Favorable Conditions of $\Theta^+$ Formation in $\gamma D$ Reaction

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We show that a $\Theta^+$ signal may appear in the $[\gamma D, pK^-]$ missing mass distribution in inclusive $\gamma D \rightarrow pK^- X$ reaction when the $pK^-$ pair is knocked out in the forward direction and its invariant mass is close to the mass of $\Lambda(1520)$. We show that the conditions of the recent CLAS experiment reduce the $\Theta^+$ formation probability making it difficult to extract a $\Theta^+$ peak from the data.

§1. Introduction

The first evidence for the pentaquark hadron $\Theta^+$, discovered by the LEPS collaboration at SPring-8, was subsequently confirmed in some other experiments. However, many other experiments failed to find the $\Theta^+$ signal. For surveys see Ref. 2. The situation became particularly dramatic after the recent publication of the high statistics results of the CLAS collaboration. Thus, the first experiment is designed to search for the $\Theta^+$ signal in $\gamma D \rightarrow pK^- nK^+$ in direct $\gamma n$ interactions at relatively low photon energy, $E_\gamma = 1.7 - 3.5$ GeV. Within the experimental significance, no $\Theta^+$ signal was observed. The CLAS null result for a given finite $\Theta^+$ decay width means large off-shell suppression in $\Theta^+ NK$ vertices of the amplitudes. The $K^*$-exchange amplitude may be additionally suppressed by the small value of $g_{\Theta NK^*}$ coupling constant because it is not related directly the $\Theta^+$ decay width and therefore remains unconstrained. Therefore, the best way to check whether the $\Theta^+$ exists or not is to study the $KN \rightarrow \Theta^+$ fusion reaction with a quasi-free kaon and a nucleon in the initial state. In this case the $g_{\Theta NK}$ coupling is fixed (for given $\Gamma_\Theta$), and there is no ambiguity with the off-shell form factor because all hadrons are almost on the mass shell. This situation may be realized in the reaction $\gamma D \rightarrow \Lambda^* \Theta^+ \rightarrow pK^- nK^+$ ($\Lambda^* \equiv \Lambda(1520)$) with the $\Theta^+$ showing up as a peak in the $nK^+$ invariant mass distribution.

There are several conditions which can enhance this effect. First, the $pK^-$ invariant mass must be close to the mass of $\Lambda^*$. In this case, the total amplitude is the coherent sum of two amplitudes with charged and neutral kaon exchange shown in Fig. 1. The dominance of the $K^*$ meson exchange in $\Lambda^*$ photoproduction results

![Fig. 1. Tree level diagrams for the reaction $\gamma D \rightarrow \Lambda^* \Theta^+$. The exchange of charged and neutral kaons is shown in (a) and (b), respectively.](https://example.com/fig1.png)
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in a constructive interference between the two amplitudes which enhances the $\Theta^+$ signal. Second, the deuteron wave function greatly suppresses the processes with a fast moving recoil nucleon, therefore, the experiment must be able to measure an extremely slowly moving recoil (spectator) nucleon which participates in the $KN \rightarrow \Theta^+ \rightarrow KN$ reaction. Third, the $pK^-$ pair must be knocked out in the forward direction. In this case, the momentum of the recoil kaon is small, and it can merge with the slowly moving spectator nucleon to produce a $\Theta^+$. In order to avoid the obvious difficulty in measuring the slowly moving recoil nucleon one has to analyze the $[\gamma D, pK^-]$ missing mass distribution. In this case, all momenta allowed by the conservation laws participate in the process, and the dominant contribution would obviously come from slowly moving nucleons. As a result, the total cross section strongly increases.

In our contribution we will discuss in more detail this qualitative presentation of favorable kinematical conditions for a manifestation of the $\Theta^+$ signal in $\gamma D$ reaction.

§2. Associated $\Theta^+ \Lambda^*$ photoproduction

We assume that main contribution in associated $\Theta^+ \Lambda^*$ photoproduction comes from the charged and neutral $K$ meson exchange, shown in Figs. 1(a) and (b), respectively, where in $K + N \rightarrow \Theta^+$ vertices we consider the $\Theta^+$ decay width as an input parameter, taking $\Gamma_{\Theta} = 1$ MeV. The amplitudes of the associated $\Lambda^*\Theta^+$ photoproduction are expressed through the transition operators of the “elementary” process $\gamma N \rightarrow \Lambda^* pK^-$ as

$$A_{(a,b)} = g_{\Theta NK} \int \frac{d^4p}{(2\pi)^4} \bar{u}_{\Theta} \gamma^5 \frac{1}{q^2 - M_K^2} u_{\Lambda^*} M_{\sigma \Lambda^* \mu} \frac{\hat{p} + M}{p^2 - M^2} \frac{\hat{p}'}{p'^2 - M^2} U_D , \quad (2.1)$$

where the transition operator $M$ defines the amplitude of $\Lambda^*$ photoproduction described in detail in Ref. 5). $\Gamma_D$ and $U_D$ stand for the deuteron $np$ coupling vertex and the deuteron spinor, respectively, $p' = p_D - p$, and $q$ is the momentum of the exchanged kaon. Calculating the amplitude we assume that the dominant contribution to the loop integrals comes from their pole terms which are evaluated by summing all possible cuttings of the loops. In this case the intermediate kaon and one of the nucleon are on mass shell. The second nucleon is “almost” on-shell, because configurations with large internal momentum are suppressed by the deuteron wave function.

The differential cross section of the associated $pK^-$ and $NK$ photoproduction, integrated over the $pK^-$ invariant mass in the range $M_Y = M_{\Lambda^*} \pm 20$ MeV and the missing mass $M_X = M_{\Theta^+}$, reads

$$\frac{d \sigma_{\gamma D \rightarrow pK^- X}}{d \cos \theta dM_X} \bigg|_{M_X = M_{\Theta^+}} \simeq \frac{N}{32\pi^2 s \Gamma_{\Theta^+}} \frac{p_f}{p_i} |A_a + A_b|^2 , \quad (2.2)$$

where $N \simeq 0.17$ is the integral over the Breit-Wigner $\Lambda^* \rightarrow pK^-$ decay distribution, $A_a$ and $A_b$ are the amplitudes of the charge and neutral current exchange,
respectively, as depicted in Fig. 1. The sum of the charged and neutral $K$ meson exchange diagrams leads to a constructive interference between $A_a$ and $A_b$, and an enhancement of the cross section of the associated $Λ^+Θ^+$ photoproduction. In Fig. 2 we show the resonant cross section as a function of the $Λ^+$ photoproduction angle in the laboratory system for several values of the photon energy. One can see that the $Θ^+$ formation in associated $Λ^+Θ^+$ photoproduction is hardly measurable if the detector acceptance does not allow measuring the $pK^-$ pairs at small angles $θ_{\text{lab}} \leq 10^0$. Since the intermediate kaon and nucleon in $KNΘ^+$ vertex are "almost" on-shell the dependence of the resonant cross section on the $Θ^+$ spin-parity is rather weak. Approximately, we have $dσ(1/2^+) \simeq dσ(1/2^-)$, $dσ(3/2^+) \simeq dσ(3/2^-)$, and $dσ(3/2^\pm) \simeq 2dσ(1/2^\pm)$. The factor 2 is a statistical factor.

§3. Background

The main background processes are depicted in Fig. 3. They are quasi-free $Λ^+K$ photoproduction (a), quasi-free non-resonant $pK^-K$ photoproduction (b), rescattering of the proton (c) and $K^-$ meson (d), and virtual vector meson ($φ, ω, ρ$) excitation (e). If the $pK^-$ pair is detected in forward direction and spectator channels are allowed, then the dominant contribution comes from the quasi-free processes (a) and (b). In case when the spectator channels are excluded, the rescattering channels become dominant. Reduction of the background from vector mesons (mainly $φ$-meson) depends on the experimental conditions. For details of background see Ref. 5).

§4. Results

In Fig. 4 we show result for the inclusive $γD → pK^-X$ reaction with favorable kinematical conditions: a $pK^-$ pair with invariant mass $|M_{pK^-} - M_{Λ^+}| \leq 20$ MeV,
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is detected in forward direction with $\theta_{\text{lab}} \leq 10^0$. In order to allow contributions of the spectator channels with slowly moving $NK$-pair, the reaction is essentially inclusive and the cross section depends on the missing $[\gamma D, pK^-]$ mass ($M_X$). One can see a distinct $\Theta^+$ peak with signal-to-noise ratio $S/N \approx 2.5$ (actual calculation is done for $\Theta^+$ spin-parity $3/2^-$). However, folding this curve with an “experimental” resolution function would somehow decrease $S/N$.

Conditions of the CLAS experiment does not satisfy these favorable conditions of $\Theta^+$ formation. Data analysis excluded (i) spectator channel, (ii) events with $\Lambda^*$, and (iii) the CLAS detector cannot detect charged particles at very forward direction. This all together results in a sizeable reduction of the $S/N$ ratio. Thus the signal of $\Theta^+$-formation channel becomes comparable or even smaller than the statistical fluctuations of the non-resonant background.\footnote{5}

§5. Conclusions

In summary, we propose that the most promising way to search for $\Theta^+$ is studying its formation in $KN \to \Theta^+$ processes with “quasi” free hadrons in the initial state. Such processes may be realized in inclusive $\gamma D \to pK^- X$ reactions and would be noticeably enhanced when the invariant mass of the $pK^-$ pair is close to the mass of $\Lambda(1520)$ and is detected in forward direction, relative to the photon beam.

Finally, we note that the $\Theta^+$ formation reaction together with other accompanying processes discussed here may be studied experimentally at the electron and photon facilities at LEPS of SPring-8, JLab, Crystal-Barrel of ELSA, and GRAAL of ESRF.

References

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