

Differential Cross Section and Photon-Beam Asymmetry for the $\vec{\gamma}n \rightarrow K^+\Sigma^-$ Reaction at $E_\gamma = 1.5\text{--}2.4$ GeV

H. Kohri,¹ D. S. Ahn,^{1,2} J. K. Ahn,² H. Akimune,³ Y. Asano,⁴ W. C. Chang,⁵ S. Date,⁶ H. Ejiri,^{1,6} S. Fukui,⁷ H. Fujimura,^{8,9} M. Fujiwara,^{1,4} S. Hasegawa,¹ K. Hicks,¹⁰ T. Hotta,¹ K. Imai,⁹ T. Ishikawa,¹¹ T. Iwata,¹² H. Kawai,¹³ Z. Y. Kim,⁸ K. Kino,^{1,*} N. Kumagai,⁶ S. Makino,¹⁴ T. Mart,¹⁵ T. Matsuda,¹⁶ T. Matsumura,^{1,4,†} N. Matsuoka,¹ T. Mibe,^{1,4,10} M. Miyabe,⁹ Y. Miyachi,¹⁷ M. Morita,¹ N. Muramatsu,^{4,1} T. Nakano,¹ M. Niiyama,⁹ M. Nomachi,¹⁸ Y. Ohashi,⁶ H. Ohkuma,⁶ T. Ooba,¹³ D. S. Oshuev,^{5,‡} C. Rangacharyulu,¹⁹ A. Sakaguchi,¹⁸ T. Sasaki,⁹ P. M. Shagin,²⁰ Y. Shiino,¹³ A. Shimizu,¹ H. Shimizu,¹¹ Y. Sugaya,¹⁸ M. Sumihama,^{18,4} Y. Toi,¹⁶ H. Toyokawa,⁶ A. Wakai,²¹ C. W. Wang,⁵ S. C. Wang,⁵ K. Yonehara,^{3,§} T. Yorita,^{1,6} M. Yoshimura,²² M. Yosoi,^{9,1} and R. G. T. Zegers²³

(LEPS Collaboration)

¹Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan

²Department of Physics, Pusan National University, Busan 609-735, Korea

³Department of Physics, Konan University, Kobe, Hyogo 658-8501, Japan

⁴Kansai Photon Science Institute, Japan Atomic Energy Agency, Kizu, Kyoto 619-0215, Japan

⁵Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China

⁶Japan Synchrotron Radiation Research Institute, Mikazuki, Hyogo 679-5198, Japan

⁷Department of Physics and Astrophysics, Nagoya University, Nagoya, Aichi 464-8602, Japan

⁸School of Physics, Seoul National University, Seoul, 151-747, Korea

⁹Department of Physics, Kyoto University, Kyoto 606-8502, Japan

¹⁰Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA

¹¹Laboratory of Nuclear Science, Tohoku University, Sendai, Miyagi 982-0826, Japan

¹²Department of Physics, Yamagata University, Yamagata 990-8560, Japan

¹³Department of Physics, Chiba University, Chiba 263-8522, Japan

¹⁴Wakayama Medical College, Wakayama, Wakayama 641-8509, Japan

¹⁵Departemen Fisika, FMIPA, Universitas Indonesia, Depok 16424, Indonesia

¹⁶Department of Applied Physics, Miyazaki University, Miyazaki 889-2192, Japan

¹⁷Department of Physics, Tokyo Institute of Technology, Tokyo 152-8551, Japan

¹⁸Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan

¹⁹Department of Physics, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

²⁰School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA

²¹Akita Research Institute of Brain and Blood Vessels, Akita 010-0874, Japan

²²Institute for Protein Research, Osaka University, Suita, Osaka 565-0871, Japan

²³Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824-1321, USA

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Differential cross sections and photon-beam asymmetries have been measured for the $\vec{\gamma}n \rightarrow K^+\Sigma^-$ and $\vec{\gamma}p \rightarrow K^+\Sigma^0$ reactions separately using liquid deuterium and hydrogen targets with incident linearly polarized photon beams of $E_\gamma = 1.5\text{--}2.4$ GeV at $0.6 < \cos\Theta_{\text{cm}}^K < 1$. The cross section ratio of $\sigma_{K^+\Sigma^-}/\sigma_{K^+\Sigma^0}$, expected to be 2 on the basis of the isospin 1/2 exchange, is found to be close to 1. For the $K^+\Sigma^-$ reaction, large positive asymmetries are observed, indicating the dominance of K^* exchange. The large difference between the asymmetries for the $K^+\Sigma^-$ and $K^+\Sigma^0$ reactions cannot be explained by simple theoretical considerations based on Regge model calculations.

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The reaction mechanism of strangeness photoproduction is important to study in order to understand the role of nucleon resonances, the hyperon resonances, and their decay branching ratios. By comparing data and theoretical models, we gain a deeper understanding of the underlying dynamics, which is often described in terms of constituent quarks as the effective degrees of freedom. For example, many hadron decays are described successfully in terms of the 3P_0 model [1], where the strange quark-antiquark ($s\bar{s}$)

pair has the quantum numbers of the vacuum, produced with its spins aligned. However, this model is cast into doubt by a recent JLAB/CLAS experiment [2], where the observation of the transferred polarization for the $\vec{e}p \rightarrow e'K^+\vec{\Lambda}$ reaction showed that the $s\bar{s}$ pair is predominantly produced with its spins antialigned. While this result may be particular to the reaction studied, and not necessarily the general case, it implies that our understanding of the mechanisms of the baryon decays and $s\bar{s}$ pair production

is incomplete. The measurement of polarization observables, in addition to the cross section, provides more information to reveal the processes given above. Herein, we present the photon-beam asymmetry for production of the Σ hyperon, which provides new polarization data.

Theoretically, kaon photoproduction is described in terms of hadron exchanges, such as N , N^* , and Δ^* in the s channel, hyperon and excited hyperon in the u channel, and K and K^* in the t channel. The contribution from meson exchanges in the t channel is expected to be large at forward angles. The photon-beam asymmetry has a unique feature: At small $|t|$ and at high energies [3,4], its value is $+1$ or -1 if the K^* or K meson is exchanged in the t channel, respectively. Thus, nucleon resonance contributions appear as modulations in photon-beam asymmetries at the photon energy corresponding to a given resonance mass. The measured asymmetries for the $\vec{\gamma}p \rightarrow K^+\Lambda$, $K^+\Sigma^0$ reactions at forward angles were close to $+1$ at high energies (above the resonance region) of $E_\gamma = 5\text{--}16$ GeV [5], whereas they were significantly smaller for the first reaction at photon energies of $E_\gamma = 1.5\text{--}2.4$ GeV [6].

Experimental information on the N^* and Δ^* resonances has been obtained primarily in studies of their pionic decays. Constituent quark models predict more nucleon resonances than have been observed experimentally. These unobserved nucleon resonances are called “missing resonances.” Quark model studies based on the 3P_0 model suggest that these resonances can couple to strangeness channels, such as $K\Lambda$ and $K\Sigma$ [7]. According to simple isospin arguments for the $K\Sigma$ channels, N^* resonances couple strongly to $K^0\Sigma^+$ and $K^+\Sigma^-$ channels, while Δ^* resonances couple strongly to $K^+\Sigma^0$ and $K^0\Sigma^0$ channels. Therefore, the comparison between $K^+\Sigma^-$ and $K^+\Sigma^0$ is an important tool in identifying contributions from N^* or Δ^* resonances.

Five nucleon resonances, $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$, $S_{31}(1900)$, and $P_{31}(1910)$, are well known in kaon photoproduction. Recent data for the $K^+\Lambda$ channel clarified the existence of a new D_{13} nucleon resonance at around 1900 MeV [8–11]. This demonstrates the utility of approaching the missing resonance problem using strange baryon production data.

In the past, experimental data were limited to $K^+\Lambda$ and $K^+\Sigma^0$ productions off the proton [5,6,8–14]. Recently, an experimental result for $K^0\Sigma^+$ off the proton was reported [15]. However, no experimental result has yet been published for kaon photoproduction off the neutron, although there exist $d(\gamma, K^+)$ measurements from the 1970s where the $K^+\Sigma^-$ is not separated from the $K^+\Sigma^0$ [5,13]. In this Letter, we present, for the first time, differential cross sections and photon-beam asymmetries for the $\vec{\gamma}n \rightarrow K^+\Sigma^-$ reaction and compare with the $\vec{\gamma}p \rightarrow K^+\Sigma^0$ reaction.

The experiment was carried out using the laser-electron photon facility at SPring-8 (LEPS) [16]. Linearly polarized

photons were produced by backward Compton scattering of an ultraviolet Ar laser from 8 GeV electrons. The energy range of tagged photons was 1.5–2.4 GeV, and the photon polarization was typically 90% at 2.4 GeV. The experimental setup was described in detail elsewhere [11]. Liquid hydrogen (LH_2) and deuterium (LD_2) targets with an effective length of 16 cm were employed.

Charged particles were detected at forward angles. The particle identification was achieved by using the time-of-flight and momentum information. The events of K^+ mesons were identified within 3σ , where σ is the momentum dependent mass resolution. The contamination of π^+ mesons in the K^+ sample was smaller than 5%. The contribution of the target windows and the plastic scintillator behind the target was smaller than 4%.

Figure 1 shows the missing mass ($\text{MM}_{\gamma K^+}$) spectra for the $p(\vec{\gamma}, K^+)X$ (LH_2) and $N(\vec{\gamma}, K^+)X$ (LD_2) reactions for $E_\gamma = 1.5\text{--}2.4$ GeV and $0.6 < \cos\Theta_{\text{cm}} < 1$. For the LD_2 data, the target was assumed to have a mass of $(M_p + M_n)/2$ and zero momentum for the $\text{MM}_{\gamma K^+}$ calculation. For the LD_2 data, the peak widths are wider than those for the LH_2 data due to Fermi motion. Λ and Σ^0 particles are produced on the proton, while the Σ^- particle is produced on the neutron. Therefore, the ratio $N(\Sigma^-)/N(\Lambda)$ in the LD_2 data is larger than the ratio $N(\Sigma^0)/N(\Lambda)$ in the LH_2 data. The cross section for hadron photoproduction on a bound proton in deuteron is almost the same as for a free proton if the nuclear effects, such as final-state interaction and shadowing effects, are small. In this analysis, the ratio $N(\Sigma^0)/N(\Lambda)$ for the LD_2 data was assumed to be the

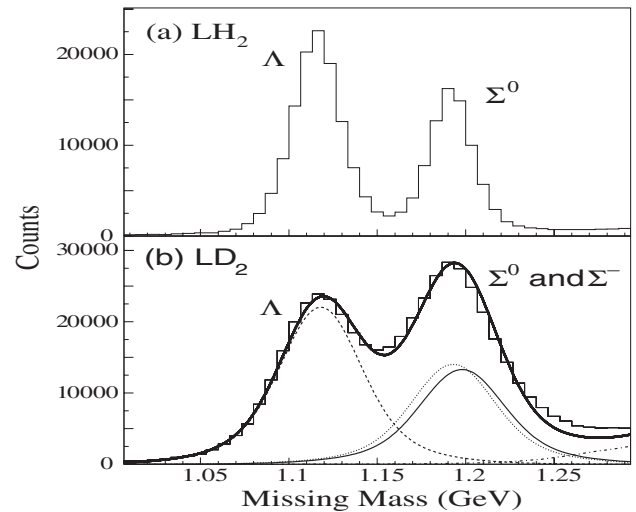


FIG. 1. Missing mass spectra obtained for K^+ photoproduction off (a) LH_2 and (b) LD_2 targets. The dashed, dotted, and solid curves correspond to $\Lambda(1116)$, $\Sigma^0(1193)$, and $\Sigma^-(1197)$ production, respectively. The dotted-dashed curve is the estimated background. The thick solid curve is the sum of all contributions. The thick solid curve deviates from the data histogram at $\text{MM}_{\gamma K^+} > 1.24$ GeV because the π^+ contamination has not been subtracted from the data histogram.

same as for the LH₂ data, and nuclear effects were evaluated as systematic errors. The $K^+\Sigma^-$ cross sections can be obtained from the difference between the production yield ratios of $N(\Sigma^-)/N(\Lambda)$ in the LD₂ data and $N(\Sigma^0)/N(\Lambda)$ in the LH₂ data.

The K^+ angular region in the center-of-mass (cm) system was divided into 4 bins and the photon energy region of 1.5–2.4 GeV was divided into 18 bins. The production yields of Λ , Σ^0 , Σ^- , and the background under the Σ peak were obtained by a fit to the missing mass spectrum with six free parameters. The peak shape of each hyperon was estimated by assuming a quasifree reaction process in the GEANT simulation, where the Paris potential [17] was used to generate the initial nuclear momentum distribution in deuterium. The peak shape was reproduced by the sum of two Gaussians having different widths and amplitudes and was fixed in the fit. Two free parameters were used to scale the heights of the Λ and Σ^- peaks. The production yield ratio of $N(\Sigma^0)/N(\Lambda)$ gave the height of the Σ^0 peak. The peak position of Λ was a free parameter, and the Σ^0 and Σ^- peaks were placed at 0.077 and 0.082 GeV higher than the Λ peak, respectively. The main background under the Σ peak was considered to be due to $\pi\Lambda$, $\pi\Sigma$, and the tail of $\Lambda^*(1405)$ and $\Sigma^*(1385)$ events. The distribution shape of

each reaction was estimated by the GEANT simulation. Two free parameters were scale factors for the heights of the $\pi\Lambda$ and $\pi\Sigma$ events, and one free parameter was used for the tail of the $\Lambda^*(1405)$ and $\Sigma^*(1385)$ events.

As a result of the fit, the production yield ratio $N(\Sigma^-)/N(\Sigma^0)$ was obtained. The $K^+\Sigma^0$ cross section was obtained from the LH₂ data using the same method as Ref. [11]. The $K^+\Sigma^-$ cross section was calculated by using the ratio

$$\frac{d\sigma_{\Sigma^-}}{d\cos\Theta_{\text{cm}}} = \frac{d\sigma_{\Sigma^0}}{d\cos\Theta_{\text{cm}}} \frac{N(\Sigma^-)}{N(\Sigma^0)}. \quad (1)$$

Since the masses of Σ^- and Σ^0 are almost the same, acceptance corrections are negligible.

Most of the nuclear effects were small and canceled by taking the yield ratios $N(\Sigma^0)/N(\Lambda)$ and $N(\Sigma^-)/N(\Sigma^0)$ in the analysis, because the total cross sections for γp and K^+p are similar to those for γn and K^+n , respectively. However, differences among Λn , $\Sigma^0 n$, and $\Sigma^- p$ final-state interactions are not negligible [18]. Final-state interactions considered by Yamamura *et al.* [18] using the NSC97f hyperon-nucleon force were incorporated in our data analyses as systematic errors.

In Fig. 2, the differential cross sections for $K^+\Sigma^-$ and $K^+\Sigma^0$ are shown. The effect of the hyperon-nucleon final-state interactions is estimated to be 16% of the $K^+\Sigma^-$ cross section. The effect of the internal two-step process mediated by a π meson [19] is negligible at $0.8 < \cos\Theta_{\text{cm}}$ and 6% and 15% at $0.7 < \cos\Theta_{\text{cm}} < 0.8$ and $0.6 < \cos\Theta_{\text{cm}} < 0.7$, respectively, for the $K^+\Sigma^-$. The Fermi motion effect of the target nucleons is 8% for $K^+\Sigma^-$. Systematic uncertainties of target thickness and photon flux are 1% and 3%, respectively, for both reactions. The effect of the contaminations in the selection of K^+ from the targets was subtracted.

In the center-of-mass energy ($W = \sqrt{s}$) region above 2.1 GeV at $0.8 < \cos\Theta_{\text{cm}}$, the cross sections for the two reactions are similar. This result is inconsistent with a model based on the exchange of pure isospin 1/2, dominantly due to K and K^* mesons, where the cross section ratio of $\sigma_{K^+\Sigma^-}/\sigma_{K^+\Sigma^0}$ is expected to be 2. Regge model calculations [4,20] agree with the data for $K^+\Sigma^0$, but largely overestimate the $K^+\Sigma^-$ data. At high energies, the KaonMAID model [21] also overestimates the data for $K^+\Sigma^-$.

Two possibilities are considered to explain the reason why the experimental ratio is so different from the theoretical expectation. One possibility is the contribution from Δ^* or N^* resonances, which may increase the cross sections for the $K^+\Sigma^0$. The contribution from the Δ^* resonances may reduce the cross sections for the $K^+\Sigma^-$ by destructive interference [13]. A second possibility is that the u -channel Λ or Λ^* exchange, which is absent in the $K^+\Sigma^-$ channel, may contribute strongly to the $K^+\Sigma^0$ channel. Since the N^* resonances couple weakly to the

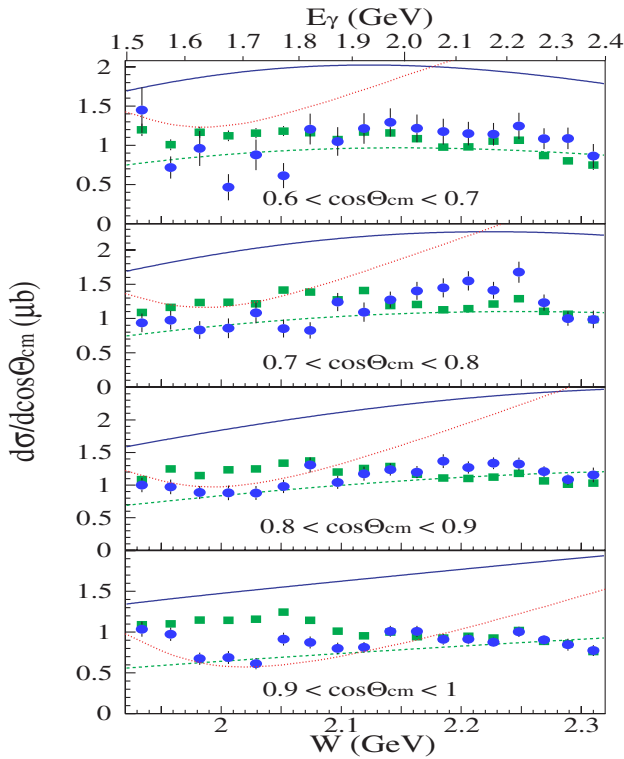


FIG. 2 (color online). Differential cross sections for $\tilde{\gamma}n \rightarrow K^+\Sigma^-$ (circles) and $\tilde{\gamma}p \rightarrow K^+\Sigma^0$ (squares). Only statistical errors are shown. The solid and dashed curves are the Regge model calculations [4,20] for the $K^+\Sigma^-$ and $K^+\Sigma^0$, respectively. The dotted curve is the KaonMAID model calculations [21] for the $K^+\Sigma^-$.

$K^+\Sigma^0$ channel, and the u -channel contribution must be very small at forward angles, the Δ^* contribution is the most reasonable explanation for the similar cross sections. If the isospin 3/2 amplitude is 10% of the isospin 1/2 amplitudes, dominantly due to K and K^* exchanges, in the $K^+\Sigma$ cross sections described in Ref. [13], the similarity of the $K^+\Sigma^-$ and $K^+\Sigma^0$ cross sections can be explained.

By using vertically and horizontally polarized photon beams, the photon-beam asymmetry can be measured without any correction for the spectrometer acceptance [6,11]. The asymmetry (Σ) is given as follows:

$$P_\gamma \Sigma \cos 2\Phi = \frac{N_v - N_h}{N_v + N_h}, \quad (2)$$

where N_v and N_h are the K^+ photoproduction yields with the vertically and horizontally polarized photons, respectively. P_γ is the polarization degree of the photon beam, and Φ is the K^+ azimuthal angle defined by the angle between the reaction plane and the horizontal plane. The K^+ angular region in the cm system was divided into 4 bins and the photon energy region of 1.5–2.4 GeV was divided into 9 bins. In order to obtain the asymmetry for the $K^+\Sigma^-$ separately, the effects of background events were subtracted from the asymmetry for events selected by the condition $|M_{\Sigma^-} - MM_{\gamma K^+}| < \sigma_{\Sigma^-}$, where σ_{Σ^-} is the width of the Σ^- peak. The asymmetries for the $K^+\Lambda$ and $K^+\Sigma^0$ were obtained from the LH₂ data using the same method as Ref. [11]. The asymmetry for the $K^+\pi\Lambda$, $K^+\pi\Sigma$, and the tail of $K^+\Lambda^*(1405)$ and $K^+\Sigma^*(1385)$ was obtained from events selected by the condition $1.25 < MM_{\gamma K^+} < 1.30$ GeV by subtracting the effect of the Σ peak tail. The effect of the contaminations in the selection of K^+ from the targets was subtracted.

In Fig. 3, the photon-beam asymmetries for $K^+\Sigma^-$ and $K^+\Sigma^0$ are shown. The effect of the final-state interactions [18] is estimated to be smaller than $\delta\Sigma = 0.1$ for $K^+\Sigma^-$. The effect of the internal two-step process mediated by a π meson [19] is negligible at $0.8 < \cos\Theta_{\text{cm}}$, and $\delta\Sigma = 0.09$ and $\delta\Sigma = 0.13$ at $0.7 < \cos\Theta_{\text{cm}} < 0.8$ and $0.6 < \cos\Theta_{\text{cm}} < 0.7$, respectively, for the $K^+\Sigma^-$. The effect due to the Fermi motion of target nucleons is smaller than $\delta\Sigma = 0.13$ for the $K^+\Sigma^-$. The systematic uncertainty of the measurement of the laser polarization is $\delta\Sigma = 0.02$ for both reactions. The present data also show reasonable consistency between the asymmetries for the $K^+\Lambda$ in the LD₂ and LH₂ data.

For $K^+\Sigma^-$, the asymmetries are positive and are larger than those for $K^+\Sigma^0$. The asymmetries close to +1 at $\cos\Theta_{\text{cm}} < 0.9$ indicate the dominance of the K^* exchange in the t channel. The asymmetries are small at $0.9 < \cos\Theta_{\text{cm}}$ because the asymmetries go to zero at $\cos\Theta_{\text{cm}} = 1$. It is quite interesting that the asymmetries for the $K^+\Sigma^0$ gradually increase with increasing center-of-mass energy, while the energy dependence of the asymmetries for $K^+\Sigma^-$ is small at $W > 2$ GeV.

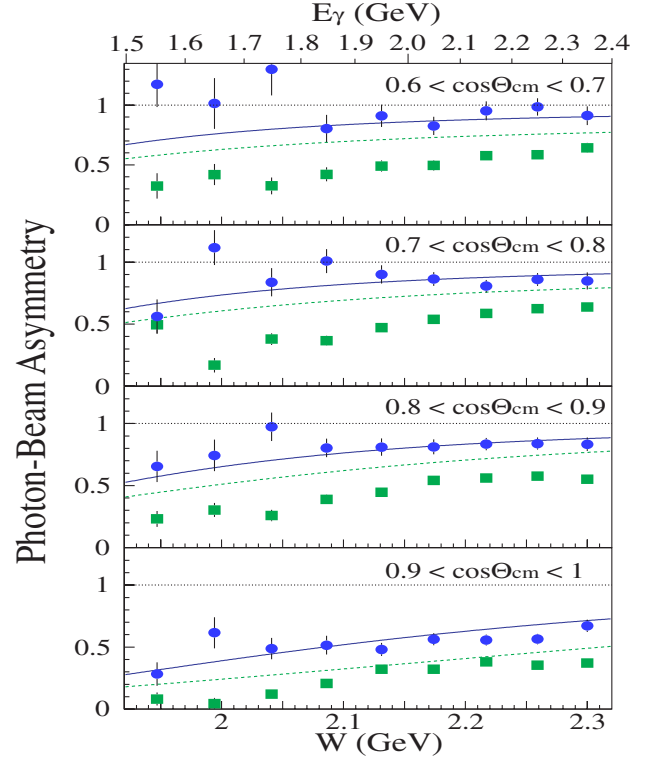


FIG. 3 (color online). Photon-beam asymmetries for $\vec{\gamma}n \rightarrow K^+\Sigma^-$ (circles) and $\vec{\gamma}p \rightarrow K^+\Sigma^0$ (squares). The solid and dashed curves are the Regge model calculations [4,20] for the $K^+\Sigma^-$ and $K^+\Sigma^0$, respectively.

The KaonMAID model [21], which is not shown in the figure, predicts negative asymmetries for the $K^+\Sigma^-$. The Regge model calculations [4,20] overestimate the data for the $K^+\Sigma^0$, while the calculations agree with the data for the $K^+\Sigma^-$. This agreement suggests that an additional contribution, which is not included in the calculations, is small in the $K^+\Sigma^-$ channel. As shown above, contributions from Δ^* resonances could explain the $K^+\Sigma^0$ data [21]. However, this Δ^* contribution reduces the $K^+\Sigma^-$ asymmetries and fails to explain the polarization data. One may speculate that the difference between theoretical and experimental asymmetries for the $K^+\Sigma^0$ is, at least in part, due to contributions from u -channel Λ and Λ^* exchanges and s -channel N^* resonances which have much stronger coupling to γp than to γn .

In summary, we have measured differential cross sections and photon-beam asymmetries for $\vec{\gamma}n \rightarrow K^+\Sigma^-$ and $\vec{\gamma}p \rightarrow K^+\Sigma^0$ at $E_\gamma = 1.5$ –2.4 GeV. The cross sections for $K^+\Sigma^-$ are similar to those for $K^+\Sigma^0$ at high energies, which is inconsistent with the exchange of pure isospin 1/2. Large asymmetries close to +1 for the $K^+\Sigma^-$ are found, indicating the dominance of K^* exchange in the t channel. A large difference between the asymmetries for the $K^+\Sigma^-$ and $K^+\Sigma^0$ cannot be explained by simple theoretical considerations based on Regge model calculations. In the energy region of a few GeV, there is no

theoretical calculation which describes the strangeness photoproduction well. The present result may imply the existence of a hidden reaction mechanism and will provide constraints in the model calculations with the aim to advance our understanding of the $s\bar{s}$ pair production mechanisms.

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*Present address: Faculty and Graduate School of Engineering, Hokkaido University, Sapporo 060-8628, Japan.

†Present address: Department of Applied Physics, National Defense Academy, Yokosuka 239-8686, Japan.

‡Present address: Nuclear Physics Institute, Moscow State University, Moscow, 119899, Russia.

§Present address: Illinois Institute of Technology, Chicago, IL 60616, USA.

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