Background study for the pentaquark search in the reaction $\gamma p \rightarrow \pi^+ K^- K^+ n$

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Abstract. A narrow baryon state with strangeness $S=+1$ and mass $M = 1555 \pm 10$ MeV/$c^2$, reported by the CLAS collaboration in the reaction $\gamma p \rightarrow \pi^+ K^- K^+ n$, has been observed at Jefferson Lab using a tagged photon beam with an energy range of 3-5.47 GeV. A thorough investigation on whether background processes, such as $\pi_2(1670)$ production, can reflect into the possible $\Theta^+$ peak was conducted by performing a partial wave analysis on the three-body mesonic background in the energy range of 4.8-5.47 GeV. The analysis also probes other possible processes, and does not find evidence for the observed signal being a result of kinematic reflection.

1. $\Theta^+$ photo-production on the proton target
A possible signal of the exotic $\Theta^+$ baryon photo-produced on a proton target in the reaction $\gamma p \rightarrow \pi^+ K^- K^+ n$ was reported by CLAS [1] and by SAPHIR [2] in the reaction $\gamma p \rightarrow K_s K^+ n$. Combined with other observations of the $\Theta^+$, there is compelling evidence for the existence of a pentaquark state. However, all positive results suffer from low statistics, and very few have demonstrated that the signals could not be the results of kinematic reflection. Thus, a thorough investigation into the CLAS result [1] is warranted.

2. Meson background processes
In the reaction $\gamma p \rightarrow \pi^+ K^- K^+ n$, the dominant background is the production of mesons which sequentially decay to $K^{-0}K^+$ or $(K^+K^-)\pi^+$, as well as the production of $\Delta$'s or $N^*$'s which decay to $n\pi^+$ in association with mesons decaying into $K^+K^-$. Both reactions tend to have the $K^+$ going in the forward direction in the center-of-mass system, while the latter also tends to associate with a backward going $\pi^+$. In the CLAS result [1], kinematic constraints were applied restricting the $\cos(\theta^+_{\pi^+}) > 0.8$ and $\cos(\theta^-_{K^+}) < 0.6$. These cuts significantly suppress background to a possible resonant signal in $(nK^+)$ invariant mass spectrum. However, to quantitatively determine the effect of these kinematic cuts, one needs to have a comprehensive understanding of the meson background, particularly the process which involves mesons decaying into $\pi^+K^-K^+$. In the following sections, a more detailed study will be discussed.
3. Partial-Wave-Analysis (PWA) of $X^+ \rightarrow \pi^+ K^- K^+$

To achieve a realistic description of the meson background, partial wave analysis offers a powerful tool that allows the investigation of the effect of cuts required to reduce the meson background. In order to insure a clean sample of meson events to perform partial wave analysis of the $(K^+ K^-)\pi^+$ system, two additional cuts were imposed: $t' (\gamma \rightarrow (K^+ K^- \pi^+)) < 0.6 \ (\text{GeV}/c^2)^2$ and $\theta^{\text{Lab}}_\pi^+ < 30^\circ$, where $t' = t - t_{\text{min}}$ (with $t$ being the momentum transferred from the beam to the $K^+K^-\pi^+$ system and $t_{\text{min}}$ is the $t$ value when scattering angle is 0). A fairly large set of partial waves was used initially, but the smaller waves, such as $3^- \rightarrow a_2(1320)\pi^+$, that had low intensity and large errors were dropped. A non-interfering isotropic background wave was generated as well by assigning a real constant to each event as the background amplitude. Table 1 lists the foreground partial waves used in the final fit. The choice of waves are based on both the knowledge of established resonances and theoretical predictions. A total of 22 waves are used in the final fit.

| $J^P$ | $M^\pi$ | Isobars | bachelors |
|-------|---------|---------|-----------|
| 0    | 0      | $K^0(892), K^0(1430)$ | $K^+$ |
| 1    | 0, 1   | $K^0(892)$ | $K^+$ |
| 1    | 0, 1   | $K^0(892)$ | $K^+$ |
| 2    | 1      | $f_2(1270)$ | $\pi^+$ |
| 2    | 1, 2   | $K^0(892)$ | $K^+$ |

The quality of the fits are checked by comparing the various distributions of the data with the prediction of the fits which were obtained by selecting Monte Carlo events based on the fitted meson production amplitudes. The comparisons of the angular distributions of the $K^+$ and the $\pi^+$ in the center-of-mass frame, as well as various mass spectra, are shown in Fig. 1 and Fig. 2. Most kinematic observables show excellent agreement between the data and the fit prediction within the error bars. The largest discrepancy comes in the $n\pi^+$ invariant mass spectrum (Fig. 1, c)). This is an indication that there is still some baryon background from $\Delta/N^*$ production in association with the $K^+K^-$ system.

The strongest meson partial wave intensities are found to be $2^-$ waves in both $K^+K^0\pi$ and $f_2(1270)\pi^+$ modes [3]. A peak is clearly seen around 1640 MeV/c$^2$ in the $J^P = 2^-$ intensities in both the $K^+K^0\pi$ and $f_2(1270)\pi^+$ waves. This is likely the production of the $\pi_2(1670)$ which is known to decay to both $KK^\pi$ and $f_2(1270)\pi$. In addition, the $J^P = 2^-$ $K^+K^\pi$ intensity also shows enhancement around 1880 MeV/c$^2$, which has been observed experimentally [4, 5, 6, 7], and is consistent with the prediction of a radial excitation state of the $\pi_2(1670)$ [8].

Once a set of meson partial waves that describes the data in terms of all physical variables is obtained, it can be used to check whether kinematic cuts used for the $\Theta^+$ analysis can produce a peak in the $nK^+$ invariant mass spectrum [1]. Because of the additional cuts needed for the PWA ($t' (\gamma \rightarrow K^+ K^- \pi^+) < 0.6 \ (\text{GeV}/c^2)^2$ and $\theta^{\text{Lab}}_\pi^+ < 30^\circ$), only one third of the total events that were used for the $\Theta^+$ search are included in the PWA event sample. After applying the same kinematic cuts to the Monte Carlo events weighted according to the PWA fitting results, such as those used for the $K^+$ and the $\pi^+$ center-of-mass angles, no enhancement around 1.55 GeV/c$^2$ was found in the $nK^+$ invariant mass spectrum. The robustness of the $\Theta^+$ signal was also checked by varying the $K^+$ angle cut or replacing the $\pi^+$ angle cut with a cut on momentum transferred from the beam to the $\pi^+$ (Fig. 2), and the predicted $nK^+$ invariant mass distribution agrees with the data very well except in the region where the $\Theta^+$ signal is
observed. This provides strong evidence that kinematic reflection from mesons which decay to $K^+K^-\pi^+$ is unlikely to generate a false $\Theta^+$ signal.

4. Background from $a_2(1320)$ and $f_2(1270)$

The other important background is the production of neutral meson resonances, such as the $a_2(1320)$ and the $f_2(1270)$ that can decay through $K^+K^-$, being produced in association with $\Delta$ and $N^*$ resonances which decay to $n\pi^+$. However, neutral $a_2$ has a small cross section, particularly compared with charged $a_2$ production, due to the zero coupling of neutral $\pi^0$ with the photon [9]. This is consistent with recent photo-production results that investigated the meson production in both charged and neutral three-$\pi$ final state [10]. Although baryon resonances such as the $\Delta(1232)$ decaying into $n\pi^+$ are visible in the data, they are greatly reduced (Fig. 3) by the center-of-mass frame angular cuts (See Sec. 2) that were used to extract the $\Theta^+$ signal in Ref. [1]. Similarly, the $K^+K^-$ invariant mass spectrum does not bear a strong hint of either the $a_2(1320)$ or the $f_2(1270)$ (Fig. 3), both of which have a considerable branching faction of $K^+K^-$ decay, once the angular cuts are applied. Therefore, the data do not indicate $a_2/f_2$ production that would mandate further partial wave analysis to determine whether the $\Theta^+$ peak could be the result of the kinematic reflection of such states.

5. Other possible kinematic reflections

As reported in Ref. [1], the data is suggestive that the $\Theta^+$ is a decay product of a heavier nucleon around 2.43 GeV/$c^2$. This, however, raises the possibility that other states such as the $\Sigma(1915)$ (decaying into $nK^-$) and the $f_2(1525)'$ (decaying into $K^-K^+$), being the daughter particles of the heavier nucleon, can create an enhancement in the $nK^+$ mass spectrum due to limited phase space if these states fall near the edge of phase space on the Dalitz plots (Fig. 4). However, as demonstrated by Fig. 4, while the $\Theta^+$ band is clearly seen when events that have the invariant mass of $nK^+K^-$ system in the range of 2.38 – 2.5 GeV/$c^2$ are selected, no significant contributions are observed either in the $nK^-$ or $K^-K^+$ invariant mass spectra from the states.
mentioned above. On the other hand, even it is plausible that there could be some $a_2(1320)$ in the data sample, the statistical significance is negligible, and the phase space allowed for $a_2$ is large enough that the narrow $\Theta^+$ peak being the result of $a_2(1320)$ interference is very small.

6. Conclusion
In this paper, the possibility that the narrow $\Theta^+$ signal reported in Ref. [1] could be a result of kinematic reflection from selected background processes is examined. A partial wave analysis of the three body meson system was performed to obtain the best possible description of the data, and the $\Theta^+$ peak [1] does not appear to be the result of meson production reflecting into the $nK^+$ invariant mass spectrum. Other processes were investigated as well and no candidates are found that could create a narrow $\Theta^+$ signal.

Figure 3. a) $n\pi^+$ invariant mass spectra; b) $K^+K^-$ invariant mass spectra; Blue histograms are from the all three data sets , while Red histograms are the same spectra with angular cuts that were applied in Ref. [1] to extract the $\Theta^+$ signal ($cos(\theta^*_{n\pi^+}) > 0.8$ and $cos(\theta^*_{K^+K^-}) < 0.6$).

Figure 4. a) Dalitz plots for $M(nK^-)^2$ vs $M(nK^+)^2$; b) the projection of a) to y axis; c) Dalitz plots for $M(K^-K^+)^2$ vs $M(nK^+)^2$; d) the projection of c) to y axis; Only events with $M(nK^-K^+)$ in the range of $2.38 - 2.5$ $GeV/c^2$ are included.

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