Experimental study of the $\gamma p \rightarrow K^0\Sigma^+$, $\gamma n \rightarrow K^0\Lambda$, and $\gamma n \rightarrow K^0\Sigma^0$ reactions at the Mainz Microtron

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This work measured $d\sigma/d\Omega$ for neutral kaon photoproduction reactions from threshold up to a c.m. energy of 1855 MeV, focusing specifically on the $\gamma p \rightarrow K^0\Sigma^+$, $\gamma n \rightarrow K^0\Lambda$, and $\gamma n \rightarrow K^0\Sigma^0$ reactions. Our results for $\gamma n \rightarrow K^0\Sigma^0$ are the first-ever measurements for that reaction. These data will provide insight into the properties of $N^*$ resonances and, in particular, will lead to an improved knowledge about those states that couple only weakly to the $\pi N$ channel. Integrated cross sections were extracted by fitting the differential cross sections for each reaction as a series of Legendre polynomials and our results are compared with prior experimental results and theoretical predictions.

I. INTRODUCTION

Most of our early knowledge of $N^*$ resonances came from experiments involving the $\pi N$ channel in the initial or final state, e.g., pion nucleon elastic or inelastic scattering [1] or single-pion photoproduction. Lattice QCD and quark models both predict more nucleon resonances in the mass range below 2000 MeV than have been observed experimentally. This is known as the “missing resonances” problem in baryon spectroscopy. For that reason, there has been a concerted effort at electromagnetic facilities, including JLab, Mainz, and Bonn, to measure $N^*$ formation reactions that do not include the $\pi N$ channel at all. The data analyzed in this work bear directly on that problem. The photoproduction of a kaon on a nucleon target can provide new information on nucleon resonances. Out of six elementary kaon photoproduction reactions ($\gamma p \rightarrow K^0\Sigma^+, \gamma n \rightarrow K^0\Lambda$, and $\gamma n \rightarrow K^0\Sigma^0$), $\gamma p \rightarrow K^+\Lambda, \gamma p \rightarrow K^+\Sigma^0, \gamma n \rightarrow K^+\Sigma^-$), a significant amount of experimental research [2-6] has been done on the charged kaon reactions.

By contrast, there have been very few published studies of $K^0$ photoproduction. Lawall et al. [7] measured $\gamma p \rightarrow K^0\Sigma^+$ at ELSA, in Bonn, using the SAPHIR detector. Events were reconstructed using the $K^0 \rightarrow \pi^+\pi^-, \Sigma^+ \rightarrow \pi^0p$, and $\Sigma^+ \rightarrow \pi^+n$ decays. Casteljus et al. [8] performed complementary measurements of $\gamma p \rightarrow K^0\Sigma^+$...
at ELSA with events reconstructed using the $K^0 \to \pi^0\pi^0$ and $\Sigma^+ \to \pi^0p$ decays. Aguar-Bartolomé et al. [9] measured $\gamma p \to K^0\Sigma^+$ at Mainz using the Crystal Ball and TAPS detectors with events reconstructed using the $K^0 \to \pi^0\pi^0$ and $\Sigma^+ \to \pi^0p$ decays. Recently, Compton et al. [10] measured $\gamma n \to K^0\Lambda$ at JLab using the CLAS detector. Data were collected in two datasets, g10 and g13, which used different run conditions. Events were reconstructed using the $K^0 \to \pi^0\pi^0$ and $\Lambda \to \pi^-p$ decays.

The main focus of the current work was to measure the differential cross section from threshold to c.m. energy $W = 1855$ MeV for the reactions $\gamma p \to K^0\Sigma^+$, $\gamma n \to K^0\Lambda$, and $\gamma n \to K^0\Sigma^0$ on a liquid deuterium target, where $W$ was calculated from the incident beam energy assuming quasifree kinematics. The measurements were performed at MAMI-C, the Mainz Microtron located in Mainz, Germany. We analyzed these reactions via the $K^0 \to \pi^0\pi^0$ decay. Further details are provided in Sec. III.

The cross-section data can be used to help determine $N^*$ resonance properties using partial-wave analyses or to test phenomenological models of kaon photoproduction. This paper reports the world’s first results on differential and total cross sections for the reaction $\gamma n \to K^0\Sigma^0$.

This paper is divided into six sections: Sec. II describes the experimental setup, Sec. III describes the data analysis, Sec. IV describes the calculation of uncertainties, Sec. V describes the results and discussion for all three reactions, and Sec. VI gives the summary and conclusions. Our measured cross sections are tabulated in the appendix.

II. EXPERIMENTAL SETUP

Data for the photoproduction of neutral kaon reactions on a liquid deuterium target were measured using the Crystal Ball (CB) [11–15], particle identification detector (PID) [16] and TAPS [13–15] detectors. All these detectors were set up at the Mainz Microtron bremsstrahlung-tagged photon beam facility in Germany. At the time the measurements were performed, MAMI-C could deliver electrons with energies up to a maximum energy of 1508 MeV. The mono-energetic electron beam could deliver electrons with energies up to a maximum of 20 MeV. Aguar-Bartolomé et al. [9] measured $\gamma n \to K^0\Lambda$, and $\Sigma^+ \to \pi^0\pi^0$ decays. Recently, Compton et al. [10] measured $\gamma n \to K^0\Lambda$ at JLab using the CLAS detector. Data were collected in two datasets, g10 and g13, which used different run conditions. Events were reconstructed using the $K^0 \to \pi^0\pi^0$ and $\Lambda \to \pi^-p$ decays.

The forward moving particles are detected by TAPS, which was configured as a photon calorimeter consisting of 384 BaF$_2$ crystals located downstream of the Crystal Ball. These BaF$_2$ crystals were arranged in a honeycomb pattern to form a hexagonal wall covering the polar angle range from 20$^\circ$ to 160$^\circ$ and the azimuthal angle range from 0$^\circ$ to 360$^\circ$.

The PID (Particle Identification Detector) [16] is a cylindrical detector with a 5-cm inner radius oriented concentric with the target inside the Crystal Ball. It was designed to work along with the CB to provide information on charged particles. The PID distinguishes between different types of charged particles and neutral particles based on the energy deposited in the PID elements versus total energy measured in a CB cluster. For further details about these detectors, such as their energy and angle resolutions or their calibrations, see [13–15, 20, 22–25]. The CB and TAPS detectors are very efficient at detecting the final-state photons. A cylindrical MWPC (MultiWire Proportional Chamber) may be used to improve the angular resolution (tracking) of charged particles. During this experiment, the MWPC was not used. Figure II shows a schematic diagram of the CB and TAPS detector setup.

III. DATA ANALYSIS

After all the detectors had been calibrated, the event selection and analysis was carried out. Detailed Monte Carlo (MC) studies were performed using 3 $\times$ 10$^6$ events generated according to phase space for each of the three $K^0$ photoproduction reactions, as well as for $\gamma p \to \eta p$ and $\gamma n \to \eta n$, which are the leading background reactions due to $\eta \to 3\pi^0 \to 6\gamma$ decays.

In each reaction the $K^0$ was identified through its decay $K^0 \to \pi^0\pi^0 \to \gamma\gamma$. The $\Sigma^+$ was identified through its decay $\Sigma^+ \to \pi^0p$, $\Lambda$ through its decay $\Lambda \to \pi^0n$, and $\Sigma^0$ through its decay $\Sigma^0 \to \gamma\Lambda \to \gamma\pi^0n$. Therefore, the detection of three $\pi^0$s in the final state was required in all cases, giving rise to six final-state photons via $\pi^0 \to \gamma\gamma$. Data for $\gamma p \to K^0\Sigma^+$, $\gamma n \to K^0\Lambda$, and $\gamma n \to K^0\Sigma^0$ reactions were sorted into various cases ($ncr$), where $n$ represents the detected number of final-state neutral particles and $c$ represents the detected number of final-state charged particles. Table IV tabulates the reactions and the corresponding cases for the present work.
If only six neutral clusters are detected, the event is case (60). To be a viable event for $\gamma p \rightarrow K^0\Sigma^+$ or $\gamma n \rightarrow K^0\Lambda$, further analysis was needed to establish these six neutral clusters as photons produced from $\pi^0$ decays. The data analysis for case (60) starts by first selecting events that have six and only six neutral clusters. If the final proton in $\Sigma^+ \rightarrow \pi^0 p$ is detected then there will be seven neutral clusters and one charged cluster in the final state, which defines case (61). If the neutron in $\Lambda \rightarrow \pi^0 n$ is detected then there will be seven neutral clusters and no charged cluster, which defines case (70).

For $\gamma n \rightarrow K^0\Sigma^0$ events, the detection of seven photon candidates is required, six coming from $\pi^0$ decays and one coming from $\Sigma^0 \rightarrow \gamma\Lambda$. If the final-state neutron is not detected, then the event corresponds to case (70); however, if the final-state neutron is detected, then the event corresponds to case (80).

Once events had been separated according to the number of neutral and charged clusters, the next step was to identify the final three $\pi^0$s from the neutral clusters. To identify the three $\pi^0$s, all distinct possible combinations of two-photon candidates were constructed. There are 15, 21, and 28 possible ways to construct distinct two-$\pi^0$ combinations from six, seven, and eight neutral clusters, respectively. A histogram of the invariant-mass of all distinct two-$\pi^0$ combinations for case (60) is shown in Fig. 2. Only those distinct two-$\pi^0$ combinations whose invariant-mass $m(\gamma\gamma)$ was between 90 and 160 MeV are the actual $\pi^0$ candidates. This invariant-mass cut is represented by solid red vertical lines in Fig. 2. A typical event had several combinations that satisfied this criterion. Only those events that had a minimum of three distinct $\pi^0$ candidates were kept. Major sources of background for the reactions of interest are $\gamma p \rightarrow \eta p$ and $\gamma n \rightarrow \eta n$, where $\eta \rightarrow 3\pi^0$. In order to eliminate this background, only those three $\pi^0$ candidates whose combined invariant mass is greater than 600 MeV were selected for further analysis [9, 26]. This cut significantly reduces the $\eta$ background contribution while only slightly reducing events from the reactions of interest. If the three $\pi^0$ candidates for a given combination are labeled as $\pi^0\eta_1$, $\pi^0\eta_2$, $\pi^0\eta_3$, then there are three ways to construct the two $\pi^0$s that could correspond to a $K^0$ decay; that is, $(\pi^0\pi^0)$, $(\pi^0\pi^0)$, or $(\pi^0\pi^0)$. A histogram of the mass of one $\pi^0$ candidate $m(\gamma\gamma)$ versus the invariant mass $m(\pi^0\pi^0)$ of the other two $\pi^0$ candidates is shown in Fig. 3. This two-dimensional plot provided information on where best to impose a cut on $m(\pi^0\pi^0)$ to reduce the background further. Only combinations in which $m(\pi^0\pi^0)$ was between

| Case | Reaction | Comment |
|------|----------|---------|
| 61   | $\gamma p \rightarrow K^0\Sigma^+$ | final $p$ detected |
| 60   | $\gamma p \rightarrow K^0\Sigma^+$ | final $p$ not detected |
|      | $\gamma n \rightarrow K^0\Lambda$ | final $n$ not detected |
| 70   | $\gamma n \rightarrow K^0\Lambda$ | final $n$ detected |
| 80   | $\gamma n \rightarrow K^0\Sigma^0$ | final $n$ detected |

TABLE I. Cases based on nucleon detection for all three $\gamma N \rightarrow K^0\gamma$.
435 and 482 MeV were selected for further analysis. This cut was applied before the energy correction discussed below. After this correction, the $K^0$ peaks in the $π^0π^0$ invariant-mass distribution were very close to 498 MeV.

Figure 3 shows a histogram of the invariant mass $m(π^0π^0)$ plotted versus the invariant mass $m(γγ)$ for Monte Carlo simulated $γn → K^0Λ$ events for case (60). The photon candidates used to calculate $m(γγ)$ were distinct from those used to calculate $m(π^0π^0)$.

For case (61), events with six neutral clusters and one charged cluster were selected. The PID was used to select the proton candidate. Similar analysis steps were used to select the best choice for the correct three-$π^0$ combination as for case (60).

For case (80), there were eight neutral clusters. Again, similar analysis steps were followed as for case (60) to identify the best choice for the correct three-$π^0$ combination. Here for each three-$π^0$ combination there was one unpaired particle.

The energy reconstruction of the $K^0$ mesons was im-
proved by applying a correction \[20\],

\[
E' = E \cdot \frac{m_{\pi^0}}{m_{\gamma\gamma}}
\]

which made use of information obtained from the good angular resolution of the CB, after the best choice for the correct three-$\pi^0$ combination had been determined. Here $E$ is the relativistic energy of each $\pi^0$, $m_{\gamma\gamma}$ is the invariant mass of the decay photons, and $m_{\pi^0} = 135$ MeV is the known $\pi^0$ mass. Before scaling, the invariant mass for $\pi^0 \rightarrow 11\gamma$ is given by

\[
(m_{\gamma\gamma})^2 = 2E_1 E_2 (1 - \cos \theta_{\gamma\gamma}),
\]

where $\theta_{\gamma\gamma}$ is the measured opening angle for $\pi^0 \rightarrow 11\gamma$. Here $E_1$ and $E_2$ are the measured energies of the two photon clusters. After scaling $(E_1 \rightarrow E'_1$ and $E_2 \rightarrow E'_2$), the scaled invariant mass $m(\gamma\gamma)$ was exactly the $\pi^0$ mass, 135 MeV. The scaled 4-momenta of the $\pi^0$s were used to calculate $m(\pi^0\pi^0)$ and $m(\pi^0N)$, where $N$ represents the nucleon. All three $\pi^0\pi^0$ combinations were considered for further analysis. In MC simulations for each $\gamma N \rightarrow K^0Y$ event, there are two incorrect $\pi^0\pi^0$ combinations for each correct combination. Monte Carlo simulations were used to determine $m(\pi^0\pi^0)$ in real data, there can be additional contributions to background in the $m(\pi^0\pi^0)$ distributions.

The $\pi^0\pi^0$ invariant-mass distributions were fitted using a binned likelihood method with the parametrization

\[
y(x) = \left[\frac{x^2 - (270)^2}{x^2}\right]^\alpha \left[\beta \exp \left(-\frac{1}{2}\left(\frac{x - \mu}{\sigma_B}\right)^2\right) + \delta \exp \left(-\frac{1}{2}\left(\frac{x - 498}{\sigma_K}\right)^2\right)\right],
\]

where $\alpha$, $\beta$, $\delta$, $\mu$, $\sigma_B$, and $\sigma_K$ were fitting parameters. The first factor ensures that the distribution goes to zero when $x = 2m_{\pi^0} = 270$ MeV. The exponent $\alpha$ is a small number ($0 < \alpha < 1$) determined by fitting the $m(\pi^0\pi^0)$ distribution for given energy bins. The parameter $\beta$ measures the yield of the background contribution. The background was represented by a scaled Gaussian distribution with centroid $\mu$ and standard deviation $\sigma_B$. The parameter $\delta$ measures the yield of the kaon signal. The kaon signal distribution was represented by a scaled Gaussian with centroid 498 MeV (the $K^0$ mass) and standard deviation $\sigma_K$. The observed $m(\pi^0\pi^0)$ distributions for each energy bin, summed over all angle bins, were fitted to determine $\alpha$ and $\sigma_K$ parameter values for each energy bin. Next the observed $m(\pi^0\pi^0)$ distributions for each angle bin, for a particular energy bin, were fitted with the values of $\alpha$ and $\sigma_K$ held fixed at their fitted values for that particular energy bin. Monte Carlo simulations were used to verify that this approximation was reasonable. The fitting parameters $\beta$, $\delta$, $\mu$, and $\sigma_K$ were allowed to vary freely in each angle and energy bin. The fitted value of $\mu$ for a particular angle and energy bin, with $\alpha$ and $\sigma_K$ held fixed as above, was called the nominal background centroid. The values of the nominal background centroid for each energy and angle bin were recorded for further analysis. The background contribution was obtained after the fit by setting $\delta$ equal to zero. Numerical integration was used to calculate the total number of kaons (the kaon yield, $N_{K^0}$) by subtracting the areas under the total and background curves.

The kaon yield was sensitive to the background contribution. A second fit of the observed $m(\pi^0\pi^0)$ distributions was performed with a different value of $\mu$ called the modified centroid. The modified centroid was chosen to be the average of the nominal centroid of the background and the signal centroid (498 MeV). This modified centroid was the maximum value of the background centroid that produced a good fit of the data. The use of these two background centroids is discussed further in Sec. IV.

Figure 5 shows the observed $\pi^0\pi^0$ invariant-mass distributions for $\gamma p \rightarrow K^0\Sigma^+$, $\gamma n \rightarrow K^0\Lambda$, and $\gamma n \rightarrow K^0\Sigma^0$ summed over all energy and angle bins. The fitted total invariant-mass distributions are represented by solid red curves and the background contributions are represented by solid black curves.

For calculating the differential cross sections, eight angle bins were used to cover the range from $\cos \theta_{\gamma\gamma} = -1.0$ to $+1.0$. The c.m. energy range $W = 1615$ to 1765 MeV was divided into five bins of width 30 MeV, and the c.m. energy range $W = 1765$ to 1865 MeV was divided into five bins of width 20 MeV. After subtracting the background, the differential cross section for a specified energy-angle bin was calculated using

\[
\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{N_{K^0}^{\gamma\gamma}}{N_{\gamma N}(\epsilon_{\gamma N} B)\pi\Delta\cos \theta_{\gamma\gamma}},
\]

where $N_{K^0}^{\gamma\gamma} = N_{K^0}^{\gamma\gamma}(E_{\gamma N}, \theta_{\gamma\gamma})$ is the kaon yield for a given energy-angle bin, $N_{\gamma N}(\epsilon_{\gamma N})$ is the photon flux for a given energy bin, $\epsilon_{\gamma N}(\epsilon_{\gamma N}, \theta_{\gamma\gamma})$ is the acceptance for a specified energy-angle bin calculated from Monte Carlo simulations, $N_{\gamma N}$ is the number of target nucleons per cm$^2$, $B$ is a product of branching ratios for the particular reaction, and $\Delta\cos \theta_{\gamma\gamma}$ is the bin width for $\cos \theta_{\gamma\gamma}$.

The differential cross section for $\gamma n \rightarrow K^0\Sigma^0$ for case (80) was calculated using

\[
\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\gamma n \rightarrow K^0\Sigma^0}_{80} = \frac{N_{K^0}^{\gamma n \rightarrow K^0\Sigma^0}_{80}}{N_{\gamma n}(\epsilon_{\gamma N} B_{80})\pi\Delta\cos \theta_{\gamma\gamma}},
\]

where $N_{K^0}^{\gamma n \rightarrow K^0\Sigma^0}_{80}$ is the measured $K^0$ yield for case (80) and $B_{80} = 0.05301 \pm 0.00074$.

For case (70), the measured $K^0$ yield has contributions from both $\gamma n \rightarrow K^0\Sigma^0$ and $\gamma n \rightarrow K^0\Lambda$: $N_{K^0}^{\gamma n \rightarrow K^0\Sigma^0} = N_{K^0}^{\gamma n \rightarrow K^0\Sigma^0} + N_{K^0}^{\gamma n \rightarrow K^0\Lambda}$. Since \( \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\gamma n \rightarrow K^0\Sigma^0} \) \( \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\gamma n \rightarrow K^0\Lambda} \)

\[
N_{K^0}^{\gamma n \rightarrow K^0\Sigma^0} = \frac{\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\gamma n \rightarrow K^0\Sigma^0}_{70}}{N_{\gamma n}(\epsilon_{\gamma N} B_{70})\pi\Delta\cos \theta_{\gamma\gamma}} \times N_{\gamma n}(\epsilon_{\gamma N} B_{70})\pi\Delta\cos \theta_{\gamma\gamma}
\]

\[
+ \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\gamma n \rightarrow K^0\Lambda}_{70} \times N_{\gamma n}(\epsilon_{\gamma N} B_{70})\pi\Delta\cos \theta_{\gamma\gamma},
\]

where $B_\Lambda = B_{70} = 0.05301 \pm 0.00074$. Values of $B_\Lambda$, $B_{70}$, and $B_{80}$ were calculated using branching ratios.
The measured $\gamma n \rightarrow K^0 \Sigma^+$ tails, see Ref. [28]. The fitted total invariant-mass distributions are represented by solid red curves and the background contributions are represented by solid black curves.

The measured $\gamma n \rightarrow K^0 \Lambda$ differential cross section for case (70) is then

$$\left( \frac{d\sigma}{d\Omega} \right)_{\gamma n \rightarrow K^0 \Lambda} = \frac{N_{K^0}^{\gamma n \Lambda}}{N_{\gamma n}^{\gamma n \Lambda} N_{B_{\Lambda}} 2\pi \Delta \cos \theta_{cm}}$$

The measured $\gamma n \rightarrow K^0 \Sigma^0$ cross sections for case (80) and the measured $K^0$ yields for case (70) were used to calculate the $\gamma n \rightarrow K^0 \Lambda$ cross sections for case (70).

Similarly, the differential cross section for $\gamma p \rightarrow K^0 \Sigma^+$ for case (61) was calculated using

$$\left( \frac{d\sigma}{d\Omega} \right)_{\gamma p \rightarrow K^0 \Sigma^+} = \frac{N_{K^0}^{\gamma p \Sigma^+}}{N_{\gamma n}^{\gamma p \Sigma^+} N_{B_{\Sigma^+}} 2\pi \Delta \cos \theta_{cm}},$$

where $N_{K^0}^{\gamma p \Sigma^+}$ is the measured $K^0$ yield for case (61) and $B_{\Sigma^+} = 0.07637 \pm 0.00046$.

For case (60), the measured $K^0$ yield has contributions from both $\gamma n \rightarrow K^0 \Lambda$ and $\gamma p \rightarrow K^0 \Sigma^+$: $N_{K^0}^{\gamma n \Lambda} + N_{K^0}^{\gamma p \Sigma^+}$. Since $(d\sigma/d\Omega)^{\gamma p \rightarrow K^0 \Sigma^+} = (d\sigma/d\Omega)^{\gamma n \rightarrow K^0 \Lambda}$,

$$N_{K^0}^{\gamma p \Sigma^+} = \frac{(d\sigma/d\Omega)^{\gamma n \rightarrow K^0 \Lambda}}{N_{\gamma n}^{\gamma n \Lambda} N_{B_{\Lambda}} 2\pi \Delta \cos \theta_{cm}} N_{\gamma p}^{\gamma p \Sigma^+} N_{B_{\Sigma^+}} 2\pi \Delta \cos \theta_{cm}.$$
Since \( \frac{d\sigma}{d\Omega} \gamma n \rightarrow K^0\Lambda = \frac{d\sigma}{d\Omega} \gamma n \rightarrow K^0\Lambda \),
\[
N_{K^0}^{\gamma n} \rightarrow K^0\Lambda = \frac{d\sigma}{d\Omega} \gamma n \rightarrow K^0\Lambda \times N_\gamma \epsilon_\gamma^{70} \times \frac{N_{K^0}}{N_{K^0}^{70}} \times \frac{B_\Lambda}{B_{\Sigma^0}} \times \frac{d\sigma}{d\Omega} \gamma n \rightarrow K^0\Lambda.
\]
Thus,
\[
\left( \frac{d\sigma}{d\Omega} \right)_{70} \gamma n \rightarrow K^0\Sigma^0 = \frac{N_{K^0}^{70}}{N_{\gamma} \epsilon_\gamma^{70} \times N_{\Sigma^0}} \times \frac{B_\Lambda}{B_{\Sigma^0}} \times \frac{d\sigma}{d\Omega} \gamma n \rightarrow K^0\Lambda.
\]

The average of the differential cross sections for the cases with and without detection of the final-state neutron, weighted according to the statistical uncertainties, was calculated for \( \gamma n \rightarrow K^0\Lambda \) and \( \gamma n \rightarrow K^0\Sigma^0 \) and then integrated cross sections were obtained by fitting these values with two-parameter expansions in Legendre polynomials. The Legendre fits include \( P_0 \) and \( P_1 \) terms for the \( \gamma n \rightarrow K^0\Lambda \) and \( \gamma n \rightarrow K^0\Sigma^0 \) results but just a \( P_0 \) term for the \( \gamma p \rightarrow K^0\Sigma^+ \) results. We used only our case (61) results for \( \gamma p \rightarrow K^0\Sigma^+ \).

### IV. CALCULATION OF UNCERTAINTIES

There are two types of uncertainty involved in calculating the differential cross section. One is the statistical uncertainty and the other is the systematic uncertainty. The statistical uncertainty describes our imprecise knowledge of the kaon signal yield. The systematic uncertainty is the combination of uncertainties from the photon flux, acceptance, and branching ratios. The kaon signal yield in real data was correlated with the centroid of the background. As mentioned earlier, the \( \pi^0\pi^0 \) invariant-mass distributions were fitted with a sum of scaled Gaussians, with background and signal parts. The kaon signal yield was determined using the nominal case background centroid and kaon signal centroid (498 MeV), and the \( n(\pi^0\pi^0) \) distribution was refitted and the kaon yield was recalculated. This is called the modified case. The statistical uncertainty was conservatively calculated using
\[
\Delta N_{K^0} = [(\text{Poisson error})^2 + (\text{model error})^2]^{1/2}. \tag{13}
\]

Here, Poisson error = \( \sqrt{N_{K^0} + 1} \), where \( N_{K^0} \) is the average number of \( K^0 \)s determined by fitting the \( n(\pi^0\pi^0) \) distributions using the nominal and modified values for the background centroid. The model error was taken as the difference in the number of \( K^0 \)s determined using the two different background centroids. The statistical uncertainty in \( \frac{d\sigma}{d\Omega} \) is given by
\[
\Delta \left( \frac{d\sigma}{d\Omega} \right)_{\text{stat.}} = \frac{d\sigma}{d\Omega} \times \frac{\Delta N_{K^0}}{N_{K^0}} \tag{14}
\]
and the systematic uncertainty is given by
\[
\Delta \left( \frac{d\sigma}{d\Omega} \right)_{\text{sys.}} = \frac{d\sigma}{d\Omega} \times \left[ \left( \frac{\Delta N_{\gamma}}{N_{\gamma}} \right)^2 + \left( \frac{\Delta \epsilon}{\epsilon} \right)^2 + \left( \frac{\Delta B_{\Lambda}}{B_{\Lambda}} \right)^2 \right]^{1/2}, \tag{15}
\]
where the contribution from the uncertainty in the photon flux varied from 1.1% to 2.4% and the contribution from the acceptance varied from about 2% to about 4% for \( \gamma n \rightarrow K^0\Lambda \) and \( \gamma n \rightarrow K^0\Sigma^0 \). The contribution from the product of branching ratios was 1.4% for \( \gamma n \rightarrow K^0\Lambda \) and \( \gamma n \rightarrow K^0\Sigma^0 \) and was 0.6% for \( \gamma p \rightarrow K^0\Sigma^+ \).

### V. RESULTS AND DISCUSSION

#### A. \( \gamma p \rightarrow K^0\Sigma^+ \)

Figure 6 shows the differential cross section for \( \gamma p \rightarrow K^0\Sigma^+ \) for the eight energy bins. Our results are shown as solid black circles. Prior results from Lawall et al. [7], measured with the SAPHIR detector at ELSA in Bonn, are shown as solid magenta squares. Prior results from Castelijns et al. [8], measured with the Crystal Barrel and TAPS spectrometers at ELSA, are shown as solid blue triangles. The most precise prior results are from Aguilar-Bartolomé et al. [9], measured on a liquid hydrogen target with the Crystal Ball and TAPS spectrometers at MAMI, and shown as solid red circles. Our differential cross-section results are in fair agreement within error bars with prior results in the \( \cos \theta_{cm} \) range from +0.6 to −0.45. Our results in the bins at \( \cos \theta_{cm} = \pm 0.875 \) and −0.675 were unreliable, due to the low statistics and low acceptance at these angle bins. Therefore, those results are not shown in Fig. 6 nor were they used to calculate the integrated cross sections. The solid blue curves in Fig. 6 are from a 15-parameter global fit to all the data, which is described below. The solid red curves are from a three-parameter global fit in which the angular distributions were approximated as being isotropic in each energy bin. The measurements in Fig. 6 are compared with isobar-model predictions by Mart [29], which are shown as dashed green curves. In general, these predictions do not agree well with the measured angular distributions.

In order to ensure a smooth variation with energy and that the cross section vanishes at threshold, a 15-parameter global fit of our results and prior differential cross-section data was performed. This fit used the parametrization
\[
\frac{d\sigma}{d\Omega} = \sum_{n=1}^{3} \sum_{l=0}^{4} a_{nl}(W - W_T)^n P_l(\cos \theta_{cm}), \tag{16}
\]
where \( W_T = 1687 \) MeV is the threshold energy for \( \gamma p \rightarrow K^0\Sigma^+ \) and \( P_l(\cos \theta_{cm}) \) is a Legendre polynomial.
The $a_{nl}$ coefficients were constant fitting parameters. Uncertainties in the fitted cross sections were conserva-
tively calculated as twice the difference between re-
sults of the 15-parameter global fit and a separate three-
parameter global fit in which the angular distributions
were approximated as being isotropic in each energy bin
(only the $a_{nn}$ coefficients were varied).

Our measured integrated cross sections for $\gamma p \rightarrow
K^0\Sigma^+$ were obtained by making one-parameter Legen-
dre fits of our measured differential cross sections. They
are shown in Fig. 4 as solid black circles. Prior results
from Lawall et al. [7], Castelijns et al. [8], and Aguar-
Bartolomé et al. [9] are shown as solid magenta squares,
solid blue triangles, and solid red circles, respectively.
The results of our 15-parameter global fit are shown as
solid cyan circles. The experimental results are com-
pared with Mart’s isobar-model predictions [29] shown
as a dashed green curve.

B. $\gamma n \rightarrow K^0\Lambda$

Since the measured $\gamma p \rightarrow K^0\Sigma^+$ cross sections for
case (61) were imprecise due to low statistics and the
low acceptance at backward and forward angles, the
fitted world values of $(d\sigma/d\Omega)_{\gamma p \rightarrow K^0\Sigma^+}$
and the mea-
sured $K^0$ yields for case (60) were used to calculate
$\gamma n \rightarrow K^0\Lambda$ cross sections for case (60). Because the
associated uncertainties in the fitted world values were
relatively large at $\cos\theta_{cm} = 0.875$, those angle bins
were excluded for all three $K^0$ photoproduction reac-
tions. The c.m. energy range $W = 1615$ to 1765 MeV
was divided into five bins of width 30 MeV, and the
c.m. energy range $W = 1765$ to 1865 MeV was divided
into five bins of width 20 MeV. The first two c.m. energy
bins $W = 1630$ and 1660 MeV were below $\gamma p \rightarrow K^0\Sigma^+$
threshold 1687 MeV. Therefore only $\gamma n \rightarrow K^0\Lambda$ events
can contribute to these bins. Figure 8 shows the differen-
tial cross section for $\gamma n \rightarrow K^0\Lambda$ for these ten energy bins.
Solid black circles show our results (weighted average of
cases (60) and (70)). The solid magenta triangles and
solid blue triangles respectively show the g10 and g13 re-
sults from Compton et al. [10] measured at JLab. Our
results agree, within uncertainties, with the JLab g10 re-
sults in the energy bins at 1720 and 1835 MeV and with
the JLab g13 results in the energy bin at 1855 MeV.
Our results are similar in shape to the JLab g13 mea-
surements at 1660, 1690, 1750, and 1795 MeV but are
smaller in magnitude. It should be noted that the g10
and g13 results, where they overlap, are consistent for
c.m. energies above about 1800 MeV, but the g13 results
below that energy are all larger (especially at forward an-
gles) than the g10 result that falls into our energy bin at
1690 MeV. The solid red curves in Fig. 5 show results of
two-parameter Legendre polynomial fits to our measure-
ments. The solid green curves show predictions based

FIG. 6. Differential cross section for $\gamma p \rightarrow K^0\Sigma^+$ for the various c.m. energy bins. The solid black circles show our results, the
solid magenta squares show prior results from Lawall et al. [7], the solid blue triangles show prior results from Castelijns et al. [8], the solid red circles show prior results from Aguar-Bartolomé et al. [9], and the dashed green curves represent isobar-model predictions by Mart [29]. The solid blue curves show results of a 15-parameter global fit to our results and prior differential
cross-section data. The solid red curves show results of a three-parameter global fit in which the angular distributions were approximated as being isotropic in each energy bin. (See text for details.)
upon a partial-wave analysis \cite{29}. Our results are in fair agreement with the predictions in all energy bins except at 1690 MeV.

We have checked various factors that might affect the normalizations of our results (e.g., the photon flux \(N_\gamma\) and detector acceptance) and have been unable to find any problems that would explain the differences between our results and the low-energy g13 results. Our results for all energy bins were handled in exactly the same manner as each other. Figure 9 shows the differential cross section for \(\gamma n \rightarrow K^0\Lambda\) as a function of c.m. energy \(W\) for individual angle bins. The results in this plot show a generally smooth energy variation, which supports the fact that the normalizations were determined consistently for the different energy bins.

Our measured integrated cross section values for \(\gamma n \rightarrow K^0\Sigma^0\) are shown in Fig. 13 as solid black circles. Our integrated cross sections were obtained by calculating the weighted average of our differential cross sections for cases (70) and (80) and then making two-parameter Legendre polynomial fits. Our experimental results are compared with an isobar-model prediction (solid blue curve) by Mart \cite{29}. Our results are in good agreement with Mart’s predictions except at the highest energy. These are the first experimental results for \(\gamma n \rightarrow K^0\Lambda\). As in the case of the differential cross sections, our results are in good agreement with Mart’s predictions except at the highest energy bin.

VI. SUMMARY AND CONCLUSIONS

Our results for \(\gamma p \rightarrow K^0\Sigma^+\) are in fair agreement with prior measurements in the \(\cos \theta_{cm}\) range from \(-0.45\) to \(+0.6\), but our results at the most forward and backward angles are unreliable. For this reason, we used \(\gamma p \rightarrow K^0\Sigma^+\) world data to extract the \(\gamma n \rightarrow K^0\Lambda\) cross section for case (60). An isobar-model prediction by Mart \cite{29} generally disagrees with all the measured differential cross sections.

Only one published set of prior measurements for \(\gamma n \rightarrow K^0\Lambda\) was available for comparing with our results. These prior results were measured with the CLAS spectrometer at JLab \cite{10} in two separate datasets. In the seven energy bins where our results can be compared, our results agree within uncertainties with the g10 results but our results have a somewhat similar shape, but smaller magnitude, compared with the g13 results below \(W = 1800\) MeV. The results presented in Ref. \cite{10} show that the g10 and g13 results, where they overlap,
are generally consistent above about $W = 1800$ MeV but not at lower energies. Our results are in fairly good agreement (except at 1690 MeV) with a prediction based on a partial-wave analysis [30] within error bars. Our results for $\gamma n \to K^0 \Lambda$ provide new measurements in the c.m. energy range from threshold (1614 MeV) to 1855 MeV.

Our results for $\gamma n \to K^0 \Sigma^0$ are the first experimental results for that reaction and span the c.m. energy range from the threshold (1691 MeV) to 1855 MeV. Our differential cross sections for $\gamma n \to K^0 \Sigma^0$ are in good agreement within error bars with isobar-model predictions by Mart [29] except at the highest energy bin. Our two independent measurements for cases (70) and (80) are consistent within error bars.

In summary, our new cross-section measurements for $\gamma n \to K^0 \Lambda$ and $\gamma n \to K^0 \Sigma^0$ will provide valuable data for future partial-wave analyses and will help better determine the properties of $N^*$ resonances that decay to $K\Lambda$ or $K\Sigma$ final states.

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FIG. 9. Differential cross section for $\gamma n \rightarrow K^0\Lambda$ versus c.m. energy $W$ for angle bins from $\cos \theta_{cm} = +0.625$ to $-0.625$. The open blue circles represent the weighted average of our results for cases (60) and (70).

FIG. 10. Integrated cross section for $\gamma n \rightarrow K^0\Lambda$. The solid black circles represent our results. The solid magenta triangles and solid blue triangles respectively show the $g_{10}$ and $g_{13}$ results from Compton et al. [10]. The solid green curve shows a prediction [30] based upon a partial-wave analysis.

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FIG. 11. Differential cross section for $\gamma n \rightarrow K^0 \Sigma^0$. Solid black circles show our results. Solid blue curves represent isobar-model predictions by Mart [29] and the solid red curves show results of two-parameter Legendre polynomial fits to our measurements.

FIG. 12. Differential cross section for $\gamma n \rightarrow K^0 \Sigma^0$ versus c.m. energy $W$ for angle bins from $\cos \theta_{cm} = +0.625$ to $-0.625$. The open blue circles represent the weighted average of our results for cases (70) and (80).

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FIG. 13. Integrated cross section for $\gamma n \rightarrow K^0\Sigma^0$. Solid black circles show our results. The solid blue curve represents an isobar-model prediction by Mart [29].

Appendix: Tabulation of Results

In this appendix, we provide our measured differential and integrated cross sections for $\gamma p \rightarrow K^0\Sigma^+$ in Tables [II] and [III], our measured differential and integrated cross sections for $\gamma n \rightarrow K^0\Lambda$ in Tables [IV] and [V], and our measured differential and integrated cross sections for $\gamma n \rightarrow K^0\Sigma^0$ in Tables [VI] and [VII].
TABLE II. Differential cross section for $\gamma p \rightarrow K^0\Sigma^+$. Systematic uncertainties less than 0.001 are not listed.

| W (MeV) | $\cos\theta_{cm}$ | $d\sigma/d\Omega$ (µb/sr) | stat. unc. (µb/sr) | sys. unc. (µb/sr) | W (MeV) | $\cos\theta_{cm}$ | $d\sigma/d\Omega$ (µb/sr) | stat. unc. (µb/sr) | sys. unc. (µb/sr) |
|---------|-----------------|-----------------|-----------------|-----------------|---------|-----------------|-----------------|-----------------|-----------------|
| 1690    | +0.625          | 0.013           | 0.004           | 0.001           | 1795    | +0.625          | 0.020           | 0.005           | 0.001           |
| 1690    | +0.375          | 0.012           | 0.004           | 0.001           | 1795    | +0.375          | 0.026           | 0.004           | 0.001           |
| 1690    | +0.125          | 0.027           | 0.007           | 0.002           | 1795    | +0.125          | 0.015           | 0.005           | 0.001           |
| 1690    | −0.125          | 0.033           | 0.006           | 0.002           | 1795    | −0.125          | 0.017           | 0.008           | 0.001           |
| 1690    | −0.375          | 0.033           | 0.012           | 0.002           | 1795    | −0.375          | 0.028           | 0.007           | 0.001           |
| 1720    | +0.625          | −               | −               | −               | 1815    | +0.625          | 0.014           | 0.014           | 0.001           |
| 1720    | +0.375          | 0.012           | 0.009           | 0.001           | 1815    | +0.375          | 0.022           | 0.013           | 0.002           |
| 1720    | +0.125          | 0.018           | 0.010           | 0.001           | 1815    | +0.125          | 0.021           | 0.015           | 0.001           |
| 1720    | −0.125          | 0.038           | 0.014           | 0.002           | 1815    | −0.125          | 0.033           | 0.015           | 0.002           |
| 1720    | −0.375          | 0.049           | 0.021           | 0.002           | 1815    | −0.375          | 0.039           | 0.015           | 0.003           |
| 1750    | +0.625          | 0.012           | 0.012           | −               | 1835    | +0.625          | 0.013           | 0.014           | 0.001           |
| 1750    | +0.375          | 0.017           | 0.009           | 0.001           | 1835    | +0.375          | 0.037           | 0.012           | 0.003           |
| 1750    | +0.125          | 0.022           | 0.009           | 0.001           | 1835    | +0.125          | 0.032           | 0.012           | 0.003           |
| 1750    | −0.125          | 0.021           | 0.013           | 0.001           | 1835    | −0.125          | 0.012           | 0.012           | 0.003           |
| 1750    | −0.375          | 0.035           | 0.018           | 0.001           | 1835    | −0.375          | 0.003           | 0.003           | −               |
| 1775    | +0.625          | 0.005           | 0.005           | −               | 1855    | +0.625          | 0.047           | 0.013           | 0.004           |
| 1775    | +0.375          | 0.006           | 0.006           | −               | 1855    | +0.375          | 0.028           | 0.015           | 0.002           |
| 1775    | +0.125          | 0.016           | 0.008           | 0.001           | 1855    | +0.125          | 0.037           | 0.013           | 0.003           |
| 1775    | −0.125          | 0.012           | 0.012           | 0.001           | 1855    | −0.125          | 0.032           | 0.014           | 0.003           |
| 1775    | −0.375          | 0.025           | 0.020           | 0.001           | 1855    | −0.375          | 0.020           | 0.016           | 0.002           |

TABLE III. Integrated cross section for $\gamma p \rightarrow K^0\Sigma^+$.

| W (MeV) | $\sigma$ (µb) | stat. unc. (µb) | sys. unc. (µb) |
|---------|---------------|-----------------|---------------|
| 1690    | 0.225         | 0.030           | 0.010         |
| 1720    | 0.188         | 0.055           | 0.006         |
| 1750    | 0.247         | 0.061           | 0.005         |
| 1775    | 0.211         | 0.075           | 0.007         |
| 1795    | 0.290         | 0.031           | 0.011         |
| 1815    | 0.336         | 0.079           | 0.023         |
| 1835    | 0.291         | 0.074           | 0.023         |
| 1855    | 0.457         | 0.077           | 0.035         |
### TABLE IV. Differential cross section for $\gamma n \rightarrow K^0 \Lambda$.

| $W$ (MeV) | $\cos \theta_{cm}$ | $d\sigma/d\Omega$ (µb/sr) | stat. unc. (µb/sr) | sys. unc. (µb/sr) | $W$ (MeV) | $\cos \theta_{cm}$ | $d\sigma/d\Omega$ (µb/sr) | stat. unc. (µb/sr) | sys. unc. (µb/sr) |
|-----------|----------------------|-----------------------------|-------------------|-------------------|-----------|----------------------|-----------------------------|-------------------|-------------------|
| 1630      | +0.625               | 0.016                       | 0.011             | 0.001             | 1775      | +0.625               | 0.039                       | 0.028             | 0.002             |
| 1660      | +0.375               | 0.029                       | 0.010             | 0.001             | 1795      | +0.375               | 0.070                       | 0.025             | 0.003             |
| 1690      | +0.125               | 0.028                       | 0.009             | 0.001             | 1720      | +0.125               | 0.073                       | 0.022             | 0.003             |
| 1720      | −0.125               | 0.056                       | 0.010             | 0.002             | 1750      | −0.125               | 0.086                       | 0.021             | 0.004             |
| 1750      | −0.375               | 0.066                       | 0.012             | 0.003             | 1775      | −0.375               | 0.101                       | 0.020             | 0.004             |
| 1795      | −0.625               | 0.058                       | 0.016             | 0.002             | 1800      | −0.625               | 0.130                       | 0.022             | 0.005             |
| 1815      | +0.625               | 0.020                       | 0.014             | 0.001             | 1825      | +0.625               | 0.037                       | 0.019             | 0.002             |
| 1835      | +0.375               | 0.025                       | 0.017             | 0.001             | 1850      | +0.375               | 0.054                       | 0.013             | 0.002             |
| 1855      | +0.125               | 0.050                       | 0.016             | 0.002             | 1870      | +0.125               | 0.059                       | 0.015             | 0.003             |
| 1870      | −0.125               | 0.067                       | 0.020             | 0.003             | 1890      | −0.125               | 0.073                       | 0.013             | 0.003             |
| 1890      | −0.375               | 0.083                       | 0.022             | 0.004             | 1900      | −0.375               | 0.068                       | 0.013             | 0.003             |
| 1900      | −0.625               | 0.089                       | 0.026             | 0.004             | 1915      | −0.625               | 0.082                       | 0.014             | 0.004             |
| 1920      | +0.625               | 0.021                       | 0.017             | 0.001             | 1935      | +0.625               | 0.094                       | 0.035             | 0.007             |
| 1935      | +0.375               | 0.041                       | 0.018             | 0.002             | 1950      | +0.375               | 0.100                       | 0.029             | 0.007             |
| 1950      | +0.125               | 0.058                       | 0.016             | 0.003             | 1965      | +0.125               | 0.112                       | 0.024             | 0.008             |
| 1965      | −0.125               | 0.073                       | 0.017             | 0.004             | 1980      | −0.125               | 0.111                       | 0.024             | 0.008             |
| 1980      | −0.375               | 0.084                       | 0.019             | 0.004             | 1995      | −0.375               | 0.121                       | 0.023             | 0.009             |
| 1995      | −0.625               | 0.109                       | 0.022             | 0.005             | 2010      | −0.625               | 0.144                       | 0.022             | 0.010             |
| 2020      | +0.625               | 0.046                       | 0.029             | 0.002             | 2035      | +0.625               | 0.089                       | 0.036             | 0.007             |
| 2035      | +0.375               | 0.069                       | 0.026             | 0.003             | 2050      | +0.375               | 0.076                       | 0.034             | 0.006             |
| 2050      | +0.125               | 0.092                       | 0.024             | 0.004             | 2065      | +0.125               | 0.069                       | 0.024             | 0.006             |
| 2065      | −0.125               | 0.084                       | 0.024             | 0.003             | 2080      | −0.125               | 0.094                       | 0.026             | 0.008             |
| 2080      | −0.375               | 0.106                       | 0.027             | 0.004             | 2095      | −0.375               | 0.103                       | 0.023             | 0.008             |
| 2095      | −0.625               | 0.141                       | 0.029             | 0.005             | 2110      | −0.625               | 0.126                       | 0.023             | 0.010             |
| 2120      | +0.625               | 0.036                       | 0.030             | 0.001             | 2135      | +0.625               | 0.097                       | 0.022             | 0.008             |
| 2135      | +0.375               | 0.055                       | 0.027             | 0.002             | 2150      | +0.375               | 0.118                       | 0.018             | 0.010             |
| 2150      | +0.125               | 0.060                       | 0.024             | 0.002             | 2165      | +0.125               | 0.108                       | 0.016             | 0.009             |
| 2165      | −0.125               | 0.094                       | 0.023             | 0.003             | 2180      | −0.125               | 0.096                       | 0.013             | 0.008             |
| 2180      | −0.375               | 0.108                       | 0.023             | 0.003             | 2195      | −0.375               | 0.105                       | 0.013             | 0.008             |
| 2195      | −0.625               | 0.129                       | 0.025             | 0.003             | 2210      | −0.625               | 0.110                       | 0.014             | 0.009             |

### TABLE V. Integrated cross section for $\gamma n \rightarrow K^0 \Lambda$.

| $W$ (MeV) | $\sigma$ (µb) | stat. unc. (µb) | sys. unc. (µb) |
|-----------|---------------|----------------|---------------|
| 1630      | 0.54          | 0.05           | 0.02          |
| 1660      | 0.70          | 0.09           | 0.03          |
| 1690      | 0.81          | 0.09           | 0.03          |
| 1720      | 1.13          | 0.13           | 0.02          |
| 1750      | 1.01          | 0.13           | 0.04          |
| 1775      | 1.04          | 0.12           | 0.04          |
| 1795      | 0.79          | 0.07           | 0.05          |
| 1815      | 1.42          | 0.13           | 0.11          |
| 1835      | 1.14          | 0.13           | 0.09          |
| 1855      | 1.32          | 0.08           | 0.02          |
TABLE VI. Differential cross section for $\gamma n \rightarrow K^0\Sigma^0$. Systematic uncertainties less than 0.001 are not listed.

| $W$ (MeV) | $\cos \theta_{cm}$ | $d\sigma/d\Omega$ (µb/sr) | stat. unc. (µb/sr) | sys. unc. (µb/sr) | $W$ (MeV) | $\cos \theta_{cm}$ | $d\sigma/d\Omega$ (µb/sr) | stat. unc. (µb/sr) | sys. unc. (µb/sr) |
|-----------|---------------------|--------------------------|-------------------|-------------------|-----------|---------------------|--------------------------|-------------------|-------------------|
| 1690      | +0.625              | 0.007                    | 0.007             | −                 | 1795      | +0.625              | 0.032                    | 0.018             | 0.002             |
| 1690      | +0.375              | 0.012                    | 0.013             | 0.001             | 1795      | +0.375              | 0.027                    | 0.019             | 0.001             |
| 1690      | +0.125              | 0.017                    | 0.008             | 0.001             | 1795      | +0.125              | 0.038                    | 0.024             | 0.002             |
| 1690      | −0.125              | 0.011                    | 0.011             | 0.001             | 1795      | −0.125              | 0.029                    | 0.022             | 0.001             |
| 1690      | −0.375              | 0.005                    | 0.005             | −                 | 1795      | −0.375              | 0.058                    | 0.025             | 0.003             |
| 1690      | −0.625              | 0.020                    | 0.019             | 0.001             | 1795      | −0.625              | 0.057                    | 0.025             | 0.003             |
| 1720      | +0.625              | 0.012                    | 0.012             | 0.001             | 1815      | +0.625              | 0.061                    | 0.051             | 0.005             |
| 1720      | +0.375              | 0.019                    | 0.017             | 0.001             | 1815      | +0.375              | 0.062                    | 0.052             | 0.005             |
| 1720      | +0.125              | 0.020                    | 0.021             | 0.001             | 1815      | +0.125              | 0.042                    | 0.037             | 0.003             |
| 1720      | −0.125              | 0.034                    | 0.020             | 0.002             | 1815      | −0.125              | 0.057                    | 0.052             | 0.004             |
| 1720      | −0.375              | 0.031                    | 0.022             | 0.002             | 1815      | −0.375              | 0.094                    | 0.047             | 0.007             |
| 1720      | −0.625              | 0.031                    | 0.029             | 0.002             | 1815      | −0.625              | 0.106                    | 0.053             | 0.008             |
| 1750      | +0.625              | 0.032                    | 0.027             | 0.001             | 1835      | +0.625              | 0.098                    | 0.066             | 0.008             |
| 1750      | +0.375              | 0.034                    | 0.031             | 0.002             | 1835      | +0.375              | 0.047                    | 0.033             | 0.004             |
| 1750      | +0.125              | 0.031                    | 0.028             | 0.001             | 1835      | +0.125              | 0.143                    | 0.050             | 0.012             |
| 1750      | −0.125              | 0.027                    | 0.025             | 0.001             | 1835      | −0.125              | 0.069                    | 0.054             | 0.006             |
| 1750      | −0.375              | 0.036                    | 0.027             | 0.002             | 1835      | −0.375              | 0.076                    | 0.052             | 0.007             |
| 1750      | −0.625              | 0.052                    | 0.045             | 0.002             | 1835      | −0.625              | 0.066                    | 0.060             | 0.006             |
| 1775      | +0.625              | 0.049                    | 0.035             | 0.002             | 1855      | +0.625              | 0.136                    | 0.072             | 0.012             |
| 1775      | +0.375              | 0.086                    | 0.032             | 0.005             | 1855      | +0.375              | 0.120                    | 0.049             | 0.011             |
| 1775      | +0.125              | 0.064                    | 0.035             | 0.003             | 1855      | +0.125              | 0.118                    | 0.048             | 0.010             |
| 1775      | −0.125              | 0.045                    | 0.032             | 0.002             | 1855      | −0.125              | 0.120                    | 0.042             | 0.010             |
| 1775      | −0.375              | 0.089                    | 0.039             | 0.005             | 1855      | −0.375              | 0.140                    | 0.041             | 0.012             |
| 1775      | −0.625              | 0.082                    | 0.032             | 0.004             | 1855      | −0.625              | 0.176                    | 0.048             | 0.015             |

TABLE VII. Integrated cross section for $\gamma n \rightarrow K^0\Sigma^0$.

| $W$ (MeV) | $\sigma$ (µb) | stat. unc. (µb) | sys. unc. (µb) |
|-----------|-------------|----------------|---------------|
| 1690      | 0.111       | 0.038          | 0.005         |
| 1720      | 0.338       | 0.067          | 0.011         |
| 1750      | 0.47        | 0.12           | 0.01          |
| 1775      | 0.98        | 0.16           | 0.03          |
| 1795      | 0.54        | 0.11           | 0.02          |
| 1815      | 0.90        | 0.23           | 0.06          |
| 1835      | 1.01        | 0.23           | 0.08          |
| 1855      | 1.71        | 0.22           | 0.13          |