Magnetic interaction induced by the anomaly in kaon-photoproductions

S. Ozaki, H. Nagahiro and A. Hosaka

Research Center for Nuclear Physics, Osaka University, Ibaraki 567-0047, Japan

Abstract

We study the role of magnetic interaction in the photoproduction of the kaon and hyperon. We find that the inclusion of a higher order diagram induced by the Wess-Zumino-Witten term has a significant contribution to the magnetic amplitude, which is compatible to the observed photon asymmetry in the forward angle region. This enables us to use the $K^*$ coupling constants which have been determined in a microscopic way rather than the phenomenological ones which differ largely from the microscopic ones.

Strangeness production is one of important subjects in hadron and nuclear physics. It is the basis of hyperon interactions and hyper-nuclear physics, where an expansion to the new dimension of strange matter is being explored. Many reactions of producing exotic states including pentaquarks are also associated with strangeness productions. Therefore, the understanding of the production mechanism is indeed a key to discuss the above interesting physics. However, the theoretical status of the production mechanism is not yet well established.

Photoproduction of kaon and hyperon is one of the simplest reactions among them [1, 2, 3, 4]. If the kaon is treated as a light particle as the pion, which are altogether regarded as the Nambu-Goldstone bosons, their interactions are governed by the low energy theorems of chiral symmetry, respecting flavor SU(3) symmetry as well. In fact, in order to produce the kaon and hyperons, energy of order of 1 GeV must be deposited and therefore, the naive application of the low energy theorems might be doubtful.

Yet, many reaction studies so far are based on the effective Lagrangian approach, the form of which is determined by symmetries compatible with flavor and chiral symmetries with much success [5, 6]. Then, various coupling constants such as kaon and vector $K^*$ coupling constants are treated as parameters. In literatures, the kaon coupling constants such as $g_{KNN}$ and $g_{K\Sigma}$ are determined microscopically from the pion coupling $g_{\pi NN}$ under flavor SU(3) symmetry rotations with suitable input of the $F/D$ ratio [7, 8]. This method may be also applied to the $K^*$ coupling constants. If we have a consistent understanding for the strong interaction, such parameters should be universal and can be applied to other reactions.
By now, many experimental data are available for the kaon photoproductions from various photon facilities including LEPS [1, 2], CLAS [3] and SAPHIA [4]. They provide detailed information on energy dependence of cross sections, angular dependence and polarization phenomena. In such a situation, it is very important to study these data based on a microscopic description which is compatible with QCD.

In the present paper, we would like to study the relevant reactions in the effective Lagrangian approach, where Born diagrams are computed as shown in Fig.1(a)-(d). There, various coupling constants are input parameters, reflecting the microscopic nature of the interactions. A unique feature of recent photoproduction experiments is in the use of the polarized photon. In particular, the LEPS group has been providing data for the photon asymmetry in the forward angle region. Here we focus on the reaction

$$\gamma + p \rightarrow K^+ + \Lambda$$

in order to clarify the existing problem and to show its resolution.

An advantage in the forward angle region is the $t$-channel dominance as shown in Fig.1(c), where one can study the interactions of the exchanged particles, exclusively. There we expect that dominant contributions are from $K$ and $K^*$ exchanges. The properties of these two meson exchanges associated with the electromagnetic interaction are of interest and can be distinguished by the azimuthal $\phi$-angular distribution by using the linearly polarized photon [9]. For productions of a pseudoscalar particle (in the present study it is the kaon), if the final state particles are produced more along the photon polarization direction, the interaction is dominated by the electric component and is induced by the $K$ exchange. In contrast, if the final state particles are produced more along the direction perpendicular to the polarization, the interaction is dominated by the magnetic component and is induced by the $K^*$ exchange [10].
Table 1: Comparison of $K$ and $K^*$ coupling constants from Refs. [5] and [7]. In Ref. [5], $K^*$ coupling constants are determined by phenomenologically in order to reproduce the photoproduction data, while in Ref. [7] they are constructed microscopically.

|                          | Phenomenological | Microscopic |
|--------------------------|------------------|-------------|
| $g_{K^*N\Lambda}$        | $-13.46$         | $-12.65$    |
| $g_{K^*N\Sigma}$         | $4.25$           | $5.92$      |
| $g_{V^0_{K^*N\Lambda}}$ | $-25.21$         | $-5.63$     |
| $g_{T^0_{K^*N\Lambda}}$ | $33.13$          | $-18.34$    |
| $g_{V^0_{K^*N\Sigma}}$  | $-15.33$         | $-3.25$     |
| $g_{T^0_{K^*N\Sigma}}$  | $-29.67$         | $7.86$      |

In order to characterize the $\phi$ angular distribution, the photon asymmetry is used, which is given by

$$A = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel}, \quad (2)$$

where $\sigma_\perp$ and $\sigma_\parallel$ are defined in Refs. [9, 10]. By this definition, the interaction is dominated by the electric component if $A$ is negative, while magnetic if positive. Observations including recent kaon photoproductions indicate that the asymmetry $A$ is positive [1, 2]. In order to explain the positive values, a rather strong magnetic interaction is needed which has been incorporated by the strong coupling of $K^*$ into the previous calculations. In Table 1 we show phenomenological coupling constants [5] which are compared with those determined microscopically [7]. The former are determined to fit the data including the asymmetry, while the latter are by SU(3) symmetry with the $F/D$ ratio guided by the vector meson dominance for $g_{V^0_{K^*}}$, and by SU(6) relation for $g_{T^0_{K^*}}$. We see that the phenomenological couplings (left) are typically five times larger than the microscopic couplings (right).

In order to supply the missing strength of the magnetic interaction, in this paper, we would like to propose an additional mechanism induced by the Wess-Zumino-Witten (WZW) term associated with the QCD anomaly [11]. In the presence of the gauged WZW term, there is a $\gamma M M M$ ($M = \text{meson}$) vertex which may contribute to kaon photoproductions with one loop as shown in Fig. 1(e). There are several good features in the consideration of such a process. First, the strength of the anomalous term of $\gamma M M M$ is unambiguously determined by QCD. It is given by

$$\mathcal{L}_{\gamma K^+ K^- \pi^0} = \frac{2}{3} e N_c \epsilon_{\mu \nu \rho \sigma} A^\mu \frac{1}{(2 f_\pi)^3} \partial^\nu K^+ \partial^\rho K^- \partial^\sigma \pi^0, \quad (3)$$

where $e$ is the electric charge, $N_c = 3$ the number of colors and $f_\pi = 93$ GeV the pion decay constant. Second, it contains the antisymmetric tensor $\epsilon_{\mu \nu \rho \sigma}$ ($\epsilon^{0123} = -\epsilon_{0123} = +1$), and contributes to the magnetic interaction of the photon. Third, the anomalous vertex contains the incident photon momentum ($k$), and therefore, the contribution is expected to increase as
the photon energy is increased. Of course, the amplitude should not keep increasing up to very large \( k \), since it violates the unitarity. However, we expect that it should happen at low energy. Motivated by these considerations, we include the one-loop process as shown in Fig. 1(e) in the photoproduction in addition to the Born diagrams.

There are two remarks in order. One is the fact that the loop integral diverges quadratically, and therefore we need to introduce a suitable regularization. Another is the problem of double photoproduction in addition to the Born diagrams. Motivated by these considerations, we include the one-loop process as shown in Fig. 1(e) in the large \( k \) the photon energy is increased. Of course, the amplitude should not keep increasing up to very large \( k \), since it violates the unitarity. However, we expect that it should happen at low energy. Motivated by these considerations, we include the one-loop process as shown in Fig. 1(e) in the photoproduction in addition to the Born diagrams.

Let us now turn to the formulation. The Born diagrams are calculated by the effective Lagrangian method. The interaction terms for the strong interactions are given by

\[
\mathcal{L}_{KN\Lambda} = -\frac{g_{KN\Lambda}}{M_N + M_\Lambda} \bar{\Lambda} \gamma_\mu \gamma_5 \partial_\mu K^- N + h.c.,
\]

(4)

\[
\mathcal{L}_{KNS} = -\frac{g_{KNS}}{M_N + M_\Lambda} \bar{\Sigma} \gamma_\mu \gamma_5 \partial_\mu K^- N + h.c.,
\]

(5)

\[
\mathcal{L}_{K^\ast N} = g_{K^\ast N} \bar{\Sigma} \gamma_\mu \partial^\mu K^- N + h.c.,
\]

(6)

\[
\mathcal{L}_{K^\ast N\Lambda} = -g_{K^\ast N\Lambda} \bar{\Lambda} \gamma_\mu K^\ast_\mu N + \frac{g_{K^\ast N\Lambda}}{M_N + M_\Lambda} \bar{\Lambda} \gamma_\mu \gamma_5 \partial_\mu K^\ast_\mu N + h.c.,
\]

(7)

where notations for various symbols are standard as defined in Ref. [10]. Here, we have adopted the pseudovector coupling for the kaon vertices. The approximate equivalence to the pseudoscalar type was discussed in Ref. [12].

There are seven electromagnetic interactions as given by

\[
\mathcal{L}_{\gamma KK} = -ie[\partial_\mu (\bar{K}^+ K^-) - (\partial_\mu K^-) K^+] A^\mu,
\]

(8)

\[
\mathcal{L}_{\gamma K^\ast} = g_\gamma K^\ast \epsilon_{\mu \rho \sigma \rho} (\partial^\mu A^\nu) (\partial_\rho K^\ast - \partial_\nu K^-) K^{\ast + \rho},
\]

(9)

\[
\mathcal{L}_{\gamma NN} = -ie\bar{N}(\gamma^\mu - \frac{\kappa_N}{2M_N} \sigma_{\mu \nu} \partial_\nu) N A_\mu,
\]

(10)

\[
\mathcal{L}_{\gamma AAA} = \bar{\Lambda} \frac{e\kappa_A}{2M_N} \sigma_{\mu \nu} \partial_\nu \Lambda A_\mu,
\]

(11)

\[
\mathcal{L}_{\gamma SS} = \bar{\Lambda} \frac{e\kappa_A}{2M_N} \sigma_{\mu \nu} \partial_\nu \Sigma A_\mu,
\]

(12)

\[
\mathcal{L}_{\gamma S\Lambda} = -\sqrt{\frac{2}{3}} \left( \frac{1}{\sqrt{3}} \right) \frac{3eg_M}{2M_N (M_N + M_\Delta)} e^{\mu \nu \rho} \bar{\Lambda} \partial_\mu \Sigma_\nu (\partial_\sigma A_\rho),
\]

(13)

\[
\mathcal{L}_{\gamma K\Lambda} = ie g_{K\Lambda} \bar{\Lambda} \gamma_\mu \gamma_5 K^- N A_\mu.
\]

(14)

Here, various electromagnetic couplings are given as follows. The anomalous magnetic moments are \( \kappa_\rho = 1.79, \kappa_\Lambda = -0.613, \kappa_\Sigma = -1.61 \). In Eq. (13) \( g_M \) is a dimensionless coupling constant for the \( \pi N \rightarrow \Delta \) magnetic transition, \( g_M = 3.02 \) [13]. The coupling constant of \( g_{\gamma KK^\ast} \) in Eq. (8) is taken to be 0.254 GeV\(^{-1}\) in order to reproduce the radiative decay \( K^{\ast \pm} \rightarrow K^\pm \gamma \) [14]. We introduce the contact \( \gamma K\Lambda \) interaction in order to preserve gauge invariance.

As usual, we need to include the form factors for which we adopt the gauge invariant and covariant form factors [13, 16].

\[
F_\chi = \frac{\Lambda_c^4}{\Lambda_c^4 + (x - m^2)^2}, \quad x = s, u, t.
\]

(15)
The cutoff parameter $\Lambda_c$ is commonly used for all types of form factors and is fixed in order to reproduce the absolute values of the cross sections. Having those setups, the computation of various cross sections is straightforward.

Obviously, the present choice of the Born diagrams are restricted, since we do not include nucleon resonances which are important near the threshold region $E_\text{cm} \sim 0.5$. However, the data show that the energy dependence becomes rather smooth in the energy region $\sqrt{s} > 2$ GeV, implying that the individual resonance effects are averaged and the background contributions become important. This is the energy region that we study in this work and is where the LEPS data covers.

In order to show the quality of our calculation, we first show the differential cross section $d\sigma/d\cos \theta$ at $W = 2.164$ GeV in Fig. 2 as compared with the experimental data from CLAS [3] and LEPS [1], where $W = \sqrt{s}$ is the total energy in the center of mass system. Here we first discuss the result of the Born diagrams which is denoted by the dashed line. In comparison with data, the choice of the cutoff parameter is important, and we set $\Lambda_c = 0.88$ GeV. We find that...
the agreement is good already at the tree level. There is some disagreement in the extremely forward region and in the backward region. Effects which are not included in the present study might be important such as Reggeon contributions \cite{17,18}, coupled channel effects \cite{19,20,21} and resonance contributions.

Now if we apply the same Born diagram calculations to the asymmetry, as already anticipated, we fail to reproduce the positive values as shown in Fig. 3, where the LEPS data \cite{1} at $W = 2.109$ GeV (dotted line) and at $W = 2.196$ GeV (dash-dotted line) are shown. We have checked that the negative values are caused by the kaon exchange dominance which is of electric nature. We would like to emphasize once again that the relatively small $K^*$ coupling constants which are determined microscopically are not compatible with the large magnetic interaction as required in experiments.

Now let us consider the loop contribution induced by the WZW term. The loop integral is proportional to

$$\int \frac{d^4q}{(2\pi)^4} \left( \frac{1}{(p - q)^2 - m_K^2} \right) \epsilon \epsilon_{\mu\nu\sigma\rho} \epsilon_{\mu q_k k_{k'}},$$

where the external momenta $k, k', p, p'$ are for the incoming photon, outgoing kaon, incoming proton and outgoing $\Lambda$, respectively, as shown in Fig. 1, and $M_B$ denotes the mass of the baryon running in the loop (either proton or $\Sigma$). We have performed the integral by introducing the Feynman parameters in the dimensional regularization. After subtracting the $1/\epsilon$ term as well as constant terms and introducing a scale parameter $\mu$ in the form of $\ln \mu$, we have estimated the integral numerically. The details of computation will be reported elsewhere \cite{22}. It is noted that due to the presence of the $\epsilon_{\mu\nu\sigma\rho}$ tensor, the loop integral contributes to the same components of the amplitude as the $K^*$-exchange does. In this sense, the loop diagram effectively renormalizes the $K^*$ coupling constants.

If we take the scale parameter $\mu$ at a hadronic scale $\sim 1$ GeV, the loop diagram brings a significant contribution to the magnetic interaction. In practice, we multiply an overall form factor $F_t$ to the one loop Fig. 1(e) term with slightly different cutoff parameter $\Lambda_c = 0.69$ GeV in order to obtain a good agreement with the experimental data. This smaller cutoff parameter is also employed for other form factors for the Born diagrams. It is somewhat unpleasant that the form factor is included here also. We shall not, however, discuss this important issue which is microscopically related to hadron structure, but simply follow the empirically successful prescription.

Now we see that the effect of the loop contribution is sufficiently large even to flip the sign of the asymmetry as shown in Fig. 3. The agreement with the experimental data is remarkable including the increasing tendency as the photon energy is increased. We have also verified that the differential cross section with the inclusion of the loop diagram agrees well with the data as shown in Fig. 2 by the solid line. The achievement of the good agreement for both the asymmetry and the differential cross section is not very trivial, while varying a single parameter $\Lambda_c$ in the present study.

In conclusion, we have shown that the large magnetic interaction as observed in polarized photon experiments for the kaon photoproduction can be qualitatively described by the inclusion
of the loop diagrams induced by the WZW term associated with QCD anomaly. This may explain the origin of the large $K^*$ couplings which have been phenomenologically necessary but significantly different from what are expected in a microscopic derivation. The present result encourages us to use the microscopic model for various meson-baryon coupling constants which are employed in the effective Lagrangian approach. Having the framework based on a microscopic description will be useful not only to the conventional reactions as discussed here but also to extensions to more exotic phenomena.

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