This is a repository copy of First measurement of $\Xi^-$ polarization in photoproduction.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/135829/

Version: Published Version

Article:
Bono, J., Guo, L., Raue, B. A. et al. (107 more authors) (2018) First measurement of $\Xi^-$ polarization in photoproduction. Physics Letters, Section B: Nuclear, Elementary Particle and High-Energy Physics. pp. 280-286. ISSN 0370-2693

https://doi.org/10.1016/j.physletb.2018.07.004

Reuse
This article is distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs (CC BY-NC-ND) licence. This licence only allows you to download this work and share it with others as long as you credit the authors, but you can’t change the article in any way or use it commercially. More information and the full terms of the licence here: https://creativecommons.org/licenses/

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.
First measurement of $\Xi^{-}$ polarization in photoproduction


a Florida International University, Miami, FL 33199, United States of America
b Rice University, Houston, TX 77005, United States of America
c Institute fur Kernphysik (Juelich), Juelich, Germany
d Argonne National Laboratory, Argonne, IL 60439, United States of America
e Arizona State University, Tempe, AZ 85287–1504, United States of America
f California State University, Dominguez Hills, Carson, CA 90747, United States of America
g University of Kentucky, Lexington, KY 40506, United States of America
h University Paris-Saclay, F-91191 Gif-sur-Yvette, France
i University of Missouri Rolla, Rolla, MO 65409, United States of America
j University of Alabama, Tuscaloosa, AL 35487, United States of America
k University of Delaware, Newark, DE 19716, United States of America
l University of Nebraska, Lincoln, NE 68588, United States of America
m University of Nevada, Las Vegas, NV 89154, United States of America
n University of Pennsylvania, Philadelphia, PA 19104, United States of America
o University of Rochester, Rochester, NY 14627, United States of America
p University of Wisconsin, Madison, WI 53706, United States of America
q University of Kentucky, Lexington, KY 40506, United States of America
r University of Missouri Rolla, Rolla, MO 65409, United States of America
s University of Alabama, Tuscaloosa, AL 35487, United States of America
t University of Florida, Gainesville, FL 32611, United States of America
u Tsinghua University, Beijing, China
v University of the Basque Country, UPV/EHU, Bilbao, Spain
w University of British Columbia, Vancouver, BC V6T 1Z4, Canada
x University of California, Davis, CA 95616, United States of America
y University of Connecticut, Storrs, CT 06269, United States of America
z University of Florida, Gainesville, FL 32611, United States of America

1. Introduction

The polarization of hyperons can be measured through the angular distribution of their parity-violating weak decay products, providing insight into the mechanisms behind their production. Such measurements involving the photo- and electroproduction of Strangeness number \( S = -1 \) hyperons \(^{1-12}\) have led to significant progress in understanding the excitation spectrum of \( S = 0 \) nucleons \(^{13-25}\). A similar opportunity exists in studying the polarization of \( S = -2 \) cascades, which could prove vital for understanding their production mechanism and in gaining an understanding of the excitation spectrum of \( S = -1 \) hyperons. However, because of the cascade’s low production cross section and the resulting lack of available data, no previous cascade polarization measurements exist in either photo- or electroproduction.

The CLAS collaboration has reported cross-section measurements for cascade photoproduction \(^{26,27}\). In these data, a strong back-angle peaking in the center-of-momentum cascade angular distribution \( \cos(\theta_C) \) was observed, which along with the invariant mass distributions of the \( K^+ \Sigma^- \) system, suggested the significant role that intermediate hyperon resonances with masses of about 2 GeV play in cascade photoproduction. These results generated theoretical interest in understanding the production mechanism behind \( S = -2 \) states. In particular, Refs. \(^{28,29}\) found it is necessary to include the contributions from the decay of high-mass hyperons (up to \( \Lambda(1890) \)) that are predominately produced in \( t \)-channel \( K^+K^- \) exchange, as illustrated in Fig. 1, to explain the CLAS cross-section measurements \(^{27}\). Furthermore, Ref. \(^{29}\) investigated the role of the addition of high-spin hyperon states around 2 GeV and found significant contributions from spin/parity \( J^P = \frac{3}{2}^- \) and \( \frac{5}{2}^+ \) resonances. In particular, the inclusion of the \( \Sigma(2030)\frac{3}{2}^- \) state improved the model’s agreement with the data.

These earlier photoproduction data from CLAS did not have either beam or target polarization, and no study on induced polarization was carried out. But as pointed out in Ref. \(^{29}\), both the induced and transferred polarization of the cascade ground state are sensitive to the production mechanism, particularly, the mass, spin and parity of intermediate hyperon resonances, as well as to the mesonic exchange mechanisms.

The majority of early data for hyperon and cascade spectroscopy was generated using \( K^- \) beams on nuclear targets. However, the significance of the \( Y^* \rightarrow K\Xi \) decay has never been firmly established except for the small branching ratios and branching-ratio upper limits reported for \( \Lambda(2100)\frac{3}{2}^- \) and \( \Sigma(2030)\frac{3}{2}^- \) \(^{30-33}\) in the 1960’s and 1970’s. In general, the excitation spectrum for \( S = -1 \) hyperons also remains under-explored, particularly in the high mass (\( > 2 \) GeV) region. When compared with model predictions, cascade polarization measurements can build on the evidence for or against intermediate hyperon resonances as the dominant production mode, discriminate among the
candidate exchange mechanisms, and even point to the existence of higher mass/spin hyperons.

The understanding of the ground state cascade production mechanism is not limited to its connection to the intermediate hyperon resonances. The current spectrum of experimentally established excited cascade states has remained virtually unchanged in the past thirty years [34]. At present, just six states are considered to have solid experimental evidence, and only half of these have established spin and parity. Furthermore, the number of cascade (as well as hyperon) states that appear in the most recent lattice QCD calculations [35] are nearly as numerous as predicted by early constituent quark models [36]. Understanding the production of excited cascades cannot be fully achieved without a better understanding of the ground state production, including polarization measurements. This manuscript reports the first measurements of both induced and transferred polarization of cascade baryons in photoproduction.

2. Experimental details

A large-statistics dataset with an integrated luminosity of 68 pb−1 was collected with CLAS [37] using a circularly polarized, tagged photon beam [38] of energy range 1.1 to 5.4 GeV incident on a liquid hydrogen target [39]. The photon beam was produced from a longitudinally polarized primary electron beam of energy 5.7 GeV, incident on a gold radiator. The electron-beam’s helicity was flipped pseudo-randomly at a rate of 30 Hz and was measured periodically by a Møller polarimeter, yielding a degree of polarization of 0.68, averaged over the entire run period. The degree of circular photon polarization was calculated and is known to be proportional to the electron beam polarization, and to increase as a function of the ratio of photon energy to the energy of the primary electron beam [40]. The target consisted of a 40-cm-long cylindrical cell containing liquid hydrogen. Momentum information for charged particles were obtained via tracking through three regions of multwire drift chambers [41], with the region-two drift chambers inside a toroidal magnetic field that was generated by six superconducting coils. Scintillators [42] outside of the drift chambers were used to measure time-of-flight (TOF) information, which, when combined with the momentum information, provided charged-particle identification.

3. Analysis

Initial event selection required timing coincidences between the photon tagger and the passage of two charged particles through the CLAS detector. The photons that produced the event were selected using vertex information obtained from tracking, and the timing information from a start counter [43], which surrounded the target. The time that an event occurred at its vertex, as measured by the start counter, was required to be within ±1 ns of the photon time provided by the accelerator radio-frequency signal. Furthermore, the vertex time determined from the TOF system was required to be within ±1 ns of the photon time for all detected charged particles.

The next step in the identification of the γp → K⁺K⁺Σ⁻ reaction with the subsequent decay of Σ⁻ → Λπ⁻ was selecting events with three charged mesons, K⁺, K⁺, and π⁻, detected. Their momentum was corrected for the energy loss in the target region, as well as other detector effects such as misalignments and errors in the magnetic field map. The signals were then extracted using the following four mass distributions:

1. Missing mass in the γp → K⁺K⁺(X) reaction, where X indicates the missing particle, labeled as MM(K⁺K⁺).
2. Missing mass in the γp → K⁺K⁺π⁻(X) reaction, where X indicates the missing particle, labeled as MM(K⁺K⁺π⁻).
3. Invariant mass of the (Λ+π⁻) system, labeled as M(Λ+π⁻), and where the known Λ mass, 1115.683 GeV [34], was combined with the missing three-momentum of the K⁺K⁺π⁻ system to define the Λ four-momentum vector.
4. Invariant mass reconstructed from the four-momentum difference of the Σ⁻ and π⁻ system, labeled as M(Σ⁻−π⁻), and where the known Σ⁻ mass, 1321.71 GeV [34], was combined with the missing three-momentum of the K⁺K⁺ system to define the Σ⁻ four-momentum vector.

The mass distributions for events passing cuts on event timing, event vertex location, and detected particle mass are shown by the data points with error bars in Fig. 2. Clear signals for the Λ and Σ⁻ are seen.

Instead of cutting on individual mass distributions, each of the above quantities was scaled by the reciprocal of their individually associated 3σ width, and treated as orthogonal displacements in a four dimensional space. A composite cut was then placed on the volume of the hypersphere that was constructed from the scaled
displacements. The width $\sigma$, of each mass distribution was measured by fitting it with a Gaussian plus a polynomial to model the signal and background, as shown by the fits in Fig. 2. The hypersphere coordinates were defined as

$$x_1 = \frac{[MM (K^+ K^-) - \Xi^{-}_{\text{mass}}]}{3\sigma_1},$$
$$x_2 = \frac{[MM (K^+ K^- \pi^-) - \Lambda_{\text{mass}}]}{3\sigma_2},$$
$$x_3 = \frac{[M (\Lambda + \pi^-) - \Xi^{-}_{\text{mass}}]}{3\sigma_3},$$
$$x_4 = \frac{[M (\Xi^- - \pi^-) - \Lambda_{\text{mass}}]}{3\sigma_4},$$
$$r = \sqrt{x_1^2 + x_2^2 + x_3^2 + x_4^2},$$

where $\sigma_1$ denotes the Gaussian width of the associated quantity as displayed in Fig. 2. A cut on the hypersphere radius $r$ represents a simultaneous cut on all four mass quantities, where a $\sigma$ cut corresponds to taking events within the hypervolume defined by $r < 1$. This cut, as opposed to simply rectangular cuts on the masses, allowed the best signal to background ratio, even though $x_1$s are not totally independent. The final data sample of 5143 events are shown in the filled histograms in Fig. 2.

The $\Xi^-$ polarization is related to the angular distribution of the decay $\pi^-$ as measured in the rest frame of the $\Xi^-$ by [44]

$$I(\cos \theta^i_{\pi^-}) = \frac{N}{2} (1 - P_{\Xi^+} \alpha \cos \theta^i_{\pi^-}),$$

where $\theta^i_{\pi^-}$ is the pion angle relative to the $i=x, y$, or $z$ axes in the $\Xi^-$ rest frame, $N$ is the total number of events in the $I(\cos \theta^i_{\pi^-})$ distribution, $P_{\Xi^+}$ is the $i$-component of the $\Xi^-$ polarization, and $\alpha$ is the $\Xi^-$ weak-decay asymmetry or analyzing power with $\alpha = -0.458 \pm 0.012$ [34]. The axes are defined in the $\Xi^-$ rest-frame (Fig. 3) as

$$\hat{z} = -\frac{\vec{p}_{\gamma}}{|\vec{p}_{\gamma}|},$$
$$\hat{y} = \frac{\hat{z} \times \vec{p}_{\Xi^-}}{|\hat{z} \times \vec{p}_{\Xi^-}|},$$
$$\hat{x} = \hat{y} \times \hat{z},$$

where $\vec{p}_{\gamma}$ and $\vec{p}_{\Xi^-}$ are the photon and cascade momentum vectors, respectively, both in the center-of-momentum frame of the beam-plus-target system. The spin observables $P$, $C_x$, and $C_z$ are connected to the recoil polarization $\vec{P}_{\Xi^-}$ through,

$$P_{\Xi^+} = P_{\Xi^+ C_x},$$
$$P_{\Xi^-} = P,$n
$$P_{\Xi^-} = P_{\Xi^- C_z},$$

where $P_{\Xi^+}$ is the degree of photon-beam polarization.

Fig. 3. Plane and angle definitions for the polarization observables of $C_x$, $C_z$, and $P$. See the text for a full description of the coordinates.

![Beam-plus-target](image)

The induced polarization, $P$, can be extracted from the forward-backward asymmetry, $A_y$, of the pion angular distribution. This method has the advantage of the cancelation of detector-acceptance effects, which follows from the fact that the polarization axis $\hat{y}$ points isotropically in the lab frame. The asymmetry is defined as

$$A_y = \frac{N^+_{\gamma} - N^-_{\gamma}}{N^+_{\gamma} + N^-_{\gamma}},$$

where $N^+_{\gamma}$ and $N^-_{\gamma}$ represent the number of events with $\cos \theta^i_{\pi^-}$ as positive and negative, respectively. The asymmetry is related to the induced $\Xi^-$ polarization by

$$P = -2A_y \alpha.$$

The double polarization observables $C_x$ and $C_z$ characterize the transferred polarization of the photon to the $\Xi^-$ and are extracted from the photon-helicity asymmetry,

$$A = \frac{N^{\text{hel}}_{\gamma^+} - N^{\text{hel}}_{\gamma^-}}{N^{\text{hel}}_{\gamma^+} + N^{\text{hel}}_{\gamma^-}},$$

where $N^{\text{hel}}_{\gamma^+}$ and $N^{\text{hel}}_{\gamma^-}$ are the number of events associated with positive and negative photon-beam helicity states, respectively. The transferred polarization is related to the photon-helicity asymmetry by

$$-\frac{A(\cos \theta^i_{\pi^-})}{|P_{\Xi^-} \alpha|} = C_i \cos \theta^i_{\pi^-}.$$

The value and uncertainty of $C_i$ can thus be obtained from the slope of $A(\cos \theta^i_{\pi^-})$. Examples of the linear fits used to extract $C_x$ and $C_z$ are shown in Fig. 4. In the asymmetry defined in Equation (7), systematic effects such as detector acceptance mostly cancel, since they occur irrespective of the photon helicity.

It was found that overall around 15% of the events surviving the final cuts were unpolarized background events. The fraction of these events were estimated in each kinematic bin by evaluating the background subtracted yield through a Gaussian fit with a polynomial background. These events were found to have polarizations consistent with zero, thus reducing the measured polarization by the dilution factor,

$$D = 1 - f_{\text{BG}},$$

where $f_{\text{BG}}$ is the fraction of background events in each sample. In order to recover the true polarization, the measured polarization observables in each bin were divided by the corresponding dilution.
factor, the values of which were found to be between 0.82 and 0.91.

Aside from the dilution factor, three main sources of systematic uncertainty contributed to the overall uncertainties in the measurements. For one, systematic effects due to acceptance-related factors, including the selection of the fiducial region of the detector, were estimated by comparing the final results obtained with and without these cuts, and were found to be, integrating over all kinematic bins, $\delta_{\text{acc}} P = 0.022$, $\delta_{\text{acc}} C_x = 0.01$ and $\delta_{\text{acc}} C_z = 0.052$. Additionally, uncertainty in the degree of photon-beam polarization, which in turn resulted from the uncertainty in the primary electron beam polarization, contributed a relative scale-type uncertainty of $\delta P C_1/C_1 = 0.03$. Finally, the uncertainty in the analyzing power of the cascade, which is $\pm 0.012$ [34], leads to a relative scale-type uncertainty of $\delta_P P/P = \delta P C_1/C_1 = 0.026$. For both the induced and transferred polarization measurements, the statistical uncertainty dominates the cumulative systematic uncertainty.

### 4. Results & comparison with theory

In the extraction of $P$, data were binned into nine regions defined by three bins of the cascade angle between the photon and target momenta in the c.m. frame with event-weighted average values of $\cos\theta_2 = -0.79$, $-0.41$, and 0.19, and three bins of photon energy with event-weighted averages of $E_y = 3.47, 4.09, \text{ and } 4.88$ GeV. Since the extractions of $C_x$ and $C_z$ require more events to achieve the same statistical uncertainty as $P$, these variables were binned into only three regions of $\cos\theta_2$ and summed over $2.8 \leq E_y \leq 5.5$ GeV, or conversely, binned into three regions of $E_y$ and summed over $-1 \leq \cos\theta_2 \leq 1$. The $P$ results are given in Table 1 and the $C_x$ and $C_z$ results are given in Table 2, as well as shown in Figs. 5, 6, and 7. These results can be found in Ref. [45].

For comparison, the polarization predictions of the three phenomenological model variants put forth by Refs. [28,29] to help explain the differential cross sections reported by Ref. [27], overlay our results in Figs. 5, 6, and 7. All three model variants share the same framework, in which cascade photoproduction proceeds through the decay of intermediate hyperon resonances that are produced via relativistic meson exchange. The predictions are based on pseudoscalar (solid red) and pseudovector (dashed blue) relativistic meson-exchange. Contributions from the $\Sigma^*(2030)$, which has spin-7/2, were introduced in Ref. [29] (dotted green).

The predicted values of $P$ and $C_x$ follow fairly flat curves, that when determined over the entire angular and/or energy range, integrate to nearly zero. Conversely, the predicted values of $C_z$ are

### Table 1

<table>
<thead>
<tr>
<th>$E_y$ (GeV)</th>
<th>$\cos\theta_2$</th>
<th>$P$</th>
<th>$\delta_{\text{sys}} P$</th>
<th>$\delta_{\text{stat}} P$</th>
<th>$\delta_{\text{total}} P$</th>
<th>$\delta_{\text{stat}} P/P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.47</td>
<td>$-1$ to 1</td>
<td>$-0.011$</td>
<td>0.12</td>
<td>0.022</td>
<td>0.12</td>
<td>0.026</td>
</tr>
<tr>
<td>4.09</td>
<td>$-1$ to 1</td>
<td>$-0.089$</td>
<td>0.12</td>
<td>0.022</td>
<td>0.12</td>
<td>0.026</td>
</tr>
<tr>
<td>4.88</td>
<td>$-1$ to 1</td>
<td>$0.006$</td>
<td>0.13</td>
<td>0.022</td>
<td>0.13</td>
<td>0.026</td>
</tr>
<tr>
<td>2.8 to 5.5</td>
<td>$-0.79$</td>
<td>$-0.045$</td>
<td>0.12</td>
<td>0.022</td>
<td>0.12</td>
<td>0.026</td>
</tr>
<tr>
<td>2.8 to 5.5</td>
<td>$-0.41$</td>
<td>0.15</td>
<td>0.12</td>
<td>0.022</td>
<td>0.12</td>
<td>0.026</td>
</tr>
<tr>
<td>2.8 to 5.5</td>
<td>0.19</td>
<td>$-0.19$</td>
<td>0.12</td>
<td>0.022</td>
<td>0.12</td>
<td>0.026</td>
</tr>
<tr>
<td>3.47</td>
<td>0.80</td>
<td>$-0.088$</td>
<td>0.21</td>
<td>0.022</td>
<td>0.21</td>
<td>0.026</td>
</tr>
<tr>
<td>4.10</td>
<td>$-0.79$</td>
<td>$-0.14$</td>
<td>0.20</td>
<td>0.022</td>
<td>0.20</td>
<td>0.026</td>
</tr>
<tr>
<td>4.88</td>
<td>0.77</td>
<td>0.036</td>
<td>0.22</td>
<td>0.022</td>
<td>0.22</td>
<td>0.026</td>
</tr>
<tr>
<td>3.50</td>
<td>0.12</td>
<td>$-0.10$</td>
<td>0.20</td>
<td>0.022</td>
<td>0.20</td>
<td>0.026</td>
</tr>
<tr>
<td>4.10</td>
<td>0.19</td>
<td>$-0.27$</td>
<td>0.21</td>
<td>0.022</td>
<td>0.21</td>
<td>0.026</td>
</tr>
<tr>
<td>4.90</td>
<td>0.26</td>
<td>$-0.12$</td>
<td>0.21</td>
<td>0.022</td>
<td>0.22</td>
<td>0.026</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>$E_y$ (GeV)</th>
<th>$\cos\theta_2$</th>
<th>$C_x$</th>
<th>$\delta_{\text{sys}} C_x$</th>
<th>$\delta_{\text{stat}} C_x$</th>
<th>$\delta_{\text{total}} C_x$</th>
<th>$\delta_{\text{stat}} C_x/C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.47</td>
<td>$-1$ to 1</td>
<td>0.21</td>
<td>0.039</td>
<td>0.09</td>
<td>0.39</td>
<td>0.039</td>
</tr>
<tr>
<td>4.09</td>
<td>$-1$ to 1</td>
<td>$-0.083$</td>
<td>0.34</td>
<td>0.01</td>
<td>0.34</td>
<td>0.039</td>
</tr>
<tr>
<td>4.88</td>
<td>$-1$ to 1</td>
<td>$-0.021$</td>
<td>0.32</td>
<td>0.01</td>
<td>0.32</td>
<td>0.039</td>
</tr>
<tr>
<td>2.8 to 5.5</td>
<td>$-0.79$</td>
<td>$-0.21$</td>
<td>0.33</td>
<td>0.01</td>
<td>0.33</td>
<td>0.039</td>
</tr>
<tr>
<td>2.8 to 5.5</td>
<td>$-0.41$</td>
<td>0.37</td>
<td>0.35</td>
<td>0.01</td>
<td>0.40</td>
<td>0.039</td>
</tr>
<tr>
<td>2.8 to 5.5</td>
<td>0.19</td>
<td>0.012</td>
<td>0.40</td>
<td>0.01</td>
<td>0.40</td>
<td>0.039</td>
</tr>
<tr>
<td>$E_y$ (GeV)</td>
<td>$\cos\theta_2$</td>
<td>$C_z$</td>
<td>$\delta_{\text{sys}} C_z$</td>
<td>$\delta_{\text{stat}} C_z$</td>
<td>$\delta_{\text{total}} C_z$</td>
<td>$\delta_{\text{stat}} C_z/C$</td>
</tr>
<tr>
<td>------------</td>
<td>----------------</td>
<td>------</td>
<td>-------------------</td>
<td>-------------------</td>
<td>-------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>3.47</td>
<td>$-1$ to 1</td>
<td>0.52</td>
<td>0.35</td>
<td>0.052</td>
<td>0.35</td>
<td>0.039</td>
</tr>
<tr>
<td>4.09</td>
<td>$-1$ to 1</td>
<td>0.67</td>
<td>0.29</td>
<td>0.052</td>
<td>0.29</td>
<td>0.039</td>
</tr>
<tr>
<td>4.88</td>
<td>$-1$ to 1</td>
<td>0.001</td>
<td>0.26</td>
<td>0.052</td>
<td>0.26</td>
<td>0.039</td>
</tr>
<tr>
<td>2.8 to 5.5</td>
<td>$-0.79$</td>
<td>0.52</td>
<td>0.32</td>
<td>0.052</td>
<td>0.33</td>
<td>0.039</td>
</tr>
<tr>
<td>2.8 to 5.5</td>
<td>$-0.41$</td>
<td>0.49</td>
<td>0.28</td>
<td>0.052</td>
<td>0.29</td>
<td>0.039</td>
</tr>
<tr>
<td>2.8 to 5.5</td>
<td>0.19</td>
<td>0.13</td>
<td>0.30</td>
<td>0.052</td>
<td>0.30</td>
<td>0.039</td>
</tr>
</tbody>
</table>

Fig. 5. $P$ (top), $C_x$ (middle) and $C_z$ (bottom) as a function of $E_y$ and summed over $\cos\theta_2$. The error bars represent the total uncertainty. The legend specifies pseudoscalar (ps) or pseudovector (pv) coupling, as well as the journal publication for the associated model.

Fig. 6. $P$ (top), $C_x$ (middle) and $C_z$ (bottom) as a function of $\cos\theta_2$ and summed over $E_y$. Error bars and curves are the same as in Fig. 5.
positive and sizable over the kinematic range and thus do not integrate to zero on any interval.

As shown in Figs. 5, 6, and 7, our measurements are generally well described by the pseudoscalar (solid red) and the 2006 pseudovector model (dashed blue). We have performed a statistical comparison of the three model variants to 15 independent data points, 9 of which come from the induced polarization, \( P \), in the un-integrated binning scheme in Table 1, while the other 6 data points come from the transferred polarization, \( C_1 \) and \( C_2 \), summed over \( E_f \). The agreement between the data and the pseudoscalar variant is good, with a \( \chi^2 = 13.0 \). The 2006 variant of the pseudovector model has \( \chi^2 = 3.0 \) and is therefore excluded by the data with \( \~99\% \) confidence. The 2011 variant of the pseudoscalar model (dotted green) has \( \chi^2 = 17.4 \). Similar results are found when comparing the model to the \( \cos\theta_Z \) integrated transferred polarization results. However it is important to point out these models were tested against the cross sections measurements up to around 4 GeV. Above that, it is possible that other mechanisms not accounted for such as the Regge trajectories and other higher-mass hyperons might need to be included.

Finally, it is worth pointing out that the photoproduced \( \Lambda \) was observed [8] to exhibit nearly 100% polarization by evaluation of \( R = \sqrt{C_1^2 + C_2^2} / P^2 \). This quantity for the \( \Sigma^- \), integrating our results over all bins, is \( 0.30 \pm 0.14 \), which is non-zero but significantly smaller than the \( \Lambda \) counterpart.

5. Conclusion

To summarize, we have made the first polarization measurements for the \( \Sigma^- \) in photoproduction by measuring the induced polarization, \( P \), as well as transferred polarization, \( C_1 \) and \( C_2 \), using a circularly polarized photon beam. We have found that the total integrated \( \Sigma^- \) polarization departs from zero by \( 2\sigma \), but is significantly smaller than in the analogous case for \( \Lambda \) photoproduction. The results have been compared, and show general agreement with the predictions of a phenomenological model of cascade photoproduction involving intermediate hyperon resonances that are produced, predominantly in the \( t \)-channel, via relativistic pseudoscalar meson exchange. The results strongly disfavored a model variant that excludes significant contributions from the \( \Sigma(2030)^+ \). Precisely determining the role of high-spin excited hyperons and the contributions from scalar versus vector exchange mechanisms will be left to future experiments at CLAS12 and GlueX [46]. Nevertheless, we have made the first step toward a detailed understanding of \( \Sigma^- \) photoproduction.

Acknowledgements

We thank K. Nakayama for many fruitful discussions in which he provided his insight and support. We acknowledge the outstanding efforts of the staff of the Accelerator and the Physics Divisions at Jefferson Lab that made this experiment possible. This work was supported in part by the U.S. Department of Energy, the National Science Foundation, the Italian Istituto Nazionale di Fisica Nucleare, the French Centre National de la Recherche Scientifique, the French Commissariat à l’Energie Atomique, the National Research Foundation of Korea, the UK Science and Technology Facilities Council (STFC), and the Physics Department at Moscow State University. The Jefferson Science Associates (JSA) operates the Thomas Jefferson National Accelerator Facility for the United States Department of Energy under contract DE-AC05-06OR23177. The FIU group is supported by the U.S. Department of Energy, Office of Nuclear Physics, under contract No. DE-SC0013620.

References

[7] M. Sumihama, et al., The polarized \( \gamma p \rightarrow K^+\Lambda \) and polarized \( \gamma p \rightarrow K^+\Sigma^0 \) reactions at forward angles with photon energies from 1.5-GeV to 2.4-GeV, Phys. Rev. C 73 (2006) 035214.
[27] L. Guo, et al., Cascade production in the reactions $\gamma p \rightarrow K^+ K^+(X)$ and $\gamma p \rightarrow K^+ K^+\pi^-(X)$, Phys. Rev. C 76 (2007) 025208.
[33] G. Burgun, et al., Resonance formation in the reactions $K^- p \rightarrow K^+ \Xi^-$ and $K^- p \rightarrow K^0\Xi^0$ in the mass region from 1915 to 2168 MeV, Nucl. Phys. B 8 (1968) 447.
[45] Data reported here may be accessed in the CLAS Physics Database at: http://clas.simp.msstate.edu/cgi-bin/jlab/db.cgi.