Role of the $N^*(2080)$ resonance in the \( \vec{\gamma}p \rightarrow K^+\Lambda(1520) \) reaction

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1. Introduction

2. Our approach
   Effective Lagrangian method.
   We will take into account the $t$–channel $K$ exchange, the contribution of $N$ and $N^*(2080)$ in the $s$–channel, and a contact term.

3. Results

4. Conclusions
Introduction

1. The $\Lambda(1520) (\equiv \Lambda^*)$ photoproduction in the $\gamma p \rightarrow K^+ \Lambda^*$ reaction is an interesting tool to gain a deeper understanding of the interaction among strange hadrons and also on the nature of baryon resonances.

2. This reaction has been examined at photon energies below 2.4 GeV in the Spring-8 LEPS experiment. For an invariant $\gamma p$ mass around 2.11 GeV, a bump structure in the differential cross section at forward $K^+$ angles was reported, which might hint to a sizable contribution from nucleon resonances in the $s-$channel. (N. Muramatsu et al. (LEPS Collaboration), Phys. Rev. Lett. 103, 012001 (2009); H. Kohri et al. (LEPS Collaboration), Phys. Rev. Lett. 104, 172001 (2010).)

3. Several phenomenological models, that used an effective hadron Lagrangian approach, can reproduce the high energy data reasonable well, but they fail to describe the bump structure in the new LEPS data.
Why $N^*(2080)$

1. The information about nucleon resonances in the relevant mass region ($\sim 2.1$) GeV is scarce.
   1), $N^*(2080)$, $J^P = 3/2^-$, status: **;
   2), $N^*(2090)$, $J^P = 1/2^-$, status: *;
   3), $N^*(2100)$, $J^P = 1/2^+$, status: *.

2. We rely on theoretical predictions based in a quark model (QM) for baryons. The two-star $D$–wave $J^P = 3/2^-$ $N^*(2080)$ ($\equiv N^*$) is predicted to have visible contributions to the $\gamma p \rightarrow K^+ \Lambda^*$ reaction. (S. Capstick, Phys. Rev. D 46, 2864 (1992); S. Capstick, and W. Roberts, Phys. Rev. D 58, 074011 (1998).)

3. The evidence of its existence is poor or only fair. Its total decay width and branching ratios are not experimentally known, either. Thus, the LEPS measurements could be used to determine some of the properties of this resonance.
We consider the $K$ exchange in the $t$–channel, the contribution of $N$ and $N^*(2080)$ in the $s$–channel, and a contact term.
Interaction Lagrangian Densities

\[ \mathcal{L}_{\gamma KK} = -ie(K^- \partial^\mu K^+ - K^+ \partial^\mu K^-)A_\mu, \]  
(1)

\[ \mathcal{L}_{Kp\Lambda^*} = \frac{g_{KN\Lambda^*}}{m_K} \bar{\Lambda}^{* \mu} (\partial_\mu K^-) \gamma_5 p + \text{h.c.}, \]  
(2)

\[ \mathcal{L}_{\gamma pp} = -e\bar{p} \left( A - \frac{\kappa_p}{2m_N} \sigma_{\mu\nu} (\partial^\nu A^\mu) \right) p + \text{h.c.}, \]  
(3)

\[ \mathcal{L}_{\gamma Kp\Lambda^*} = -ie \frac{g_{KN\Lambda^*}}{m_K} \bar{\Lambda}^{* \mu} A_\mu K^- \gamma_5 p + \text{h.c.}, \]  
(4)

\[ \mathcal{L}_{\gamma NN^*} = \frac{ief_1}{2m_N} \bar{N}^{* \mu}_\gamma F^{\mu\nu} N - \frac{ef_2}{(2m_N)^2} \bar{N}^{* \mu}_\mu F^{\mu\nu} \partial\nu N + \text{h.c.}, \]  
(5)

\[ \mathcal{L}_{K\Lambda^*N^*} = \frac{g_1}{m_K} \bar{\Lambda}^{* \mu}_\mu \gamma_5 \gamma_\alpha (\partial^\alpha K) N^{* \mu} + \]  

\[ \frac{ig_2}{m_K^2} \bar{\Lambda}^{* \mu}_\mu \gamma_5 (\partial^\mu \partial_\nu K) N^{* \nu} + \text{h.c.}, \]  
(6)
Rarita-Schwinger spinor for $\Lambda(1520)$ and $N^*(2080)$

\[
\sum_s u_\rho(p, s) \bar{u}_\sigma(p, s) = \frac{\not{p} + M}{2M} P_{\rho\sigma}(p),
\]

and,

\[
P_{\rho\sigma}(p) = -g_{\rho\sigma} + \frac{1}{3} \gamma_\rho \gamma_\sigma + \frac{2}{3M^2} p_\rho p_\sigma + \frac{1}{3M} (\gamma_\rho p_\sigma - \gamma_\sigma p_\rho).
\]
Scattering amplitudes

\[-i T_i = \bar{u}_\mu (p_2, s_{\Lambda^*}) A^{\mu \nu}_i u(k_2, s_p) \epsilon_\nu (k_1, \lambda)\]  \quad (9)

The reduced $A^{\mu \nu}_i$ amplitudes read:

$A^{\mu \nu}_t = - e \frac{g K N^*}{m_K} \frac{1}{q^2 - m_K^2} q^\mu (q^\nu - p_1^\nu) \gamma_5 f_c,$  \quad (10)

$A^{\mu \nu}_s = - e \frac{g K N^*}{m_K} \frac{1}{s - M_N^2} p_1^\mu \gamma_5 \left\{ k_1 \gamma^\nu f_s + (k_2 + M_N) \gamma^\nu f_c \right\}$

\[+ (k_1 + k_2 + M_N)i \frac{k^p}{2 M_N} \sigma_{\nu \rho} k_1^\rho f_s \}, \quad (11)

$A^{\mu \nu}_c = e \frac{g K N^*}{m_K} g^{\mu \nu} \gamma_5 f_c,$  \quad (12)

$A^{\mu \nu}_R = \gamma_5 \left( \frac{g_1}{m_K} p_1 g^{\mu \rho} - \frac{g_2}{m_K^2} p_1^\mu p_1^\rho \right) \frac{k_1 + k_2 + M_{N^*}}{s - M_{N^*}^2 + i M_{N^*} \Gamma_{N^*}} P^\rho_{\sigma}$

\[\left( \frac{e f_1}{2 m_N} (k_1^\sigma \gamma^\nu - g^{\sigma \nu} k_1) + \frac{e f_2}{(2 m_N)^2} (k_1^\sigma k_2^\nu - g^{\sigma \nu} k_1 \cdot k_2) \right) f_R, \quad (13)\]
Form factors

We take the following parameterization for the four-dimensional form-factors

\[ f_i = \frac{\Lambda_i^4}{\Lambda_i^4 + (q_i^2 - M_i^2)^2}, \quad i = s, t, R \]  

(14)

\[ f_c = f_s + f_t - f_s f_t, \quad \text{and} \quad \begin{cases} q_s^2 = q_R^2 = s, & q_t^2 = q^2, \\ M_s = M_N, & M_R = M_{N^*}, \\ M_t = m_K. \end{cases} \]  

(15)

1. We respect gauge invariance.


3. We will consider different cut-off values for the background and resonant terms, i.e. \( \Lambda_s = \Lambda_t \neq \Lambda_R \).
Parameters

1. \( g_{KN\Lambda^*} = 10.5 \), determined from the \( \Lambda^* \rightarrow pK^- \) decay width.

2. \( N^*N\gamma \) coupling constants \( f_1 \) and \( f_2 \), obtained from the \( N^* \) helicity amplitudes \( A_{1/2} \) and \( A_{3/2} \);

\[
A_{1/2}^{p^*} = \frac{e \sqrt{6}}{12} \sqrt{\frac{k_\gamma}{M_NM_{N^*}}} \left( f_1 + \frac{f_2}{4M_N^2}M_{N^*}(M_{N^*} + M_N) \right), \tag{16}
\]

\[
A_{3/2}^{p^*} = \frac{e \sqrt{2}}{4M_N} \sqrt{\frac{k_\gamma M_{N^*}}{M_N}} \left( f_1 + \frac{f_2}{4M_N^2}(M_{N^*} + M_N) \right), \tag{17}
\]

where \( k_\gamma = (M_{N^*}^2 - M_N^2)/(2M_{N^*}) \).

3. The strong couplings \( g_1, g_2 \) and the cut-off parameters \( \Lambda_s = \Lambda_t \) and \( \Lambda_R \) are free parameters, and we will fit them to the new LEPS data.
Cross Sections

The differential cross section, in the center of mass frame (c.m.), for a polarized photon beam reads,

\[
\left. \frac{d\sigma}{d\Omega} \right|_{\text{C.M.}} = \frac{|\vec{k}_1^{\text{C.M.}}| |\vec{p}_1^{\text{C.M.}}|}{4\pi^2} \frac{M_N M_\Lambda^*}{(s - M_N^2)^2} \left( \frac{1}{2} \sum_{s_p, s_\Lambda} |T|^2 \right)
\]

\[
= \frac{1}{2\pi} \frac{d\sigma}{d(cos\theta_{\text{C.M.}})} \left\{ 1 - \sum \cos 2(\phi_{\text{C.M.}} - \alpha) \right\}
\]

(18)
Input Parameters

We have performed three different fits.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit A</th>
<th>Fit B</th>
<th>Fit C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{1/2}^p[\text{GeV}^{-1/2}]$</td>
<td>$-0.020 \pm 0.008$</td>
<td>$-0.020 \pm 0.008$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$A_{3/2}^p[\text{GeV}^{-1/2}]$</td>
<td>$0.017 \pm 0.011$</td>
<td>$0.017 \pm 0.011$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$e f_1$</td>
<td>$0.18 \pm 0.07$</td>
<td>$0.18 \pm 0.07$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$e f_2$</td>
<td>$-0.19 \pm 0.07$</td>
<td>$-0.19 \pm 0.07$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$M_{N^*}[\text{MeV}]$</td>
<td>2080</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$\Gamma_{N^*}[\text{MeV}]$</td>
<td>300</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
</tr>
</tbody>
</table>
### Fitted Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_1$</td>
<td>$5.0 \pm 0.2^{+2.8}_{-1.5}$</td>
<td>$2.0 \pm 0.1^{+1.4}_{-0.5}$</td>
<td>$1.4 \pm 0.3$</td>
</tr>
<tr>
<td>$g_2$</td>
<td>$-9.7 \pm 2.0^{+6}_{-5}$</td>
<td>$-3.3 \pm 0.9^{+1.8}_{-3.4}$</td>
<td>$5.5 \pm 1.8$</td>
</tr>
<tr>
<td>$\Lambda_s = \Lambda_t$ [MeV]</td>
<td>$613 \pm 2^{+5}_{-8}$</td>
<td>$613 \pm 2^{+1}_{-5}$</td>
<td>$604 \pm 2$</td>
</tr>
<tr>
<td>$\Lambda_R$ [MeV]</td>
<td>$990 \pm 50^{+30}_{-20}$</td>
<td>$5.0 \pm 3.9^*$</td>
<td>$909 \pm 55$</td>
</tr>
<tr>
<td>$e f_1$</td>
<td>$- - -$</td>
<td>$- - -$</td>
<td>$0.177 \pm 0.023$</td>
</tr>
<tr>
<td>$e f_2$</td>
<td>$- - -$</td>
<td>$- - -$</td>
<td>$-0.082 \pm 0.023$</td>
</tr>
<tr>
<td>$M_{N^*}$ [MeV]</td>
<td>$- - -$</td>
<td>$2138 \pm 4^{+1}_{-21}$</td>
<td>$2115 \pm 8$</td>
</tr>
<tr>
<td>$\Gamma_{N^*}$ [MeV]</td>
<td>$- - -$</td>
<td>$168 \pm 10^{+19}_{-15}$</td>
<td>$254 \pm 24$</td>
</tr>
<tr>
<td>$\chi^2/dof$</td>
<td>$2.4$</td>
<td>$1.4$</td>
<td>$1.2$</td>
</tr>
</tbody>
</table>
# Predicted Observables

<table>
<thead>
<tr>
<th>Observable</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{1/2}^p$ [GeV$^{-1/2}$]</td>
<td>$- - -$</td>
<td>$- - -$</td>
<td>$0.0036 \pm 0.0086$</td>
</tr>
<tr>
<td>$A_{3/2}^p$ [GeV$^{-1/2}$]</td>
<td>$- - -$</td>
<td>$- - -$</td>
<td>$0.058 \pm 0.021$</td>
</tr>
<tr>
<td>$\Gamma_{N^* \to \Lambda^* K}$ [MeV]</td>
<td>$110 \pm 10^{+160}_{-50}$</td>
<td>$43 \pm 5^{+61}_{-20}$</td>
<td>$19 \pm 7$</td>
</tr>
<tr>
<td>$\frac{\Gamma_{N^* \to \Lambda^* K}}{\Gamma_{N^*}}$ [%]</td>
<td>$36 \pm 3^{+53}_{-18}$</td>
<td>$26 \pm 3^{+36}_{-12}$</td>
<td>$7.5 \pm 2.8$</td>
</tr>
</tbody>
</table>

\[ \Gamma_{N^* \to \Lambda^* K} = \frac{|\vec{p}_1^{C.M.}|}{18\pi M_{\Lambda^*}^2} \left\{ |\vec{p}_1^{C.M.}| \frac{4 g_2^2}{m_K^4} + |\vec{p}_1^{C.M.}|^2 (2 E_{\Lambda^*} - M_{\Lambda^*}) \frac{(M_{N^*} + M_{\Lambda^*}) g_1 g_2}{M_{N^*} M_{\Lambda^*}} \frac{M_{N^*}^2}{m_K^3} + \left( \frac{M_{N^*} + M_{\Lambda^*}}{M_{N^*}} \right)^2 (E_{\Lambda^*}^2 - E_{\Lambda^*} M_{\Lambda^*} + \frac{5}{2} M_{\Lambda^*}^2) \frac{g_1^2}{m_K^2} \right\} \] (19)
Numerical Results

Results have been obtained from the eight-parameter fit C.

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Numerical Results (Fit C)

1. Blue horizontal line shaded region (right panel), $\theta_{\text{c.m.}} = 120^0$;
2. Blue horizontal line shaded region (left panel), $\theta_{\text{c.m.}} = 180^0$;
3. red vertical line shaded region in both panels, $\theta_{\text{c.m.}} = 150^0$. 

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1. Red horizontal lines, $E_\gamma = 1.9$ GeV;
2. Blue vertical lines, $E_\gamma = 2.4$ GeV.
Polar angle average photon-beam asymmetry $\langle \Sigma \rangle$

\[
\langle \Sigma \rangle = \frac{\int_{0.6}^{1.0} \frac{d\sigma}{d(\cos \theta_{C.M.})} \sum (\cos \theta_{C.M.}, E_\gamma) d(\cos \theta_{C.M.})}{\int_{0.6}^{1.0} \frac{d\sigma}{d(\cos \theta_{C.M.})} d(\cos \theta_{C.M.})},
\]

(20)
Conclusions

1. We have studied the $\gamma p \rightarrow \Lambda^* K^+$ reaction at low energies within an effective Lagrangian approach. In particular, we have paid special attention to a bump structure in the differential cross section at forward $K^+$ angles reported in the recent SPring-8 LEPS experiment. Starting from the background contributions studied in previous works, we have shown that this bump might be described thanks to the inclusion of the nucleon resonance $N^*(2080)$ (spin-parity $J^P = 3/2^-$). We have fitted its mass, width and hadronic $\Lambda^* K^+$ and electromagnetic $N^* N \gamma$ couplings to data.

2. We have found that this resonance would have a large decay width into $\Lambda^* K$, which will be compatible with the findings of the QM approach of Capstick and collaborators.

3. Our predictions for the backward angles and the polar angle average photon-beam asymmetry are not so good when compared with the experimental data.
Thank you very much for your attention!

谢谢！