Beam polarization asymmetries for the \( p(\gamma, K^+)\Lambda \) and \( p(\gamma, K^+)\Sigma^0 \) reactions at \( E_\gamma = 1.5 - 2.4 \text{ GeV} \)

R.G.T. Zegers, M. Sumihama, D.S. Ahn, J.K. Ahn, H. Akimune, Y. Asano, W.C. Chang, S. Daté, H. Ejiri, H. Fujimura, M. Fujiwara, K. Hicks, T. Hotta, K. Imai, T. Ishikawa, T. Iwata, H. Kawai, Z.Y. Kim, K. Kino, H. Kohri, N. Kumagai, S. Makino, T. Matsumura, N. Matsuoka, T. Mibe, K. Miwa, M. Miyabe, Y. Miyachi, M. Morita, N. Muramatsu, T. Nakano, M. Niiyama, N. Nomachi, T. Ooba, H. Ohkuma, D.S. Oshuev, C. Rangacharyulu, A. Sakaguchi, T. Sasaki, P.M. Shagin, Y. Shiino, H. Shimizu, Y. Sugaya, H. Toyokawa, A. Wakai, C.W. Wang, S.C. Wang, K. Yonehara, T. Yorita, M. Yoshimura, and M. Yosoi

(The LEPS collaboration)

1 Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
2 Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
3 Advanced Science Research Center, Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-1195, Japan
4 Department of Physics, Pusan National University, Busan 609-735, Korea
5 Department of Physics, Konan University, Kobe, Hyogo 658-8501, Japan
6 Synchrotron Radiation Research Center, Japan Atomic Energy Research Institute, Mikazuki, Hyogo 679-5198, Japan
7 Institute of Physics, Academia Sinica, Taipei 11529, Taiwan
8 Japan Synchrotron Radiation Research Institute, Mikazuki, Hyogo 679-5198, Japan
9 School of Physics, Seoul National University, Seoul, 151-747, Korea
10 Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701
11 Department of Physics, Kyoto University, Kyoto 606-8502, Japan
12 Laboratory of Nuclear Science, Tohoku University, Sendai, Miyagi 982-0826, Japan
13 Department of Physics, Yamagata University, Yamagata 990-8560, Japan
14 Department of Physics, Chiba University, Chiba 263-8522, Japan
15 Wakayama Medical University, Wakayama, Wakayama 641-8509, Japan
16 Department of Physics and Astrophysics, Nagoya University, Nagoya, Aichi 464-8602, Japan
17 Department of Physics and Engineering Physics, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, S7N 5E2
18 Center for Integrated Research in Science and Engineering, Nagoya University, Nagoya, Aichi 464-8603, Japan
19 Institute for Protein Research, Osaka University, Suita, Osaka 565-0871, Japan

(Dated: September 23, 2018)

Beam polarization asymmetries for the \( p(\gamma, K^+)\Lambda \) and \( p(\gamma, K^+)\Sigma^0 \) reactions are measured for the first time for \( E_\gamma = 1.5 - 2.4 \text{ GeV} \) and \( 0.6 < \cos(\theta_{p,\gamma}) < 1.0 \) by using linearly polarized photons at the Laser-Electron-Photon facility at SPring-8 (LEPS). The observed asymmetries are positive and gradually increase with rising photon energy. The data are not consistent with theoretical predictions based on tree-level effective Lagrangian approaches. Including the new results in the development of the models is, therefore, crucial for understanding the reaction mechanism and to test the presence of baryon resonances which are predicted in quark models but are sofar undiscovered.

PACS numbers: 14.20.Gk, 25.20.Lj, 13.60.Le, 13.30.Eg

Strangeness photoproduction is a powerful tool to obtain a deeper insight into baryon resonances. It provides additional information about the baryon resonances to that obtained from \( \pi N \) scattering and \( \pi \)-production reactions. Of special interest are nucleon resonances that have been predicted in quark models and for which no experimental evidence has been found via the \( \pi \)-induced or \( \pi \)-production reactions. Some of these resonances, referred to as ‘missing’, could couple strongly to the \( K \Lambda \) and \( K \Sigma \) channels. To better understand the problem of ‘missing’ resonances and to see whether predictions of baryon resonances can be tested, it is, therefore, very interesting to study experimentally the \( p(\gamma, K^+)\Lambda \) and \( p(\gamma, K^+)\Sigma^0 \) reactions.

Measurements of the energy dependence of the total cross section for the \( p(\gamma, K^+)\Lambda \) reaction at SAPHIR/Bonn resulted in renewed interest because of the presence of a resonance-like structure near \( W = 1900 \text{ MeV} \). Mart and Bemhold showed that this structure could be explained by introducing a \( D_{13}(1895) \) resonance for which a considerable branching into the \( K \Lambda \) channel is predicted. Measurements of the cross section at CLAS/JLAB suggest that the resonance-like structure actually consists of several components which manifest themselves at different \( K^+ \)-scattering angles.

The theoretical calculations are typically performed in a tree-level effective-Lagrangian approach. Janssen et al. showed, however, that large ambiguities arise from (i) the
choice of included resonances, (ii) coupling constants, (iii)
form factors and (iv) the treatment of the non-resonant
‘background’ [5, 7]. Great care is thus advised in
drawing definite conclusions based on the cross-section
data only. Alternative theoretical approaches in which,
for example, off-shell effects are taken into account [5],
can also describe the SAPHIR data well without inclu-
sion of ‘missing’ resonances. Moreover, coupled-channels
effects are not negligible [10]. One way to limit the free-
doms in the model calculations is to analyze results from
all photon-induced channels simultaneously [11].

For the development of the models it is of vital im-
portance to measure additional observables and improve
the quality of the cross section data. Results for the
recoil-polarization asymmetry in the $p(\gamma,K^+)\Lambda$
reaction (self-analyzing by the $\Lambda$ weak decay) are already available
from the SAPHIR data set. Extensive programs to mea-
sure cross sections and recoil polarizations are underway
at JLAB/CLAS [4] and ESRF/GRAAL [12]. Additionally,
measurements of the beam polarization asymmetry
($\Sigma$) are great assets to the database because of the high
sensitivity to the model parameters and the presence of resonances [8, 9].
This asymmetry is defined through
$\left(\frac{d\sigma}{d\Omega}\right)_{pol} = \frac{d\sigma}{d\Omega}[1 + P_{\gamma} \Sigma \cos(2\phi')]$, where
$\left(\frac{d\sigma}{d\Omega}\right)_{pol}$ is the cross section using a linearly-polarized photon beam, $d\sigma/d\Omega$
is the unpolarized cross section, $P_{\gamma}$ the degree of photon po-
larization, $\phi'$ the azimuthal angle between the photon
polarization plane and the vector normal to the
$K^+$ reaction plane. Access to this observable is most easily ob-
tained at backward-Compton scattering facilities [12, 14]
because the photon beam is easily and reliably polarized
to a high degree.

In this Letter, we present for the first time mea-
surements of the beam polarization asymmetries of the
$p(\gamma,K^+)\Lambda$ and $p(\gamma,K^+)\Sigma^0$ reactions. These data were
taken at the new SPring8/LEPS facility in Japan [14].
Photons with a maximum energy of 2.4 GeV were pro-
duced from backward Compton scattering of 351-nm
laser photons off 8-GeV electrons in the SPring-8 stor-
age ring. The photons were tagged by measuring the
scattered electron energies with a resolution $\sigma=15$ MeV.
The degree of polarization of the backscattered photon
beam was 95% at 2.4 GeV and 55% at 1.5 GeV. Half of
the data was taken with horizontally-polarized photons
and the other half with vertically-polarized photons. The
direction of the polarization was switched about every 2
hours. The typical photon flux was $10^6$/s. A 50-mm
thick-liquid-hydrogen target was used.

Charged particles were momentum-analyzed by trac-
ing their paths in a magnetic dipole field by means of a
silicon-strip vertex detector and one drift chamber posi-
tioned upstream from the dipole magnet, and two drift
chambers positioned downstream of the dipole magnet.
The upstream drift chamber consists of 6 wire planes (3
vertical planes, 2 planes at $+45^\circ$ and 1 plane at $-45^\circ$)
each of the downstream drift chambers consists of
5 wire planes (2 vertical planes, 2 planes at $+30^\circ$ and 1
plane at $-30^\circ$). Electron and positron tracks due to pair
production were largely removed at the trigger level by
means of an aerogel Čerenkov veto counter. The event
sample was further cleaned up by removing tracks with a
large track-reconstruction error (confidence level < 2%)
which were mostly due to decay-in-flight events. The
time-of-flight of each track was measured; the start sig-
nal was produced by a plastic-scintillator trigger counter
placed behind the target cell, and an array of 40 plastic
scintillators placed behind the tracking detectors pro-
vided the stop signal. The time-of-flight resolution was
about 150 ps for a typical path length of 4 m. By com-
bining time-of-flight and momentum, the mass of each
track was reconstructed with a resolution ($\sigma$) of 30 (105)
MeV/c$^2$ for a 1 (2) GeV/c kaon. A 3$\sigma$-mass cut was used
to select the positively-charged kaons, with the ad-
titional condition that 0.31 < $mass < 0.74$ GeV/c$^2$
to ensure that the $K^+$ cut does not overlap with the cuts
for the $\pi^+$ and proton. At the highest momenta ($\sim 2$
GeV/c), where the mass resolution was worst, the con-
tamination from the $\pi^+$-particles and protons amounted
to 2% (3.5%) and 2.5% (5%) for the $K^+\Lambda$ ($K^+\Sigma^0$)
production, respectively. These numbers were determined by
extrapolating the Gaussian-shaped mass distributions of
the $\pi^+$’s and protons into the $K^+$ region. $K^+$-mesons
scattered between 0° and 60° degrees in the center-of-
mass frame were detected by the LEPS detector [14].
The track-angle resolution was 2.3 mrad.

Fig. 1 shows the missing-mass spectrum obtained for
the $p(\gamma,K^+)X$ reaction. Besides $\Lambda(1116)$ and $\Sigma^0(1193)$,
additional peaks due to $\Lambda(1405)$, $\Sigma^0(1385)$ (the two are
not resolved) and $\Lambda(1520)$ are observed. A small bump
below 1 GeV/c$^2$ is due to misidentified $\pi^+$ tracks. The
missing-mass resolutions for the $\Lambda$ ($\Sigma^0$) were $\sigma = 17(16)$
and 10(9) MeV/c$^2$ at the highest and lowest momenta,
respectively. A momentum-dependent 2$\sigma$ cut was used
to select the events in each peak. The contamination of
$\Lambda$ ($\Sigma^0$) events in the $\Sigma^0$ ($\Lambda$) peak is less than 0.8%
(0.4%). In total, $7.3 \times 10^4$ $K^+\Lambda$ and $4.9 \times 10^4$ $K^+\Sigma^0$

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{missing_mass_spectrum.png}
\caption{Missing-mass spectrum for the $p(\gamma,K^+)X$ reaction.}
\end{figure}
very nearly the same. Fig. 2 shows the measured ratio is valid because the acceptances for our data taken with the detector acceptance is not present in Eq. 1, which integrated photon yield for each polarization mode, corrected for the dead-time of the data-acquisition system and the random tagger-hit rate. The azimuthal angle \( \phi \) is measured with respect to the horizontal plane. Note that the detector acceptance is not present in Eq. 1, which is valid because the acceptances for our data taken with a horizontally and vertically-polarized photon beam are very nearly the same. Fig. 2 shows the measured ratio in the r.h.s. of Eq. 1 for the total \( K^+ \Lambda \) (a) and \( K^+ \Sigma^0 \) (b) samples. By fitting with a \( C \cos(2\phi) \) function and dividing \( C \) by \( P_\gamma \), \( \Sigma \) is obtained. When using the full data sets, the statistical errors are smaller than the systematic ones (see below).

The \( K^+ \Lambda \) and \( K^+ \Sigma^0 \) data sets were each divided into 9, 0.1-GeV wide, photon-energy bins ranging from 1.5 to 2.4 GeV. The narrow energy binning is important, since the excitation spectrum may vary rapidly due to the presence of resonances. The chosen bin-size is smaller than or comparable to the widths of the relevant baryon resonances. For each energy bin, the events were further divided according to \( K^+ \) scattering angles; 5 bins in \( \cos(\theta_{K^+}^{cm}) \) from 0.6 to 1.0, each with a width of 0.1, except for the 2 most forward bins which had a width of 0.05. For each sub-sample, the beam polarization asymmetry was determined following the above-described procedure (the reduced \( \chi^2 \) of the fits with a \( C \cos(2\phi) \) to the measured asymmetries varied from 0.4 to 2.1). Although the contamination from protons and \( \pi^+ \)'s in the \( K^+ \) sample was small, it gives rise to a non-negligible shift of the measured asymmetry for the \( K^+ \). This was corrected for by determining contamination level from the protons and \( \pi^+ \)'s and their respective asymmetries (determined by selecting \( \pi^+ \)'s and protons in the mass spectra but keeping all other selections described above; for protons the asymmetries are close to 0 and for \( \pi^+ \)'s they are positive, but in general slightly lower than for the \( K^+ \)). Since the asymmetry of the total sample is the average of the asymmetries for the \( K^+ \) events and the proton and \( \pi^+ \) contaminations, weighted by their relative contributions in each sample, the asymmetries for the \( K^+ \)-sample can be extracted. The correction ranged from 0.00 \pm 0.01 for the lowest photon energies to \(+0.03 \pm 0.02 \) at the highest photon energies.

The final results are shown in Fig. 3. The observed asymmetries are positive and increase gradually with rising photon energy. The error bars correspond to the combined statistical (ranging from 0.09 at \( E_\gamma = 1.5 \) GeV to 0.04 at \( E_\gamma = 2.4 \) GeV) and systematic errors (\( \sim 0.02 \)). The latter arise from (i) the photon-yield normalization errors (\( k \) in Eq. 1), and the uncertainties in the degree and angle of linear polarization (systematic error: 0.01), (ii) the partial loss of events in a subset of the data due to a trigger problem in case the decay proton from the \( \Lambda \) (\( \Lambda \rightarrow p\pi^- \) or \( \Sigma^0 \rightarrow \Lambda \gamma \), \( \Lambda \rightarrow p\pi^- \)) hit the trigger counter. The loss is slightly dependent on the polarization direction and the effect on the measured asymmetries was estimated by mimicking the trigger problem in the subset of the data where it did not occur (systematic error (0.01 (0.015)) for \( \Lambda \) \( \Sigma^0 \) production), (iii) contamination from events produced at the trigger counter, which is only significant at very forward \( K^+ \) scattering angles \( \cos(\theta_{K^+}^{cm}) > 0.95 \). (the systematic error is negligible for \( \Lambda \) production and 0.01 for \( \Sigma^0 \) production).

In Fig. 3 the experimental data are compared with the theoretical predictions using the MAID2000 program (dashed lines) and by Janssen et al. (solid lines). These calculations are the most up-to-date available and good examples to see model ambiguities and the sensitivity of the beam polarization asymmetry on the model assumptions. Both calculations are obtained on the basis of a tree-level effective Lagrangian model and make use of the cross-section data from SAPHIR to fix the various parameters in the models through a fitting procedure. The same \( s \)-channel resonances are taken into account, including the ‘missing’ \( D_{13}(1895) \) resonance. With the \( D_{13}(1895) \) resonance, the calculations reproduce the experimental cross sections better but also give dramatically different predictions for the beam polarization asymmetry, including a change of sign \( \frac{\pi^+}{\Lambda} \). The difference between the two sets of predictions lies in the treatment of the non-resonant background terms: Janssen et al. introduce hyperon resonances in the \( u \)-channel to counterbalance the strength produced by the Born terms in a physically relevant way. The calculations also differ in the choice for the hadronic form factor.

For the \( K^+ \Lambda \) channel, the calculations in MAID2000 over-predict the beam polarization asymmetries and those by Janssen et al. under-predict the measurements.
For the $K^+\Sigma^0$ channel, the calculations predict similar absolute values for the beam polarization asymmetries, but with opposite sign. The measurements give positive values, but the magnitude is lower than the values by Janssen et al. The discrepancy between the data and calculations does not necessarily mean that the models have fundamental shortcomings. It could merely indicate that the freedoms are too large and that fitting to cross section data only does not give sufficient boundary conditions. The photon polarization data presented here are great assets to guide the theoretical work.

For $E_\gamma > 2.0$ GeV the above-mentioned models are no longer applicable. Regge-model calculations [17], which reproduce the asymmetry at higher photon energies ($E_\gamma > 5$ GeV) well, are not applicable for energies below $\sim 2.5$ GeV since the s-channel resonances are not taken into account. The new data up to 2.4 GeV provide, therefore, another challenge for future theoretical work.

In short, we present beam polarization asymmetry data for the $p(\gamma, K^+)\Lambda$ and $p(\gamma, K^+)\Sigma^0$ reactions for $1.5 < E_\gamma < 2.4$ GeV and $0.6 < \cos(\theta_{K^+}) < 1.0$. Based on the calculations by Mart and Bennhold [5], the positive sign measured in case of the former reaction indicates the presence of a missing $D_{13}$ resonance. However, in light of the large freedoms in the models, such strong conclusions are premature. Using the new results to constrain the calculations, similar to the case for $\pi$ photoproduction at lower energy, will lead to a strongly enhanced understanding of the reaction mechanisms and are pivotal for testing the presence of missing resonances.

The authors thank the staff at SPring-8 for providing excellent experimental conditions during the long course of the experiment. This research was supported in part by the Ministry of Education, Science, Sports and Culture of Japan, the National Science Council of the Republic of China (Taiwan) and the National Science Foundation.

---

1. S. Capstick and N. Isgur, Phys. Rev. D 34, 2809 (1986).
2. S. Capstick and W. Roberts, Phys. Rev. D 49, 4570 (1994).
3. S. Capstick and W. Roberts, Phys. Rev. D 58, 074011 (1998).
4. M. Tran et al., Phys. Lett. B 445, 20 (1998).
5. T. Mart and C. Bennhold, Phys. Rev. C 61, (R)012201 (1999).
6. R. Schumacher et al., in Proceedings of the XVI Conference on Particles and Nuclei (2002), to be published.
7. S. Janssen et al., Phys. Rev. C 65, 015201 (2002), and private communication.
8. S. Janssen et al., Phys. Rev. C 66, 035202 (2002), and private communication.
9. B. Saghai, in Proceedings of the International Symposium on Hadrons and Nuclei (2001), pp. 57–66.
10. W.-T. Chiang et al., Phys. Lett. B 519, 101 (2001).
11. G. Penner and U. Mosel, Phys. Rev. C 66, 055212 (2002).
12. J. Bocquet et al., Nucl. Phys. A691, 466c (2001).
13. O. Bartalini, Phys. Lett. B 544, 113 (2002).
14. T. Nakano et al., Nucl. Phys. A684, 71c (2001).
15. T. Mart et al., MAID2000, http://www.kph.uni-mainz.de/MAID/kaon/kaonmaid.html.
16. F. Lee et al., Nucl. Phys. A695, 237 (2001).
[17] M. Guidal et al., Nucl. Phys. A627, 645 (1997).