KAON PHOTOPRODUCTION ON THE NUCLEON:
STATUS AND FUTURE PROSPECTS

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Kaon photo- and electroproduction off the nucleon is investigated in the framework of
an isobaric model up to energies of about 1 GeV above threshold for all six isospin
channels. The hadronic coupling constants in the model are determined by fitting to
the available experimental data. We give a brief status report on the state of these
models and discuss problems to be attacked in the future. We include hadronic form
factors and show that they are essential for a proper description of the dynamics even
though their inclusion has to be done carefully in order to preserve gauge invariance.
We also investigate the effects of the $K^0$ electromagnetic form factors for two quark
models on the longitudinal and transverse differential cross sections. It is found that
only the reaction $n(e, e'K^0)\Lambda$ is sufficiently sensitive to extract the $K^0$ form factor.

1 Introduction

For more than three decades, kaon electromagnetic production has been used as
a tool to study strange hadrons and their resonances. However, only with the recent
advance of high energy, high duty cycle electron accelerators like TJNAF can the full
potential of this reaction be exploited. The process can be performed on nucleons or
nuclei. With the nucleon as a target, the final state consists of a kaon and a hyperon,
and one can study the reaction mechanism, coupling constants, electromagnetic form
factors of the kaon or hyperon, or even form factors at the hadronic vertices which
until now have usually been neglected. Using a nucleus as the target, one can study
the hypernuclear spectroscopy and the $YN$ interaction.

Our understanding of the kaon-baryon interaction is much poorer than our knowl-
edge of the pion-nucleon force, exemplified by the uncertainty in the kaon-hyperon-
nucleon coupling constants. Unlike the well established pion-nucleon interaction
which yields the pion-nucleon coupling constant $g_{\pi NN}^2/4\pi$ around 14, the kaon
coupling constants extracted from different reactions (from hadronic to electromagnetic)
vary wildly as shown in Table 1. For most of the past decades there was a serious
discrepancy between values for the coupling constants extracted from electromagnetic
Table 1. The leading hadronic coupling constants from several models. Sets VI-VIII come from fits to isobaric photoproduction models.

| Set | Source |
|-----|--------|
| I   | SU(3)  |
| II  | $K^-N$ scattering |
| III | $Y-N$ scattering |
| IV  | $N\bar{N} \to YY$ LEAR data |
| V   | QCD sum rules |
| VI  | $p(\gamma, K^+)\Lambda, p(e, e'K^+)\Lambda$ |
| VII | $p(\gamma, K^+)\Lambda, p(e, e'K^+)\Lambda$ |
| VIII| $p(\gamma, K^+)\Lambda, p(e, e'K^+)\Lambda, p(\gamma, K^+)\Sigma^0, p(e, e'K^+)\Sigma^0, p(\gamma, K^0)\Sigma^+, n(e, e'K^+)\Sigma^-$ |

| $\frac{g_{K\Lambda N}}{\sqrt{4\pi}}$ | $\frac{g_{K\Sigma N}}{\sqrt{4\pi}}$ | Reference |
|---------------------------------|---------------------------------|-----------|
| $-4.40$ to $-3.0$               | $+0.9$ to $+1.3$               |           |
| $|3.53|$                        | $|1.53|$                        |           |
| $-3.86$                         | $+1.09$                        |           |
| $-3.92$                         | -                               |           |
| $-1.96$                         | $+0.33$                        |           |
| $-3.16$                         | $+0.80$                        |           |
| $-2.38$                         | $+0.23$                        |           |
| $-3.74$                         | $+0.86$                        |           |

Recent $(\gamma, K)$ studies, however, have shown that the electromagnetic values can be brought into better agreement with the hadronic analyses.

Up to now, most analyses have focused only on the $p(\gamma, K^+)\Lambda$ and $p(\gamma, K^+)\Sigma^0$ channels. The lack of experimental data for other isospin channels was a limiting factor for almost three decades. Considerable efforts have been devoted to model the first reaction, for which most cross section data are available. This situation, which lead to an incomplete understanding of the kaon photoproduction process, is about to change with new data from SAPHIR for the neutral kaon channel and the imminent start of experiments in Hall B at TJNAF that will explore all possible isospin channels.

2 Isobaric Models

In general, the $T$-matrix for any photoproduction process can be written in terms of a Bethe-Salpeter equation

$$M = V + V G T,$$

where $V$ represents the driving term for the particular photoproduction process, $G$ is the meson-baryon two-particle propagator, and $T$ is the hadronic meson-baryon
final state interaction. While approaches using the above description are becoming increasingly successful in the description of pion photoproduction, the hadronic final state interaction is usually neglected in kaon photoproduction models. Thus, the $T$-matrix is simply approximated by the driving term which is usually assumed to be given by a series of tree-level Feynman diagrams.

Figure 1 shows the set of standard Feynman diagrams included in the description of the process. Besides the Born terms with the nucleon, hyperon and kaon in the respective $s$-, $u$-, and $t$-channel, $N^*$, $Y^*$ and $K^*$ resonances are introduced in the same channels. The coupling constants which are products of strong and electromagnetic couplings are then fitted to the available data. Until now the quality of the data has neither permitted a clear identification of the relevant resonances in the $(\gamma, K)$ process nor allowed a clear separation of the resonance contributions from the background. The recent study of Ref. 5 gives a very comprehensive description that includes resonances up to spin $5/2$. They achieve an excellent fit with strong couplings within the SU(3) range. However, due to the large number of resonances the resulting elementary operator is rather cumbersome for nuclear applications.

In general, the transition matrix elements can be written as

$$M_{fi} = \bar{u}(p_Y) \sum_{j=1}^{6} A_j(s, t, k^2) M_j(u(p_N)),$$

where $s$ and $t$ are the usual Mandelstam variables, and the the gauge and Lorentz invariant matrices $M_j$ are given in many references 5, 8, 9. The amplitudes $A_j$ depend on the particular model employed for background and resonances.

2.1 Hadronic form factors and gauge invariance

No analysis of kaon photoproduction has ever included a form factor at the hadronic vertex. However, since most of the present isobaric models diverge at higher energies, the need for such hadronic form factors has been known for a long time. Furthermore, recent work on the additional isospin channels demonstrated that models which give a good description of the $(\gamma, K^+)$ data can give unrealistically large predictions for the $(\gamma, K^0)$ channels. As we show below, incorporating a hadronic form factor helps alleviate this problem. On the other hand, it is well known that the inclusion of form factors at the hadronic vertices, $KY N$, leads to a problem with gauge invariance, since not every diagram shown in Fig. 1 retains gauge invariance by itself. The resonance contributions are constructed to be independently gauge invariant, but this is not the case for the Born diagrams shown in Figs. 1 (a), (b), and (c).

As an example, for the $p(\gamma, K^+)^{\Lambda}$ channel the amplitude for the diagram (a) in
Figure 1. Feynman diagrams for kaon photoproduction. The diagrams in (a), (b), and (c) represent the s-, u-, and t-channel Born terms, respectively, while diagrams (d), (e), and (f) show the corresponding resonance contributions. Note that the $\Delta$ resonance contributes only to $\Sigma$ production. The vertex factors $f_1^s$, $f_2^s$, $f_1^u$, and $f_2^u$, as well as the corresponding propagators are given e.g. in Refs. 8, 9.

Fig. 1 is given by

$$M^p = \bar{u}_\Lambda \frac{i e g_{K\Lambda N} \gamma_5}{s - m_p^2} \left[ \frac{\kappa_p}{m_p} (p_p \cdot k q - p_p \cdot \epsilon k) - (1 + \kappa_p) \epsilon \frac{q}{k} \right] u_p ,$$

where the last term is not gauge invariant by itself. The amplitude from diagram (b) is

$$M^{K^+} = \bar{u}_\Lambda \frac{i e g_{K\Lambda N} \gamma_5}{t - m_K^2} \left( \frac{4}{s - m_p^2} q K \epsilon p_p \cdot k \right) u_p .$$

(d) (c) (a) (b) (e) (f)
Assuming a point-like hadronic vertex, the term of Eq. (3) along with Eq. (4) can be combined together to form a gauge-invariant term.

However, if we include hadronic form factors $F_h(p^2, q^2, p^2)$ at both vertices, those terms will become

$$\Delta M = \bar{u}_\Lambda \frac{ie g_{K \Lambda N} \gamma_5}{s - m_p^2} \frac{4}{t - m_K^2} \left[ q_K \cdot \epsilon \ p_p \cdot k \ F_h(m_p^2, t, m_\Lambda^2) 
- p_p \cdot \epsilon \ q_K \cdot k \ F_h(s, m_K^2, m_\Lambda^2) \right] u_p ,$$

(5)

which will not vanish when substituting $\epsilon \rightarrow k$, since the hadronic form factors, $F_h(m_p^2, t, m_\Lambda^2)$ and $F_h(s, m_K^2, m_\Lambda^2)$, have different arguments\textsuperscript{11}. In order to restore gauge invariance, Ohta\textsuperscript{12} has derived an additional amplitude by making use of the minimal-substitution prescription. In our formalism, Ohta’s additional amplitude has the form

$$\Delta M_{\text{Ohta}} = \bar{u}_\Lambda \frac{ie g_{K \Lambda N} \gamma_5}{s - m_p^2} \frac{4}{t - m_K^2} \left[ q_K \cdot \epsilon \ p_p \cdot k \left\{ F_h(m_p^2, m_K^2, m_\Lambda^2) - F_h(m_p^2, t, m_\Lambda^2) \right\} 
- p_p \cdot \epsilon \ q_K \cdot k \left\{ F_h(m_p^2, m_K^2, m_\Lambda^2) - F_h(s, m_K^2, m_\Lambda^2) \right\} \right] u_p ,$$

(6)

where $F_h(m_p^2, m_K^2, m_\Lambda^2) = 1$, i.e. if all particles are on-shell. Adding this amplitude to Eq. (5) restores gauge invariance, but at the price of removing the off-shell hadronic form factors at tree level for non gauge-invariant diagrams.

A consistent procedure for the inclusion of hadronic form factors in photoproduction is, however, somewhat complicated, since the form factor should be different for different channels\textsuperscript{13}. Such an investigation is still underway. For a qualitative study of the influence of hadronic form factors on kaon production, we choose to multiply the whole amplitude with a simple monopole form factor

$$F_h(\Lambda_c, t) = \frac{\Lambda_c^2 - m_K^2}{\Lambda_c^2 - t} ,$$

(7)

with $\Lambda_c$ as a cut-off parameter to be determined by our fit.

2.2 Results

Preliminary results of our fits are displayed in Table 2, where all available data in the different isospin channels have been included in a simultaneous fit. In this study we have used the complete data set, including preliminary Bonn data. In a previous investigation we found that including the few charged $\Sigma$ photoproduction data lead to substantially suppressed coupling constants $g_{K\Sigma N}$ and $g_{K\Lambda N}$\textsuperscript{10}. This result is changed completely by the inclusion of the hadronic form factor. As shown by sets I and II
Table 2. The coupling constants of set I were obtained by fitting all differential and total cross section data except those of charged Σ and the new Bonn polarization data, set II by including all data.

| Set   | Coupling Constant | I |   | II |   |
|-------|------------------|---|---|----|---|
|       | KΣ | KΛ | KΣ | KΛ |
| g_{KΣN}/\sqrt{4\pi} | 0.769 | 1.224 |
| g_{KΛN}/\sqrt{4\pi} | -1.911 | -3.092 |
| G_V(K^*)/4\pi | 0.084 | -0.132 | -0.080 | -0.189 |
| G_T(K^*)/4\pi | -0.240 | 0.141 | -0.080 | -0.123 |
| G_{N4}(1650)/\sqrt{4\pi} | -0.142 | -0.033 | -0.007 | -0.064 |
| G_{N6}(1710)/\sqrt{4\pi} | -0.768 | -0.133 | 2.102 | -0.065 |
| G_{Δ(1/2)}(1900)/\sqrt{4\pi} | 0.120 | - | 0.234 | - |
| G_{Δ(1/2)}(1910)/\sqrt{4\pi} | 0.746 | - | -0.990 | - |
| Λ_c | - | 0.853 |
| N | 723 | 748 |
| $\chi^2/N$ | 7.33 | 5.98 |

in Table 2, the hadronic form factor given in Eq. (7) has a profound influence on the coupling constants and the $\chi^2$. The two leading coupling constants increase to values consistent with SU(3) (see Table 1) and the $\chi^2$ is significantly reduced. We believe that the absence of the hadronic form factors in previous models is the main reason for the disagreement between the hadronic and electromagnetic extractions of the kaon-nucleon-hyperon couplings. Not only the Born couplings but also the resonance couplings are significantly changed both in sign and magnitude when the form factor is included. The cut-off mass of 850 MeV appears to be reasonable in comparison to meson-nucleon scattering models.

The impact of the hadronic form factors on the total cross sections in all six isospin channels is displayed in Fig. 2. While both the $K^+Λ$ and $K^+Σ^0$ data are fairly well reproduced in either model it is the neutral $K^0$ and charged Σ production where the form factor makes an important difference. In $K^+Σ^-$ production the form factor can reduce the total cross section by more than a factor of four which is a significant improvement over the previous models. In general, the form factor improves the convergence of the cross sections at the higher energies where most models tend to overpredict the data by large amounts. Nevertheless, more resonances will have to be included in a more realistic model. Below we give a brief list of additional issues that will need to be addressed in future models:

1. **Pseudoscalar versus pseudovector coupling**

   Most models until now have employed pseudoscalar coupling for the kaon-
hyperon-nucleon vertex, mostly because previous studies indicated that using pseudovector coupling would lead to a further suppression of the leading Born couplings in the fit to the data. However, with the inclusion of the hadronic form factor these studies have to be repeated since this suppression has vanished. In view of the successes of chiral symmetry arguments in the SU(2) sector one may want to apply pseudovector coupling even though the larger mass of the kaon may make those arguments less valid.

2. Unitarity and crossing

Neglecting the final meson-baryon interaction in the full \((\gamma, K)\) T-matrix automatically leads to a violation of unitarity since flux that can "leak out" into inelastic channels has not been properly accounted for. In principle, enforcing
unitarity dynamically requires solving a system of coupled channels with all possible final states. This is clearly a daunting task, especially since it would require information on channels such as $\Lambda(K^+, K^+)\Lambda$ for which no experimental information is available for obvious reasons. Including unitarity properly would break crossing symmetry which has been imposed by a number of models. Crossing can only be maintained at the tree level but would have to be given up in a coupled channels model. This becomes apparent when one compares the intermediate hadronic states of $p(\gamma, K^+)\Lambda$ with those of $p(K^-, \gamma)\Lambda$. While these two processes are related via crossing at the tree level, the photoproduction process proceeds through intermediate states with zero strangeness while the radiative capture reaction requires $S = -1$. A first step towards the enforcement of unitarity would be the inclusion of phases between the different resonances which could be fitted to the data. Thus, the data themselves would determine the amount of final state interaction in a phenomenological way.

3. **Duality**

The idea of duality comes from high-energy hadron-hadron interactions where it was shown that including all resonances in the $t$-channel along with all resonances in the $s$-channel would amount to double counting. At present, it is not clear how and if this issue would apply to low-energy kaon photoproduction. Clearly, the very truncated model space in both $s$- and $t$-channel probably minimizes double counting, albeit not in a consistent fashion. While models have been constructed with no $K^*$ resonances that allowed a fairly good description of the data, no model has attempted the reverse, eliminating $s$-channel resonances while including as many $t$-channel contributions as possible. Such a model may not give a good $\chi^2$ since it would miss the peaks of the resonances in the cross sections but may give an adequate average description of the cross section. Future work will have to verify this possibility. An important difference to duality in hadron-hadron interaction is the presence of gauge invariance which requires that both $s$- and $t$-channels be present at the Born level. Thus, the double counting argument could only apply to the resonance contributions in these channels.

3 **The $K^0$ Electromagnetic Form Factor**

Among the many applications of the kaon electromagnetic production process is its potential to access electromagnetic form factors of strange hadrons. The recent completion of TJNAF has sparked increased interest in form factors of baryons and mesons. In particular, for the charged pion and kaon experimental proposals have been approved at TJNAF, while up to now no study has been performed to esti-
mate the effect of the neutral kaon form factor on experimental observables accessible at this facility. The underlying reason, as pointed out by Ref. 17, is the difficulty to perform a direct measurement of the form factor due to the relatively small cross sections, in the presence of a large background. The first step in this direction is to measure a number of structure functions of the neutral kaon electroproduction cross section, as proposed by Magahiz et al. 18.

We have examined the sensitivity of the three reactions, $p(e, e'K^0)\Sigma^+$, $n(e, e'K^0)\Sigma^0$, and $n(e, e'K^0)\Lambda$ to two different relativistic quark models of the $K^0$ form factor, the light-cone quark (LCQ) and quark-meson vertex (QMV) model. We point out that the $K^0$ form factor is a prime candidate to be obtained from lattice gauge calculations and therefore should be measured with high priority. As shown in Fig. 3, we found only very small effects in the observables for the $\Sigma$ production reactions (see Fig. 3). This can be understood from the fact that the leading Born coupling constant, $g_{K\Sigma N}$, which multiplies the $K^0$ t-channel pole term, ranges between $0.1 < |g_{K\Sigma N}/\sqrt{4\pi}| < 1.0$. It is therefore much smaller than $g_{K\Lambda N}$, which governs the $K\Lambda$ Born terms and has a range of $2.0 < |g_{K\Lambda N}/\sqrt{4\pi}| < 4.4$. Future experiments will therefore have to use the $n(e, e'K^0)\Lambda$ reaction, where we found sizable effects from the $K^0$ form factor.

As expected, the transverse cross section is not sensitive to the $K^0$ form factor, because the $K^0$ pole amplitude is proportional to the function of $k^2$ and vanishes at
the photon point, $k^2 = 0$. Therefore, the $K^0$ form factor contributes mostly to the L and LT cross sections. At backward angles, the predictions based on the various models are clearly distinguishable. The longitudinal cross section computed with the form factor of the LCQ-model is almost 50\% larger than the calculation without $K^0$ pole terms, while the QMV-model calculation lies between those two. While we only show the L and T structure functions here, the sensitivity of the LT term is similar to the L term. Thus, experiments at TJNAF’s Hall B would not need to perform an L/T separation in order to access the form factor.

In order to reduce the model dependency and to obtain accurate quantitative predictions, sufficient information from kaon photoproduction experiments is required. The analysis of those measurements has to determine the relevant resonances and coupling constants and thus define the production amplitude as precisely as possible.

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