Photoproduction mechanism for charged reaction of $K^*\Lambda$ with nucleon

A W Putra$^1$, A Salam$^1$, and I Fachruddin$^1$

$^1$Departemen Fisika, FMIPA, Universitas Indonesia, Depok 16424, Indonesia

E-mail: agus.salam@sci.ui.ac.id

Abstract. The photoproduction of vector meson $K^*(892)$ on the nucleon has been investigated in the framework of the effective Lagrangian model by utilizing the Feynman diagram of the lowest orders in calculating the transition amplitudes. Beside the Born and the contact terms, we consider the $\Sigma^*(1780)$ as an additional hyperon resonance alongside with the $\Sigma^*(1385)$ in the $u$-channel. It is found that the $\Sigma^*(1780)$ has remarkable effects in the backward scattering region where there are still discrepancies between the theoretical predictions and the experimental data.

1. Introduction

Over the years, the research in $K^*(892)$ vector meson photoproduction has seen quite a substantial growth in popularity. Until Yongseok Oh and Hungchong Kim [1,2], there were already several research done on the topic of $K^*$ photoproduction. At this time, theoretical background used to support these research were based on the quark-meson couplings model, in which the coupling constants were assumed to be independent of the flavor. This allows the strong coupling constants to be specified using other reactions. [3,4], in which the coupling constants were assumed to be independent of the flavor. This allows the strong coupling constants to be specified using other reactions.

There were several notable characteristics to the approach by Oh and Kim. To obtain the complete production amplitude, they included the contributions from the $t$-channel $K^*$, $K$, $\kappa$ exchanges, the $s$-channel nucleon exchange, the $u$-channel $\Lambda$, $\Sigma$, $\Sigma^*$ exchanges, and a contact exchange. In the $t$ exchange channel, the controversial scalar $\kappa$ meson is included since, unlike in kaon photoproduction where it is prohibited because of parity and angular momentum conservation, the $\gamma K\kappa$ coupling is allowed and therefore considered. Plus, the restriction of nucleon resonance only (as per isospin conservation, the $\Delta$ resonances must be excluded) in the $s$ exchange channel creates a potential for further investigations on additional nucleon resonance.

In this research, we only focus on the charged reaction $\gamma p \rightarrow K^*\Lambda$. Although both $K^*$ and nucleon are isodoublets, in the neutral reaction $\gamma n \rightarrow K^0\Lambda$ we see that the $t$-channel $K^*$ and the contact exchange are not present (while in the $s$-channel nucleon exchange, the scattering amplitude loses the ‘problematic’ term), thus do not contribute to the final scattering amplitude. Conveniently, the exclusion of the $t$-channel $K^*$ and the contact term in the neutral reaction causes the total scattering amplitude to be automatically transverse by itself (in other words, the gauge invariance condition is satisfied), since we also see that for the $t$-channel $K^*$ exchange, the unmodified $s$-channel nucleon exchange, and the contact term are not independently transverse by itself. In addition, we have included an additional resonance particle in the $u$-channel as an example to demonstrate the effect of
additional contributions in the backward scattering region that was noted in the latest preliminary data. Furthermore, since there has been a continuation of the 2006 research published that uses a new preliminary experimental data on the charged $K^*$ cross sections, we have also updated some of the used parameters accordingly [5].

2. Formalism

![Feynman diagrams for all channels](image)

**Figure 1.** Feynman diagrams for all channels (a) t-channel, (b) s-channel, (c) u-channel, and (d) contact diagram exchange.

From the diagram shown in Fig. 1 and the results taken from the effective Lagrangian model [1], we can write the production amplitude for each channel,

\[ M_{K^*}^{\mu\nu} = \eta_{K^*} e^{g_{K^*N\Lambda} \mu} \left( 2q^\mu g^{\nu a} - q^a g^{\mu\nu} + k^\mu g^{\nu a} \right) \left[ g_{a\beta} - \frac{(k - q)_a(k - q)_\beta}{M_{K^*}^2} \right] \frac{\gamma^\beta - \frac{ik_{K^*N\Lambda}}{2M_N} \sigma^{\beta\gamma}(k - q)_\gamma}{2M_N}, \]

\[ \mathcal{M}_{K^*}^{\mu\nu} = \frac{i g_{K^*N\Lambda}}{\left( t-M_{K^*}^2 \right)^2} \eta_{K^*} \eta_{N\Lambda} \left[ \gamma^\mu - \frac{ik_{K^*N\Lambda}}{2M_N} \sigma^{\mu\nu} q_a \left( k + p + M_N \right) \left( \frac{\gamma^\nu - \frac{ik_{K^*N\Lambda}}{2M_N} \sigma^{\nu\gamma} q_a}{2M_N} \right) \right], \]

\[ \mathcal{M}_{u(N)}^{\mu\nu} = \eta_{N\Lambda} e^{g_{K^*N\Lambda} \mu} \left( \frac{g_{1}\eta_{N\Lambda}}{2M_N} + \frac{g_{2}\eta_{N\Lambda}}{M_N^2} \right) \eta_{\Sigma}(k^\mu g^{\nu a} - k^a g^{\nu\mu}) \Delta_{ab}(\Sigma^*, p - q) \left( \frac{1}{2M_N} \right) \frac{1}{\left( \frac{\Sigma^* - p}{M_N} \right)^2} \gamma^{\nu} \left( \frac{q^a g^{\nu a} - q^a g^{\nu a}}{2M_N^2} \right), \]

\[ \mathcal{M}_{contact}^{\mu\nu} = -\eta_{K^*} e^{g_{K^*N\Lambda} K^*} \eta_{N\Lambda} \frac{1}{2M_N} \sigma^{\mu\nu}, \]

where the variable $\eta_{K^*}, \eta_{N\Lambda}, \eta_{\Sigma}, \eta_{\Sigma^*}$ and $Q_N$ is set to +1 for our charged reaction (this denotes the charge isodoublet term of each exchanges). We also see that the variable $g_{K^*N\Lambda}, g_{N\Lambda N^\Lambda}, g_{K^*N^\Lambda}, g_{K^*N^2}, g_{K^*N^2}, g_{K^*N\Lambda}, g_{K^*N^2}$ and $f_{K^*N^2}$ is the strong coupling constants, whereas the variable $g_{1}, g_{2}, g_{K^*N^2}, g_{K^*N^2}, g_{K^*N^2}$ and $g_{2}$ is our electromagnetic constants. Furthermore, for the u-channel $\Sigma^*$ hyperon propagator we use Rarita- Schwinger spin-projection for spin 3/2 particles,

\[ \Delta_{ab}(R, p) = \left( p + M_R \right) \left[ -g_{\alpha\beta} + \frac{1}{3} \gamma_{\alpha\beta} + \frac{1}{M_R^2} \gamma_{\alpha\beta} \left( \gamma_{\rho\sigma} p_{\rho\sigma} - p_{\rho\sigma} \gamma_{\rho\sigma} \right) + \frac{2}{3M_R^2} \gamma_{\rho\sigma} p_{\rho\sigma} \right]. \]

We also note that to incorporate the decay width for each of the resonance particle, we need to substitute the mass term from their propagator $M_R \rightarrow M_R - i\Gamma_{R}/2$. Using the values retrieved from the
2006 paper [1], we use $\Gamma_{K^*} = 50.8$ MeV for the $t$-channel $K^*$ exchange, $\Gamma_{\kappa} = 550$ MeV for the $t$-channel $\kappa$ exchange, and $\Gamma_{\Sigma^*} = 37$ MeV for the $u$-channel $\Sigma^*$ exchange.

3. Result and Discussion
3.1. Coupling constants and Form factors
Before we dissect each channel contributions of the charged $K^*$ photoproduction and insert our candidate hyperon particle, we will begin by reproducing all of the differential cross sections from the original paper and comparing it to the available preliminary experimental data [5]. We use the already-established strong and electromagnetic coupling constants for our reactions in Tables 1 and 2.

| Table 1. Known strong coupling constants for the meson-baryon interactions. [7] |
|---|
| $g_{K^*\Lambda}$ | $g_{\kappa\Lambda}$ | $g_{KN\Lambda}$ | $g_{K^*\Sigma}$ | $g_{K^*\Sigma^*}$ |
| -4.26 | -8.3 | -13.24 | -2.46 | 2.66 | -0.47 | -5.21 |

| Table 2. Electromagnetic constants used for the charged reactions. |
|---|
| $g_{KK^*}$ | $g_{K\kappa}$ | $\kappa_p$ | $\kappa_\Lambda$ | $\mu_{\Lambda\Sigma}$ | $g_1$ | $g_2$ |
| 0.254/GeV | 0.12/GeV | 1.79 | -0.61 | 1.61 ± 0.08 | 3.78 | 3.18 |

Furthermore, to calculate the differential cross section for each channel we will use the following values for our form factors in Table 3.

| Table 3. The form factor cutoff parameters for each channel [3]. |
|---|
| $\Lambda_{K^*}$ | $\Lambda_{\kappa}$ | $\Lambda_{\Lambda}$ | $\Lambda_{N}$ | $\Lambda_{\Sigma}$ | $\Lambda_{\Sigma^*}$ |
| 0.9 GeV | 1.25 GeV | 1.25 GeV | 0.9 GeV | 0.9 GeV | 0.9 GeV | 0.9 GeV |

3.2. Results and analysis

![Figure 2](image-url) (a – c) Differential cross sections $d\sigma/d\cos\theta$ [in $\mu$b] for charged $K^+$ photoproduction for each $E_\gamma$ versus the preliminary experimental data by CLAS [8].

In Fig. 2, we can clearly see how the original model proposed by Oh and Kim predicted the differential cross sections of the charged $K^*$ photoproduction compared the data provided by the CLAS collaborations in their 2011 publication [2]. Unlike our reproduction however, they have included an additional $N^*$ resonance in the $s$-channel exchange, which potentially resolves the noticeable discrepancies that occurred in the energy range below 2.45 GeV. Since our model have not included the additional resonance yet, we can see this effect by the noticeable discrepancies that
occurred in the 2.15 – 2.35 GeV energy ranges. Thus, we decided to use an energy range outside the nucleon resonance influence – in our case we use $E_\gamma = 2.45$ GeV as our parameter.

To see the role of each exchange channel contributions, in Fig. 3 we have divided our configurations into 3 distinct differential cross section graphs containing some of our selected configuration. The graph (a) of Fig. 3 shows us that the $K$ meson exchange contributes significantly
compared to the other channels across the scattering region. Next to $K$, we see that the $\kappa$ scalar meson also has a quite huge contribution in the forward scattering region.

However, we also learned that the combination of the $K^*$, $N$, and the contact exchanges have an interesting effect on the forward scattering region in which that they “dampened” other channel’s contributions. This can happen because there are “cross terms” in the total scattering amplitude – this symbolizes the coupling interactions between two different channels. Finally, we clearly see how the $u$-channel hyperon particles contribute to the backward scattering region.

In addition, we have also tried to resolve the backward scattering region discrepancies using the experimental $\Sigma^*(1780)$ hyperon resonance particle in addition to the more established $\Sigma^*(1358)$. Since its coupling constant is still unknown, we vary its coupling constant within the accepted ranges of $+10$ and $-10$ from looking at the other exchanges. We see in Fig. 3(d) that with the form factor of 900 MeV used by the majority of our exchanges, using a negative-valued coupling constant resulted in an increase from the original model, and vice versa. We also see that using a higher form factor cut off resulted in a more drastic contributions to the backward scattering region up to a point.

4. Conclusion
From the differential cross sections produced using different configuration channels, we learned that each channel could affect the shape of the final scattering amplitude based on their interactions, and how their coupling interaction with other channel can results in an amplification or a dampening effect by means of comparing their differential cross sections with their contribution (or ‘lack’ of contribution when we disable their exchanges). We also learned that how some channels can have more influence than the other to the final scattering amplitude by looking at their form factor cut offs and their coupling constants. Furthermore, we also see the possibility of additional hyperon resonances to take part of the backward scattering region in the $K^*$ photoproduction.

5. References
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