Beam-Polarization Asymmetries for the $p(\vec{\gamma}, K^+)\Lambda$ and $p(\vec{\gamma}, K^+)\Sigma^0$ Reactions for $E_\gamma = 1.5$–2.4 GeV

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Beam polarization asymmetries for the $p(\vec{\gamma}, K^+)\Lambda$ and $p(\vec{\gamma}, K^+)\Sigma^0$ reactions are measured for the first time for $E_\gamma = 1.5$–2.4 GeV and $0.6 < \cos(\theta_{K^+}^{\mathrm{c.m.}}) < 1.0$ 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 thus far undiscovered.

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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 πN scattering and π-production reactions. Of special interest are nucleon resonances that have been predicted in quark models [1] and for which no experimental evidence has been found via the π-induced or π-production reactions. Some of these resonances, referred to as "missing," could couple strongly to the $K\Lambda$ and $K\Sigma$ channels [2,3]. 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 [4] resulted in renewed interest because of the presence of a resonancelike structure near $W = 1900$ MeV. Mart and Bennhold showed that this structure could be explained by introducing a $D_{13}(1895)$ resonance [5] for which a considerable branching into the $K\Lambda$ channel is predicted [3]. Measurements of the cross section at CLAS/JLAB [6] suggest that the resonancelike 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 nonresonant "background" [7,8]. Great caution is thus advised in drawing definite conclusions based on the cross-section data only. It has also been shown that coupled-channel effects are not negligible [9]. One way to limit the freedoms in the model calculations is to analyze results from all photon-induced channels simultaneously [10].

For the development of the models, it is of vital importance 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 Λ weak decay) are already available from the SAPHIR data set. Extensive programs to measure cross sections and recoil polarizations are underway at JLAB/CLAS [6] and ESRF/GRAAL [11]. Additionally, measurements of the beam polarization asymmetry (Σ) are great assets to the database because of the high sensitivity to the model parameters and the presence of resonances [5,7]. This asymmetry is defined through $(\frac{d\sigma}{d\Omega})_{\text{pol}} = \frac{d\sigma}{d\Omega}[1 + \Sigma P_{\vec{\gamma}} \cos(2\phi')]$, where $(\frac{d\sigma}{d\Omega})_{\text{pol}}$ is the cross section using a linearly polarized photon beam, $\frac{d\sigma}{d\Omega}$ that for an unpolarized beam, $P_{\vec{\gamma}}$ the degree of photon polarization, and ϕ' the azimuthal angle between the photon polarization plane and the vector normal to the K^+ reaction plane. Access to this observable is most easily obtained at backward-Compton scattering facilities because the photon beam is easily and reliably polarized to a high degree [12–14]. Note that, because of the self-analyzing property of the hyperons, the availability of polarized photon beams opens the door to measure double-polarization observables which would allow for an almost model-independent analysis.

In this Letter, we present for the first time measurements of the beam polarization asymmetries of the $p(\vec{\gamma}, K^+)\Lambda$ and $p(\vec{\gamma}, K^+)\Sigma^0$ reactions. These data were taken at the new SPring8/LEPS facility [13,14]. Photons with a maximum energy of 2.4 GeV were produced from backward-Compton scattering of 351-nm laser photons off 8-GeV electrons in the SPring-8 storage 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 every 2 h to reduce systematic effects. The typical photon flux was 10^6/s. A 50-mm thick liquid-hydrogen target was used.

Charged particles were momentum analyzed by tracing their paths in a magnetic dipole field by means of a silicon-strip vertex detector and one drift chamber positioned upstream from the dipole magnet, and two drift chambers positioned downstream of the dipole magnet. The upstream drift chamber consists of six wire planes (three vertical planes, two planes at +45°, and one plane at two vertical planes, two planes at +30°, and one plane at −30°). Electron and positron tracks due to pair production were 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 signal 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 provided the stop signal. The time-of-flight resolution was about 150 ps for a typical path length of 4 m. By combining time of flight and momentum, the mass of each track was reconstructed with a resolution (σ) of 30(105) MeV/c^2 for a 1(2) GeV/c kaon. A 3σ-mass cut was used to select the positively charged kaons, with the additional condition that $0.31 < \text{mass} < 0.74$ GeV/c^2 to ensure that the K^+ cut does not overlap with the cuts for the π^+ and proton. At high momenta (~ 2 GeV/c), where the mass resolution was worst, the contamination from the π^+ 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 π^+ and protons into the K^+ region. K^+ mesons scattered between 0° and 60° in the center-of-mass frame were detected by the LEPS detector [13]. The track-angle resolution was 2.3 mrad.

Figure 1 shows the missing-mass spectrum obtained for the $p(\vec{\gamma}, K^+)X$ 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 π^+ tracks. The missing-mass resolutions for the Λ (Σ^0) were $\sigma = 17(16)$ and 10(9) MeV/c^2 at the highest and lowest momenta, respectively. A momentum-dependent 2σ cut was used to select the events in each peak. The contamination of Λ (Σ^0) events in the Σ^0 (Λ) peak is less than 0.8% (0.4%). In total, 7.3×10^4 $K^+\Lambda$ and 4.9×10^4 $K^+\Sigma^0$ events satisfied all conditions given above.

The beam polarization asymmetries (Σ) are determined using the relation

$$\Sigma P_{\vec{\gamma}} \cos(2\phi) = \frac{kN_v(\phi) - N_h(\phi)}{kN_v(\phi) + N_h(\phi)}, \qquad (1)$$

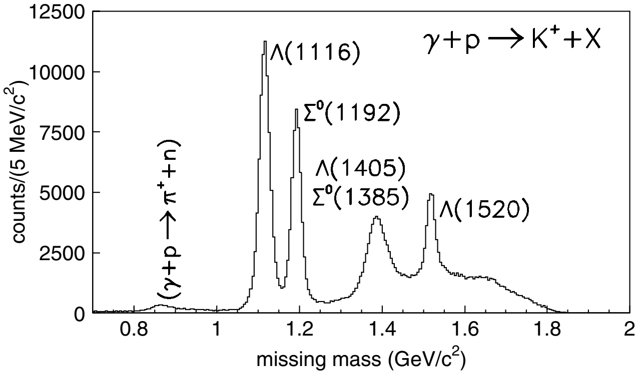

FIG. 1. Missing-mass spectrum for the $p(\vec{\gamma}, K^+)X$ reaction taken at the LEPS/SPring-8 facility.

where N_v (N_h) is the number of events detected at angle ϕ, with a vertically (horizontally) polarized photon beam and k is a normalization factor (0.92) obtained from the 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 ϕ is measured with respect to the horizontal plane. The detector acceptance is not present in Eq. (1), because the acceptances for our data taken with a horizontally and vertically polarized photon beam are the same within 1%. Figure 2 shows the measured ratio in the right-hand side 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 $P_{\tilde{\gamma}}$, Σ 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 nine, 0.1-GeV wide, photon-energy bins ranging from 1.5 to 2.4 GeV. Binning narrower than the width of the various resonances is important, since the excitation spectrum may vary rapidly due to their presence. For each energy bin, the events were further divided according to K^+ scattering angles; five bins in $\cos(\theta_{K^+}^{\mathrm{c.m.}})$ from 0.6 to 1.0, each with a width of 0.1, except for the two most forward bins which had a width of 0.05. For each subsample, the beam polarization asymmetry was determined following the above-described procedure [the reduced χ^2 of the fits with a $\cos(2\phi)$ to the measured asymmetries varied from 0.4 to 2.1]. Although the contamination from protons and π^+ in the K^+ sample was small, it gives rise to a non-negligible shift of the measured asymmetry for the K^+. This was corrected by determining contamination levels from the protons and π^+ and their respective asymmetries (determined by selecting π^+ and protons in the mass spectra but keeping all other selections described above; for protons the asymmetries are close to 0 and for π^+ they are positive, but 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 π^+ contaminations, weighted by their relative contributions in each sample, the asymmetries for the K^+ sample can be extracted. The correction ranged from 0.00 ± 0.01 for the lowest photon energies to $+0.03 \pm 0.02$ at the highest energies.

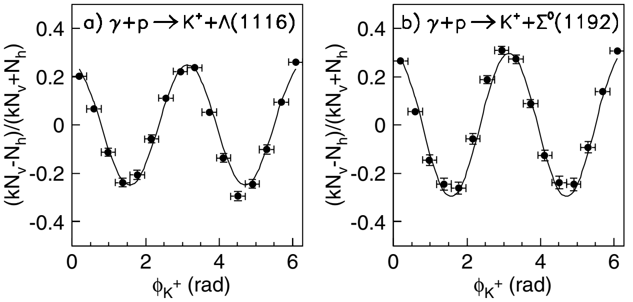

FIG. 2. Asymmetry spectra for the $p(\vec{\gamma}, K^+)\Lambda$ (a) and $p(\vec{\gamma}, K^+)\Sigma^0$ (b) reactions for all events. A fit to the data with $C\cos 2\phi$ is superimposed. Vertical (horizontal) errors indicate statistical uncertainties (angle intervals).

The final results are shown in Fig. 3. The observed asymmetries are positive and increase gradually with photon energy. The error bars correspond to the combined statistical (from 0.09 at $E_{\tilde{\gamma}} = 1.5$ GeV to 0.04 at $E_{\tilde{\gamma}} = 2.4$ GeV) and systematic errors (~ 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) Although the detector ran stably over the full course of the experiment, a trigger problem in a subset of the data caused some event loss in cases where the decay proton from the Λ ($\Lambda \rightarrow p\pi^-$ 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 Λ (Σ^0) production]. (iii) Contamination from events produced at the trigger counter, which is only significant at very forward K^+ scattering angles [$\cos(\theta_{K^+}^{\mathrm{c.m.}}) > 0.95$]; the systematic error is negligible for Λ production and 0.01 for Σ^0 production. Asymmetries extracted from the horizontally and vertically polarized data sets separately were consistent with the results from the combined analysis, and the effect on the asymmetries of acceptance differences between the two respective data sets were estimated to be less than 0.01.

In Fig. 3, the experimental data are compared with the theoretical predictions using the KAON-MAID program [5,15,16] (dashed lines) and by Janssen *et al.* [7,8] (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 [5]. The difference between the two sets of predictions lies in the treatment of the nonresonant 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 KAON-MAID overpredict the beam polarization asymmetries, and those by Janssen *et al.* underpredict the measurements. For the $K^+\Sigma^0$ channel, the calculations predict similar

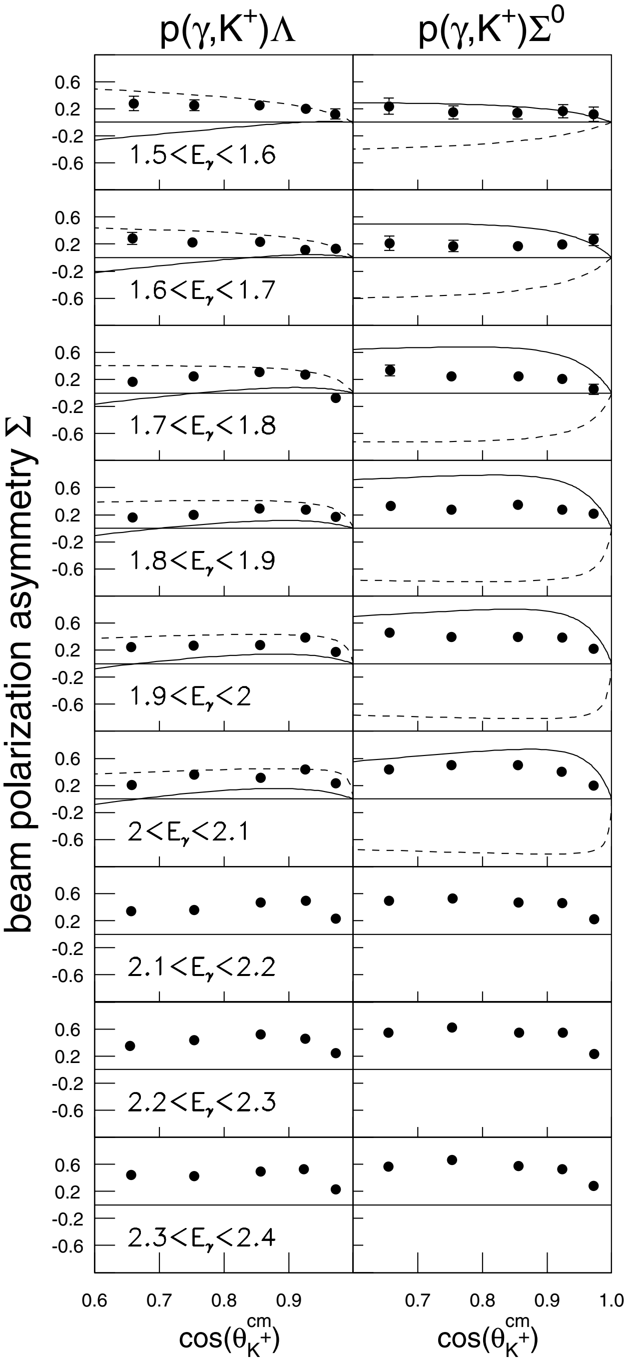

FIG. 3. Beam polarization asymmetries for the $p(\vec{\gamma}, K^+)\Lambda$ (left) and $p(\vec{\gamma}, K^+)\Sigma^0$ (right) reactions as a function of $\cos(\theta_{K^+}^{\mathrm{c.m.}})$ for different photon-energy bins. The error bars are mostly smaller than the markers. Theoretical predictions using the KAON-MAID program [15] (dashed lines) and by Janssen *et al.* [7,8] (solid lines) are compared with the experimental data.

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 valid. Regge-model calculations [17], which reproduce the asymmetry at higher photon energies ($E_\gamma > 5$ GeV) well, strongly overpredict the asymmetries presented here because the s-channel resonances are not taken into account. The new data up to 2.4 GeV thus provide another challenge for future theoretical work.

In short, we present beam polarization asymmetry data for the $p(\vec{\gamma}, K^+)\Lambda$ and $p(\vec{\gamma}, K^+)\Sigma^0$ reactions for $1.5 < E_\gamma < 2.4$ GeV and $0.6 < \cos(\theta_{K^+}^{\mathrm{c.m.}}) < 1.0$. 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 π 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.

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