gamma)\sigma(E_\gamma)A(E_\gamma)dE_\gamma, \tag{1}$$

where the various terms are detemined as follows.

- $E_\gamma$ is the photon energy (with $E_\gamma^{lo}$ and $E_\gamma^{hi}$ being the range of photon energies in the experiment). We assume that this variable ranges from the threshold for production to the maximum accessible by the tagger.

- $N_t$ is the number of target particles. For an 18cm $LH_2$ target, this is $7.3 \times 10^{-10}\, nb^{-1}$.

- $N_b$ is the number of beam particles. For our option #1 (50nA beam with a $3 \times 10^{-4}$ radiator), the total photon flux is $(50nA)(3 \times 10^{-4})/(1.6 \times 10^{-19}\frac{C}{e}) = 9.38 \times 10^7 \frac{\gamma}{s}$. We assume a $1/E$ bremsstrahlung spectrum, with a minimum energy of 100 MeV. Based on an accelerator energy of 5.7 GeV, we obtain the formula $N_b = 2.00 \times 10^{12}/\left[E_\gamma(\text{GeV}) - \text{day}\right]$. For the E03-113 running conditions, a similar calculation gives $N_b = 6.21 \times 10^{11}/\left[E_\gamma(\text{GeV}) - \text{day}\right]$.

- $\sigma$ is the cross section. This was estimated by Liu [13], who used an SU(3) hadronic model with a U(1) gauge photon to estimate the cross sections for the reactions $\gamma n \to K^+K^+\Xi_5^{--}$ and $\gamma p \to K^0K^0\Xi_5^+$. This is the first-ever calculation of the cross section for the photoproduction of the $\Xi_5$. He finds that the dominant production mechanism for $\Xi_5^{--}$ photoproduction is charged kaon exchange, while for the $\Xi_5^+$ it is $K^*$ exchange. Consequently, $\Xi_5^+$ photoproduction is strongly dependent on the value of the $g_{K^*N\Xi}$ coupling constant, while $\Xi_5^{--}$ photoproduction is largely independent of its value. Using a value for this coupling of 1.8, he finds that $\Xi_5^{--}$ photoproduction on the neutron is about an order of magnitude larger than $\Xi_5^+$ photoproduction on the proton. His results are shown in Fig. 11.

- $A$ is the CLAS acceptance. We used a phase-space event generator to produce $\gamma n \to K^+K^+\Xi_5^{--}$ events, which we then ran through the CLAS GSIM simulation. These events were then analyzed using the same analysis program we used to look at the process $\gamma p \to K^+K^+\Xi^-$. From this analysis, we calculated an acceptance of

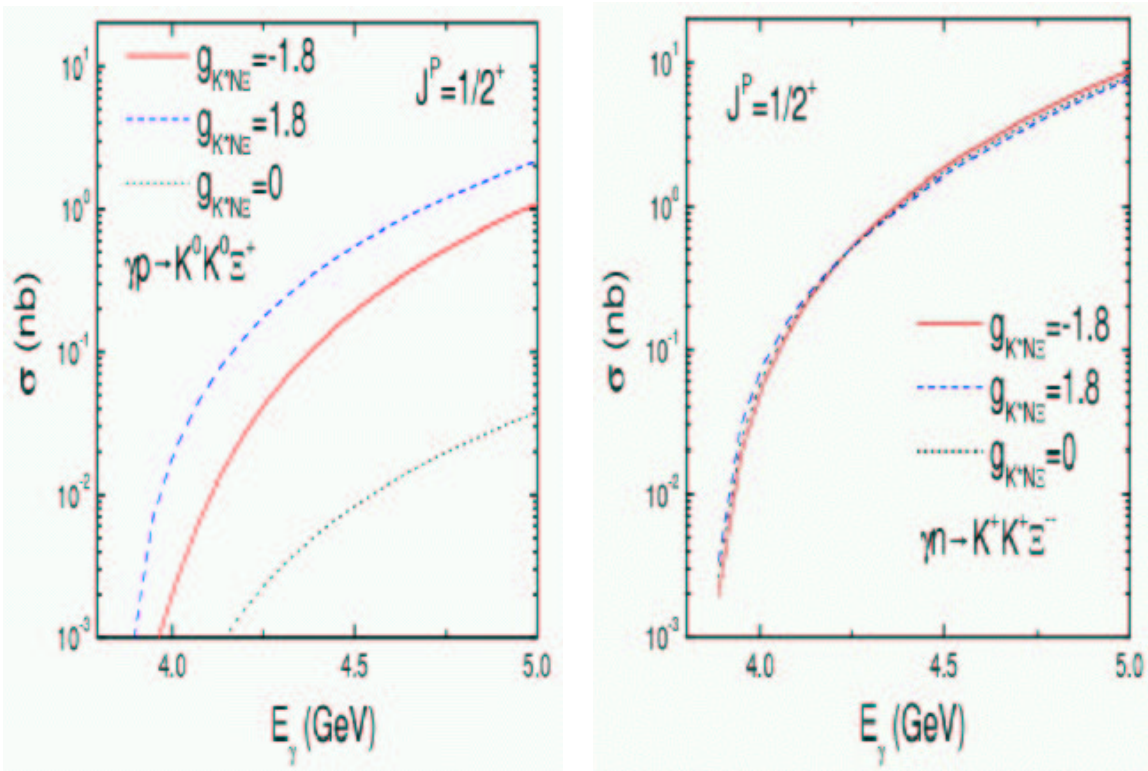


Figure 11: Calculated cross sections for $\gamma p \to K^0 K^0 \Xi^+$ (left) and $\gamma n \to K^+ K^+ \Xi^{--}$ (right), from [13].

approximately 0.5% near the threshold, rising to approximately 2% at the endpoint energy. Further acceptance studies of this process using more realistic event generators are underway.

We numerically integrated Eq. 1, and plotted the results in Fig. 12. By integrating the area under the curve, we estimate the production of 458 events under our "optimal" conditions, and 84 events under the *g10* conditions. These numbers are before taking into account the detection of the spectator proton. Modifying these numbers by the 40% factor mentioned above, we expect to see 180 events for $E_e = 5.7$ GeV for ten days, or 35 events for a 40-day run at 5.0 GeV with E03-113.

## VII. BACKGROUND ESTIMATES

As previously discussed, the largest physics background is due to $\phi$ production, as in the process $\gamma n \to K^+ \phi \Sigma^-$. Non-physics backgrounds are dominated by $\pi/K$ misidentification.

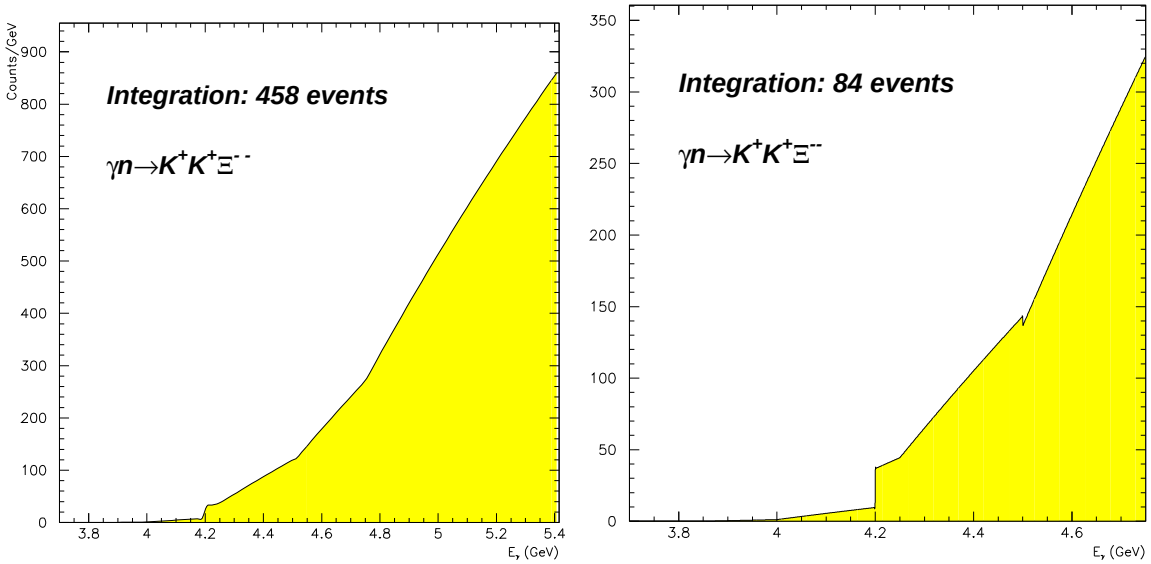


Figure 12: Numerical integration of Eq. 1 under two possible sets of running conditions for this experiment. The left plot shows the expected number of events if we take a 50nA beam for a ten-day run, while the right plot shows the results using the conditions of the *g10* run with ten extra days. The numbers given in the plots are before detecting the spectator proton.

The detailed effects of these backgrounds on our measurement are expected to be small, and are currently under investigation.

## VIII. TRIGGER

If we run with experiment E03-113, we expect to use the *g10* trigger of two charged particles in CLAS. Exeriment E03-113 estimates that using a 4.0 GeV beam of 15nA with a $3\times10^{-4}$ radiator incident on an 18cm liquid deuterium target, that the total DAQ rate should be 2.7 kHz. By raising the beam energy to 5.0 GeV, we anticipate that the DAQ rate will increase somewhat, but will still be below the total acceptable DAQ rate of approximately 3.5 kHz. With a beam energy of 5.7 GeV and beam current of 50 nA, we will use the new start counter being proposed by Weygand *et al.*, along with the same triggering scheme of three charged particles in CLAS. Since the $\Xi_5$ decays into several charged particles, requiring three particles in the new start counter should not adversely affect our triggering efficiency. For this trigger, Weygand *et al.* anticipate a real trigger rate of approximately $1-2$ kHz, with a total trigger rate of about $2-3$ kHz, which is within the capabilities of the DAQ.

Table II: Options for an experiment on $\Xi_5$ photoproduction. The radiator in each case is $3 \times 10^{-4}$; the target positions are still under study. Note that option 2 represents a run in parallel with *g10*.

| | $E_e$ (GeV) | $I_e$ | Time (days) | $\int \mathcal{L}dt$ ($pb^{-1}$) | $N_{\Xi_5^{--}}$ |
|---|---|---|---|---|---|
| 1 | 5.7 | 50 nA | 10 | 60 | 180 |
| 3 | 5.0 | 15 nA | 10 added to *g10* | 70 | 35 |

A similar estimate has not yet been done for a deuterium target, but we do not expect the rate to be substantially higher.

## IX. SUMMARY

We summarize the options for this proposal in Table II. The management of Jefferson Lab has stated that the confirmation of the $\Xi_5$ state found by NA49 is among their highest priorities. By looking for this particle in the $K^+K^+p$ missing mass in the reaction $\gamma d \to K^+K^+p\,\Xi_5^{--}$, we make use of a proven successful technique. The feasibility of this method has been demonstrated in our photoproduction measurements of the $\Xi^-$ and its excited states, as shown in Figs. 2 and 6. This method is fundamentally different from that employed by NA49. The counting rate depends strongly on the electron endpoint energy; higher energies result in higher counting rates. Based on the expected higher cross section on the neutron and our ability to make an exclusive measurement, the target of choice is deuterium. We estimate that a ten-day run at high energy and current could result in 180 events, if the CLAS start counter is replaced.

An alternative, prompted by the possible early availability of beam time and the urgency of this measurement, is to run together with E03-113, with the electron energy raised to 5.0 GeV. We may compensate for an expected lower cross section at high energies by extending the *g10* run by ten days. For such a run, we anticipate obtaining approximately 35 events.


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