Differential cross section and photon beam asymmetry for the $\gamma n \rightarrow K^+\Sigma^-$ reaction at $E_\gamma =1.5-2.4$ GeV

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Differential cross sections and photon beam asymmetries have been measured for the $\gamma n \rightarrow K^+\Sigma^-$ and $\gamma p \rightarrow K^+\Sigma^-$ reactions separately using liquid deuterium and hydrogen targets with incident linearly polarized photon beams of $E_\gamma =1.5-2.4$ GeV at $0.6<\cos \Theta_{\text{kin}}<1$. 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 are 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 $\bar{e}p \rightarrow e'K^+\bar{\Lambda}$ 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 $\Sigma$ hyperon, which provides new polarization data.

Theoretically, kaon photoproduction is described in terms of hadron exchanges, such as $N$, $N^*$, and $\Delta^*$ in the
The particle identification was achieved by using the $\mathbf{K}^0\pi^0$ from the neutron although there exist results has yet been published for kaon photoproduction in the proton was reported [15]. However, no experimental data for the first time, differential cross sections and photon beam asymmetries at the photon energy corresponding to a given resonance mass. The measured asymmetries for the $\mathbf{K}^0\mathbf{p}$ → $\mathbf{K}^0\mathbf{\Lambda}$, $\mathbf{K}^0\mathbf{\Sigma^0}$ reactions at forward angles were close to +1 at high energies (above the resonance region) of $E_\gamma$ = 5-16 GeV [6], whereas they were significantly smaller for the first reaction at photon energies of $E_\gamma$ = 1.5-2.4 GeV [6].

Experimental information on the $N^*$ and $\Delta^*$ 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 $\mathbf{K}\mathbf{\Lambda}$ and $\mathbf{K}\mathbf{\Sigma}$. According to simple isospin arguments for the $\mathbf{K}\mathbf{\Sigma}$ channels, $N^*$ resonances couple strongly to $\mathbf{K}^0\mathbf{\Sigma}^0$ and $\mathbf{K}^+\mathbf{\Sigma}^-$ channels, while $\Delta^*$ resonances couple strongly to $\mathbf{K}^+\mathbf{\Sigma}^0$ and $\mathbf{K}^0\mathbf{\Sigma}^0$ channels. Therefore, the comparison between $\mathbf{K}^+\mathbf{\Sigma}^-$ and $\mathbf{K}^+\mathbf{\Sigma}^0$ is an important tool in identifying contributions from $N^*$ or $\Delta^*$ resonances.

Five nucleon resonances, $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$, $S_{11}(1900)$, and $P_{31}(1910)$ are well known in kaon photoproduction. Recent data for the $\mathbf{K}^+\mathbf{\Lambda}$ channel clarified the existence of a new $D_{13}$ nucleon resonance at around 1900 MeV [6]. This demonstrates the utility of approaching the missing resonance problem using strange baryon production data.

In the past, experimental data were limited to $\mathbf{K}^+\mathbf{\Lambda}$ and $\mathbf{K}^+\mathbf{\Sigma}^0$ productions off the proton and deuteron [6]. Recently, an experimental result for $\mathbf{K}^0\mathbf{\Sigma}^+$ which measured the $d(\gamma,\mathbf{K}^+)$ measurements from the 1970’s where the $\mathbf{K}^+\mathbf{\Sigma}^-$ is not separated from the $\mathbf{K}^+\mathbf{\Sigma}^0$. In this Letter, we present, for the first time, differential cross sections and photon beam asymmetries for the $\gamma\mathbf{p}\rightarrow\mathbf{K}^+\mathbf{\Sigma}^-$ reaction and compare with the $\gamma\mathbf{p}\rightarrow\mathbf{K}^+\mathbf{\Sigma}^0$ reaction.

The experiment was carried out using the laser-electron photon facility at SPring-8 (LEPS) [6]. Linearly polarized photons were produced by backward Compton scattering of an ultra-violet 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 $\mathbf{K}^+$ mesons were identified within $3\sigma$, where $\sigma$ is the momentum dependent mass resolution. The contamination of $\pi^+$ mesons in the $\mathbf{K}^+$ 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 (MM) spectra for the $2p(\gamma,K^+)X$ (LH$_2$) and $N(\gamma,K^+)X$ (LD$_2$) reactions for $E_\gamma = 1.5-2.4$ GeV and 0.6 < $\cos \Theta_{cm}$ < 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 $M_{K^+}$ calculation. For the LD$_2$ data the peak widths are wider than those for the LH$_2$ data due to Fermi motion. $\mathbf{\Lambda}$ and $\mathbf{\Sigma}^0$ particles are produced on the proton, while the $\mathbf{\Sigma}^-$ particle is produced on the neutron. Therefore, the ratio $N(\mathbf{\Sigma})/N(\mathbf{\Lambda})$ in the LD$_2$ data is larger than the ratio $N(\mathbf{\Sigma}^0)/N(\mathbf{\Lambda})$ 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 $N(\mathbf{\Sigma}^0)/N(\mathbf{\Lambda})$ for the LD$_2$ data was assumed to be the same as for the LH$_2$ data, and nuclear effects were evaluated as systematic errors. The $\mathbf{K}^+\mathbf{\Sigma}^-$ cross sections can be obtained from the difference between the production yield ratios of $N(\mathbf{\Sigma})/N(\mathbf{\Lambda})$ in the LD$_2$ data and $N(\mathbf{\Sigma}^0)/N(\mathbf{\Lambda})$ in the LH$_2$ data.

The $\mathbf{K}^+$ 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 $\mathbf{\Lambda}$, $\mathbf{\Sigma}^0$, $\mathbf{\Sigma}^-$, and the background under the $\mathbf{\Sigma}$ peak were obtained by a fit to the missing mass spec-
trum with six free parameters. The peak shape of each hyperon was estimated by assuming a quasi-free reaction process in the GEANT simulation, where the Paris potential \(\text{[17]}\) 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 \(\Lambda\) and \(\Sigma^-\) peaks. The production yield ratio of \(N(\Sigma^0)/N(\Lambda)\) gave the height of the \(\Sigma^0\) peak. The peak position of \(\Lambda\) was a free parameter, and the \(\Sigma^0\) and \(\Sigma^-\) peaks were placed at 0.077 GeV and 0.082 GeV higher than the \(\Lambda\) peak, respectively. The main background under the \(\Sigma\) 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. \([18]\). The \(K^+\Sigma^-\) cross section was calculated using the ratio,

\[
\frac{d\sigma_{\Sigma^-}}{d\cos \Theta_{\text{cm}}} = \frac{d\sigma_{\Sigma^0}}{d\cos \Theta_{\text{cm}}} \times \frac{N(\Sigma^-)}{N(\Sigma^0)} \tag{1}
\]

Since the masses of \(\Sigma^-\) and \(\Sigma^0\) 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 \(\gamma p\) and \(K^+p\) are similar to those for \(\gamma n\) and \(K^+n\), respectively. However, differences among \(\Lambda n, \Sigma^0 n,\) and \(\Sigma^- p\) final-state interactions are not negligible \([18]\). Final-state interactions considered by Yamamura et al. \([13]\) 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 \(\pi\) 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 \(\Delta^*\) or \(N^*\) resonances which may increase the cross sections for the \(K^+\Sigma^0\). The contribution from the \(\Delta^*\) resonances may reduce the cross sections for the \(K^+\Sigma^-\) by destructive interference \([15]\). A second possibility is that the \(u\)-channel \(\Lambda\) or \(\Lambda^*\) 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 \(K^+\Sigma^0\) channel, and the \(u\)-channel contribution must be very small at forward angles, the \(\Delta^*\) 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.
The asymmetry ($\Sigma$) is given as follows:

$$P_\gamma \Sigma\cos 2\Phi = \frac{N_+ - N_-}{N_+ + N_-}$$

(2)

where $N_+$ and $N_-$ are the $K^+$ photoproduction yields with the vertically and horizontally polarized photons, respectively. $P_\gamma$ is the polarization degree of the photon beam, and $\Phi$ 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 $|M_{\Sigma^-} - MM_{K^+}| < \sigma_{\Sigma^-}$, where $\sigma_{\Sigma^-}$ is the width of the $\Sigma^-$ peak. The asymmetries for the $K^+\Lambda$ and $K^+\Sigma^0$ were obtained from the LH$_2$ 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 $1.25 < MM_{K^+} < 1.30$ GeV by subtracting the effect of the $\Sigma$ 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 is estimated to be smaller than $\delta \Sigma = 0.1$ for $K^+\Sigma^-$. The effect of the internal two-step process mediated by a $\pi$ meson is negligible at $0.8 < \cos \Theta_{cm}$, and $\delta \Sigma = 0.09$ and $\delta \Sigma = 0.13$ at $0.7 < \cos \Theta_{cm} < 0.8$ and $0.6 < \cos \Theta_{cm} < 0.7$, 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 LD$_2$ and LH$_2$ data.

For $K^+\Sigma^-$, the asymmetries are positive and are larger than those for $K^+\Sigma^0$. The asymmetries close to $+1$ at $\cos \Theta_{cm} < 0.9$ indicate the dominance of the $K^*$ exchange in the $t$-channel. The asymmetries are small at $0.9 < \cos \Theta_{cm}$ because the asymmetries go to zero at $\cos \Theta_{cm} = 1$. 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.

The KaonMAID model 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 $\Delta^*$ resonances could explain the $K^+\Sigma^0$ data [21]. However, this $\Delta^*$ 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 $\Lambda$ and $\Delta^*$ exchanges and $s$-channel $N^*$ resonances which have much stronger coupling to $\gamma p$ than to $\gamma n$.

In summary, we have measured differential cross sections and photon beam asymmetries for $\gamma n \rightarrow K^+\Sigma^-$ and $\gamma p \rightarrow K^+\Sigma^0$ 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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