Neutral kaon photoproduction on the deuteron has been investigated by including the final state effects and compared with the experimental data. Comparison shows that the models used in this calculation can reproduce the data in the $\Sigma$ channel regions fairly well but still give over predictions in the $\Lambda$ channel. It seems that the tensor target asymmetries are more suitable for studying the final state effects. The extractions of the elementary photoproduction amplitude are also demonstrated.

**Keywords**: Kaon, photoproduction; deuteron.

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1. Introduction

The mostly investigated kaon photoproduction on the nucleon are the proton channels, i.e., $\gamma p \to K^+\Lambda$ and $\gamma p \to K^+\Sigma^0$, since the experimental data are available for these channels. Unfortunately, it is not the case for the neutron channels, since free neutron targets are not available. Instead, one can use deuteron as effective neutron targets because it has a small binding energy and simple structures. Therefore, kaon photoproduction on the deuteron is the natural candidate for investigating the kaon photoproduction on the neutron.

Furthermore, since the reaction on the deuteron yields several particles in the final state, it is important to include final state effects in the calculations. It seems that kaon photoproduction on the deuteron can serve as an alternative reaction for studying the $YN$ interaction through the $YN$ rescattering at the final state. A previous study has investigated $YN$ final state interaction effect by using realistic $YN$ potentials. Another previous study has included $KN$ rescattering effect and $\pi N \to KY$ intermediate process in its calculations for charged kaon channels by
using separable interactions. Concerning the study of neutron channels, Li et al.\cite{8} has shown the possibility to extract the elementary amplitude from the reaction on the deuteron.

Very recently an experiment of neutral kaon photoproduction on the deuteron has been done at the Laboratory of Nuclear Science (LNS), in Sendai\cite{9}. They measured the cross section of the $d(\gamma, K^0)YN$ process at a photon energy around the threshold with forward kaon angles.

This paper is structured as follow. The formalism for calculating the transition matrix and observables are shown in Sect. 2. The results and comparisons with experimental data are presented in Sect. 3 and we close the paper with conclusions in Sect. 4.

2. Formulations
In this work we use the KAON-MAID model\cite{2} which includes the $D_{13}(1895)$ resonance beside the Born terms and other resonances as shown in Figure 1 for the elementary operator. Separate hadronic form factors for each vertex were used in order to restore gauge invariance.

![Diagram](image)

Fig. 1. Diagram (a), (b), and (c) : Born terms. Diagram (d), (e), and (f) : Resonance terms. Coupling constants are determined by fitting to the experimental data.

Throughout the paper we work in the deuteron rest frame. For the inclusive process $d(\gamma, K)YN$ the cross section is given by

$$
\frac{d\sigma}{dp_K d\Omega_K} = \int d\Omega_{CM} \frac{m_Y m_N |\vec{p}_K|^2 |\vec{p}_Y^m|}{4(2\pi)^2 E_\gamma E_K W} \times \frac{1}{6} \sum_{\mu_Y \mu_N \mu_{\Delta}} \left| \sqrt{2} (\bar{\psi}_Y \vec{p}_N \mu_N \psi_K^m |T_{\alpha}^K| \Psi_{\mu_\Delta}) \right|^2,
$$

where $W^2 = (P_d + Q)^2$ and $|\vec{p}_Y^m|$ is the hyperon momentum calculated in the center of mass frame of the two final baryons.
The total amplitudes on the deuteron are calculated according to the diagrams shown in Figure 2. For the deuteron wave function and $YN$ interaction we use the Nijmegen models as in the previous studies. Separable interactions rank-1 are applied for the calculations of $KN$ rescattering and $\pi N \rightarrow KY$ process.

\begin{align*}
\text{Fig. 2. Diagram (a) impulse approximation (IA), (b) $YN$ rescattering, (c) $KN$ rescattering, and (d) $\pi N \rightarrow KY$ process. Total amplitude } & T_{\gamma K \lambda} = t_{\gamma K}^\lambda + t_{YN}^K + t_{KN}^K + t_{K \pi}^\lambda. \\
\end{align*}

With respect to polarization observables, we consider the tensor target asymmetries $T_{2M}$ which are given by

\begin{equation}
T_{2M} \frac{d\sigma}{d\Omega_K} = (2 - \delta_{M0}) \Re e V_{2M}, \quad M = 0, 1, 2, \quad (2)
\end{equation}

where

\begin{align*}
V_{2M} &= \sqrt{15} \sum_{\mu' Y \mu N' \lambda} \sum_{\mu_d \mu'_d} (-1)^{1-\mu_d'} \left( \frac{1}{\mu_d} - \frac{1}{\mu_d'} - \mu_d - \mu_d' - M \right) \\
& \times \int_{p_{K_{\text{min}}}^{\text{max}}} p_d \int d\Omega_{Y}^m \kappa \mathcal{M}_{\mu' Y \mu N' \mu_d \lambda} \mathcal{M}_{\mu Y \mu N \mu'_d \lambda} \quad (3)
\end{align*}

with a kinematic factor

\begin{align*}
\kappa &= \frac{m_Y m_N |\vec{p}_K|^2 |\vec{p}_Y^m|^2}{24(2\pi)^2 E_Y E_K W}. \quad (4)
\end{align*}

For extracting the elementary amplitudes, we use the expression

\begin{align*}
\frac{d\sigma}{dp_K d\Omega_K d\Omega_Y} &= \frac{m_Y m_N |\vec{p}_K|^2 |\vec{p}_Y|^2}{4(2\pi)^2 E_Y E_K} \left| (E_Y + E_N) |\vec{p}_Y| - E_Y \vec{Q} \cdot \vec{p}_Y \right|^{-1} \\
& \times \frac{1}{6} D \sum_{\mu' Y \mu N' \lambda} \left| \langle \vec{p}_Y \mu Y | t_{\gamma K}^\lambda | - \vec{p}_N \mu N' \rangle \right|^2, \quad (5)
\end{align*}

where

\begin{align*}
D &= \frac{3}{2} |Y_{00}|^2 u_0^2 + \left( \frac{3}{10} |Y_{20}|^2 + \frac{3}{4} |Y_{21}|^2 + \frac{3}{2} |Y_{22}|^2 \right) u_2^2. \quad (6)
\end{align*}
On the r.h.s. of Eq. (5) the sum of the squared amplitudes of the elementary process $\gamma N \rightarrow KY$ has been completely separated from the deuteron wave function.

3. Results

Figure 3 shows comparisons between the inclusive cross sections of the models and of the experimental data for reaction $d(\gamma, K^0)KY$ as a function of kaon momentum $p_K$ at forward kaon angle $\theta_K = 0$. The left panel for photon energy $E_\gamma = 0.97$ GeV and the right one for $E_\gamma = 1.0$ GeV. The curves are calculated in the impulse approximation only and the data are taken from Tsukada et al. There are several sets of coupling constant by KAON-MAID model. The first one is the set obtained after fitting with the experimental data by including the $D_{13}(1895)$ resonance or the so called missing resonance. It is shown by the solid line in the figure and we call this as set A. The other ones are the sets without the missing resonance, which are shown by the different dashed lines in the figure and we call these as sets B.

As can be seen from the figure, the set A gives over predictions, while the sets B can describe the data fairly well in the $\Sigma$ channels (up to $p_K = 0.4 \text{ GeV/c}$ for $E_\gamma = 0.97 \text{ GeV}$ and up to $p_K = 0.5 \text{ GeV/c}$ for $E_\gamma = 1.0 \text{ GeV}$) and are still poor for the $\Lambda$ channel (up to threshold of $p_K$ for both photon energies). The discrepancies between the set A and the experimental data are originated from the value of coupling constant in the vertex of $\gamma KK_1$ of the set A (see diagram (f) of Figure 2). We can see it from the figure as follow. By setting the value of $\gamma KK_1$ coupling to zero in the set A (indicated with no $K_1$ in the figure), then the cross section reduces to the value in the order of sets B and the experimental data.

Figure 4 shows the tensor target asymmetries as a function of kaon angle $\theta_K$ for photon energy $E_\gamma = 1.1 \text{ GeV}$. The solid lines are obtained after including all final state effects, the dashed ones only $\text{IA+YN+KN}$, the short-dashed ones only $\text{IA+YN}$, and the dotted ones only impulse approximation (IA). As can be seen in
Figure 4 shows the elementary amplitude as a function of kaon angle $\theta_K$ for different photon energy and different spectator proton momentum. The solid lines are the extracted elementary amplitudes from the reaction on the deuteron, while the dashed ones are obtained from the free process. As can be seen in the figure that the agreement between the extracted and the ones from the free process are very good especially in the quasi-free scattering kinematics, where the spectator proton has zero momentum.

4. Conclusions

The sets B of KAON-MAID models describe the experimental data better than the set A. This indicates that the data on the deuteron can be used to study the elementary process. Tensor target asymmetries are more suitable for investigating the $YN$ interaction through the rescattering effects at the final state of $\gamma d \rightarrow KYN$. For the process $d(\gamma, K^0YN)N$, the rescattering effects are negligibel at the quasi-free scattering (QFS) kinematics. This gives us a possibility to extract the elementary amplitude. At QFS kinematics the extracted and the free-process amplitudes agree well. This demonstrates that kaon photoproduction on the deuteron in the QFS
kinematics can be used for investigating the elementary process in the neutron channels. This suggests that QFS kinematics is suitable for measurements.

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