Near threshold angular distributions of the $d(\gamma, \Lambda)X$ reaction

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Abstract
A study of the $d(\gamma, \Lambda)X$ reaction was performed using a tagged photon beam at the Research Center for Electron Photon Science (ELPH), Tohoku University. The photoproduced $\Lambda$ was measured in the $p\pi^-$ decay channel by the upgraded Neutral Kaon Spectrometer (NKS2+). The momentum integrated differential cross section was determined as a function of the scattering angle of $\Lambda$ in the laboratory frame for five energy bins. Our results indicated a peak in the cross section at angles smaller than $\cos \theta_{\Lambda}^{LAB} = 0.95$. The experimentally obtained angular distributions were compared to isobar models, Kaon-Maid (KM) and Saclay-Lyon $\Lambda$ (SLA), in addition to the composite Regge-plus-resonance (RPR) model. Both SLA($rK1K_\gamma = -1.4$) and RPR describe the tendency of the data quite well in contrast to the KM model that substantially under predicted the cross section. With the anticipated forthcoming data on $\Lambda$ integrated and momentum dependent differential cross sections of $d(\gamma, \Lambda)X$ production measurements [1], we present our preliminary findings on the angular distributions in this report from data taken in 2010.

Keywords: strangeness, photoproduction, tagged photon

I. INTRODUCTION

Experimental and theoretical study of the photo-nuclear production of strangeness has been carried out on a proton and most recently the focus has been shifted to the neutron to fully idealize a universal description of the process for all six isospin channels. A neutron target is unrealistic, thus it only makes sense to use a deuteron as a practical neutron target. At present, there has been extensive experimental investigation of the elementary kaon photoproduction process on a proton target via...
the $p(\gamma, K^+)\Lambda(\Sigma)$ reactions by measuring cross sections and some polarization observables at JLab (CLAS) [10–13], Spring-8 (LEPS) [16, 17], ELSA (SAPHIR) [8, 9], GRAAL [20, 21] and the MAMI [19]. Most recently, a few collaborations have used a liquid deuterium targets in experiments and have measured neutral kaons in the $p(\gamma, K_0)\Lambda(\Sigma)$ reactions at ELSA and MAINZ [7, 18]. Prior to the decommissioning in 1999, the SAPHIR group reported on the total and differential cross sections as well as hyperon polarizations in the aforementioned reactions. Their results confirmed that the cross section quickly climbs at 1.1 GeV, plateaus and the declines at photon energies close to 1.45 GeV. The published results in 2004 by SAPHIR [9] were $p(\gamma, K^+)\Lambda$ consistent with the previous SAPHIR data [8]. They concluded that there are strong resonances contributions to the production of $\Lambda$ at threshold energies and for $(\Lambda, \Sigma)$ at approximately 1.45 GeV. It was also found that the hyperons $(\Lambda, \Sigma^0)$ are intensively polarized and are produced with opposite polarization signs [9]. At the time of publication, the CLAS collaboration reported the largest set of data for these reactions at photon energies of 1.6–2.53 GeV and angles of $-0.85 \leq \cos\theta_{CM}^{K^+} \leq 0.95$. The large experimental data sets that have been measured for the $p(\gamma, K^+)\Lambda$ reaction with CLAS and SAPHIR [8–10, 12, 13] are still not adequate to constrain theoretical models and successfully predict the cross section of the unmeasured channels.

The aim of this experiment was placed on neutral particle ($K^0$ and $\Lambda$) final states in associated strangeness photoproduction at threshold energies. The production of these particles may occur through two channels, $\gamma d \rightarrow K^0\Lambda(p)$ and $\gamma d \rightarrow K^+\Lambda(n)$.

Our experiment was conducted in the threshold region and therefore it acknowledges that the reaction is significantly less perturbed by higher nucleon resonances, allowing for a simplification in the description of the reaction and thus permitting the study with less uncertainty. The first results of the energy dependence of the integrated cross section for forward angles and the momentum dependent differential cross sections was previously reported [5]. Our analysis was centered on the angle dependence of $\Lambda$ photoproduction at threshold energies, thus providing an original measurement and a means to augment the understanding of neutral kaon production. Theoretically descriptions of the reaction have used different approaches that included the use of var-
ious form-factors, nucleon and hyperon resonances. The data provided here seeks to be used for reconstructing a trust worthy model that aims to reduce the number of uncertain free parameters while also being capable of extracting information regarding the excitation spectrum.

II. THE NKS2+ EXPERIMENT

Previous exploration of the \( p(\gamma, K^+)\Lambda \) and \( d(\gamma, K^0)\Lambda p \) processes measured by the Neutral Kaon Spectrometer (NKS) and NKS2 experimental collaborations yielded encouraging results [2–6]. The reported data provided the first measured information in the neutral channel and demonstrated the importance of the \( n(\gamma, K^0)\Lambda \) reaction [3]. These earliest data of the neutral kaon photo-production on a neutron was measured by the NKS collaboration and the obtained results has since been published [4]. As an outcome of the series of the NKS experiments, the re-envisioned Neutral Kaon Spectrometer, NKS2, was newly designed and constructed at LNS in 2004, replacing the original version. Its main purpose was to investigate the photoproduction process, particularly the production of neutral strange particles via single \( K^0 \) and \( \Lambda \) observation with an accept ance less biased in the forward region compared with the NKS spectrometer. These reported results influenced an extension of the proposed measurable physical observables, which directly propelled advances in the spectrometer design. The NKS2 has since then undergone an additional upgrade in order to improve the spectrometers acceptance, chiefly in the forward hemisphere. The most recent has been the redesign of the inner detector package by installing an Inner Hodoscope (IH) and a Vertex Drift Chamber (VDC) and being renamed as the NKS2+.

II.1. Experimental Setup

A photon beam was generated from a carbon wire radiator (\( \phi 11 \mu m \)) and was guided through a collimator in order to reduce the beam halo, a sweep magnet, and into the NKS2+ where it was directed to the target located in the spectrometer. Moving from the inner most position outwards, was the target which was surrounded by a Vertex Drift Chamber (VDC) and an Inner Hodoscope comprised of twenty plastic scintillator segments (IH), which acted as the start signal for time of flight measurements. These pair of detectors were surrounded and fully enclosed in a Cylin-
drical Drift Chamber (CDC). All detectors were themselves located between the poles of a dipole magnet with a 680 mm aperture and a 80 cm diameter. The typical magnetic field was 0.42 Tesla at the center position. The target was inserted from top side of magnet yoke and a cryostat stayed on the yoke. The cell shape was cylindrical (30 mm length and 50 mm φ). The cell window (40 mm φ) in thickness was made from a polymide film. The target system, adapted for the NKS2+, which was able to control the liquefaction of deuterium and sustain it in a liquid phase. During the experiment, the temperature of the liquid deuterium and the pressure of the residual gas were monitored and recorded to estimate the density. The average density of the liquid deuterium was estimated at 0.172 g/cm³ with minor ambiguities. This corresponded to an approximated average number of deuteron targets of 0.168 μb⁻¹.

III. DATA ANALYSIS

The detector commissioning was finished in late 2009 and the experiment using tagged photon beams in the range of 0.8 ≤ Eγ ≤ 1.08 GeV was carried out 2010. There was an additional experimental time scheduled, but unfortunately has been postponed due to the significant damage at ELPH attributed the Tohoku-Pacific Ocean Earthquake of 2011/Mar/11. The energy of the pho-
ton beam through bremsstrahlung was determined by measuring the scattered electrons from a carbon wire. The accepted number of events and photons were $0.64 \times 10^9$ and $0.89 \times 10^{12}$, respectively. The direct approach to measuring the photoproduction of strangeness is by reconstructing the invariant mass of the produced particles that contain a hyper charge. A coincidence signal between the photon tagging counter (Tagger), IH and OH, along with an absence of a signal from the upstream Electron Veto (EV) counter in tandem to a two hit minimum requirement on the IH and OH was the main trigger. A triggered event thus ensured that the event originated from a real photon and also that the decay particles passed through the IH, drift chambers (VDC & CDC) and exited the spectrometer via the OH. We employed only the upstream side of EV in the trigger; The downstream side was not included in the trigger to avoid the introduction of a bias in the data set.

### III.1. PID and Event Selection

The normal tagged photon beam rate was about 2 MHz with a trigger rate of roughly 2 kHZ and a 65% DAQ efficiency. The momenta of the detected particles were determined by the CDC and the particle species was identified by TOF measurements, with the IH and OH providing the start and stop timing signals respectively. The standard TOF resolution was about 400 ps, which was more than ade-

![FIG. 2. Mass squared vs. rigidity ($|\vec{p}|$) multiplied by particles's charge and the projected mass squared distributions are seen left to right, where $\pi^\pm$ can be identified by the charge.](image-url)
FIG. 3. The reconstructed invariant mass, $p\pi^-$ and missing mass, $\gamma N \rightarrow p\pi^- X$, distributions are given in the figure left to right respectively. The missing mass distribution from a neutron, assumed at rest within the deuteron nucleus was obtained for events in which a selection was placed on the invariant mass distribution between 1.105 – 1.125 GeV/$c^2$.

In order to successfully separate pions and protons at momenta less than 800 MeV/c see Fig. 2. A two particle track reconstruction strategy was used by the CDC, which achieved a position resolution between 300 - 400 $\mu$m over its ten layers. A selection requirement was placed on the opening angle between reconstructed particle tracks equivalent to $-0.9 \leq \cos\theta_{oa} \leq 0.9$ in order to reduce the $e^+e^-$ background in the data set. The produced $\Lambda$ was detected in the $p\pi^-$ decay channel. The measured momentum multiplied by the respective particle’s charge as a function of squared mass and the projected squared mass distributions are given in Fig. 2. Here, the $\pi$ was identified by its charge, demonstrating PID capability of the NKS2+. The lifetime of $\Lambda(c\tau = 7.89$ cm) suggests that the decay take places away from the primary interaction vertex inside the target. Consequently, a selection outside the target was specified to reject particles originating from the principal vertex.

### III.2. Invariant Mass Spectra

Various cuts, but not limited to, timing, $\chi^2$ and kinematical requirements were applied to the raw invariant mass to extract a clear $\Lambda$ peak from the continuum, shown in Fig. 3. The observed $\Lambda$ (roughly 400 events) was detected in the $p\pi^-$ decay channel with a corresponding (Gaussian) width of $2.87 \pm$
0.19 MeV/c (σ) and a signal to background (S/B) of 2.1. In addition, by placing a tight event selection requirement on the $p\pi^-(\Lambda)$ invariant mass, between $1.105 - 1.125$ GeV/c$^2$, the missing mass ($K$) distribution, gated for a neutron at rest within the deuteron nucleus was obtained. The missing mass (Gaussian) width was $31 \pm 2.0$ MeV/c$^2$ (σ) with a mean value of $504 \pm 2.0$ MeV/c$^2$ resulting from detector resolutions. The spread in the distribution is associated with the Fermi motion within the deuteron and the fact that the missing mass spectrum was generated by an inclusive measurement of $p\pi^-$, therefore the missing mass has contributions from the $K^+\Lambda$ and $K^0\Lambda$ processes. The missing mass technique confirms that the event of interest, $d(\gamma,\Lambda)KN$, was measured. A contribution to the yielded $\Lambda$ events originates from the $\Sigma^0 \rightarrow \Lambda\gamma$ channel, but was considered to be minor and could not be separated as the NKS+ lacked a photon detector.

The measured $\Lambda$ momentum (top) and angular (bottom) distributions and monte carlo simulations at energies of $E_\gamma = 0.90 - 1.08$ GeV are shown in Fig 4 as the black cross data points and histograms respectively. The NKS2+ acceptance for $\Lambda$, calculated by using the analogous analyzer that was utilized for the experimental data set, for the data generated through simulation is given in Figure 5. Mathematically, the acceptance was estimated as the ratio of the triggered or reconstructed $\Lambda$ events, including the efficiencies of various detector components, to the generated events in the same kinematical bins. It was found by the following: $\varepsilon^\Lambda_{\text{accept}}(p,\cos\theta) = \frac{N_{\text{trig}}}{N_{\text{gen}}}$, where $N_{\text{trig}}$ was the sum of the $\Lambda$ histogram events within the appropriate kinematic-
IV. RESULTS AND DISCUSSION

In this section, the differential cross sections of $\Lambda$ as a function of scattering angle after background subtraction are presented for five incident photon energy bins. In these results only the statistical errors are shown. The obtained cross sections are compared to isobar and Regge-plus-resonance model calculations.

IV.1. Results

The differential cross section for the inclusive measurement of $\Lambda$ can be calculated from experimentally measured variables as:

$$\frac{d\sigma}{dpd\Omega} = \frac{N_{\Lambda}^{\text{yield}}(p, \cos\theta)}{N_{\gamma} \cdot N_{\text{target}} \cdot \varepsilon_{\text{accept}}(p, \cos\theta) \cdot \zeta^\Lambda \cdot \varepsilon_{\text{GE}}^\Lambda \cdot \varepsilon_{\text{specific}}^\Lambda \cdot 2\pi d(\cos\theta)}$$

where $N_{\Lambda}^{\text{yield}}$ was the yield of $\Lambda$, $N_{\gamma}$ was the number of incident photons on the target, and $N_{\text{target}}$ was the number of target neutrons. The branching ratio for the decay mode, $\Lambda \rightarrow p\pi^-$ (63.9%), was represented by $\zeta^\Lambda$ and the acceptance was $\varepsilon_{\text{accept}}^\Lambda(p, \cos\theta)$. The term $\varepsilon_{\text{GE}}^\Lambda$ referred to the efficiencies that are univer-
sal to the spectrometer while $\varepsilon_{\text{specific}}$ denoted the efficiencies that were intrinsic to the inclusive $\Lambda$ measurement. Theoretical predictions of the $d(\gamma, \Lambda)K^0$ and $d(\gamma, \Lambda)K^+$ reactions, calculated by the KM, SLA, and RPR models, are given in Fig. 6. The apparent dominance of the $d(\gamma, \Lambda)K^0$ reaction, for the SLA calculation increases to more than twice that of $d(\gamma, \Lambda)K^+$ simultaneously with extending photon beam energies at angles of $\cos\theta_{LAB} \geq 0.95$. The disparity in the contribution of each process arises from the resonance content of each model’s approach to Born terms suppression. The SLA incorporates hyperon resonances to assist in curbing of large non-physical Born term contributions, while the KM model only relies on nucleon resonances. In the $K^0\Lambda$ channel, the importance of the $r_{K_1K}$ parameter is remarkably dissimilar for both models. The $r_{K_1K}$ parameter in the KM framework was determined by fitting $K^0\Sigma$ data. Therefore, the conclusion can be drawn that the higher sensitivity of the $K_1$ meson is afforded to SLA but conversely seems to modestly affect the KM predictions [22].

The angle dependent distributions were compared to the calculated predictions of effective Lagrangian (isobar) models, Kaon-Maid (KM) [23] and Saclay-Lyon A (SLA) [24, 25], as well as the hybrid Regge-plus-resonance (RPR) model [26–28]. The comparison of the measured angle dependent cross sections to the summation of the contributing cross sections of the $d(\gamma, K^+){\Lambda n}$ and $d(\gamma, K^0){\Lambda p}$ reactions in the laboratory frame as a function of $\cos\theta_{LAB}^{\Lambda}$ are plotted alongside the theoretical predictions for KM, SLA, and RPR in Fig. 7, where the curves for KM, SLA, and RPR are drawn as the dotted, dashed, and solid curves respectively.

IV.2. Discussion

The angle dependent distributions were compared to the calculated predictions of effective Lagrangian (isobar) models, Kaon-Maid (KM) [23] and Saclay-Lyon A (SLA) [24, 25], as well as the hybrid Regge-plus-resonance (RPR) model [26–28]. The comparison of the measured angle dependent cross sections to the summation of the contributing cross sections of the $d(\gamma, K^+){\Lambda n}$ and $d(\gamma, K^0){\Lambda p}$ reactions in the laboratory frame as a function of $\cos\theta_{LAB}^{\Lambda}$ are plotted alongside the theoretical predictions for KM, SLA, and RPR in Fig. 7, where the curves for KM, SLA, and RPR are drawn as the dotted, dashed, and solid curves respectively.
In the sequence of reported integrated energy bins RPR accomplishes a good description of the experimental results achieving agreements within the statistical error. In the lower energy bins (a) 0.95 – 1.0 GeV, (b) 1.0 – 1.02 GeV, the model over predicts the angular cross section by approximately 20 – 30%. In the higher energy bins, it is evident that the model over predicts the cross sections by around 10 – 15% for $\cos^{LAB}_\Lambda \leq 0.95$. The strongest accord between the data and the RPR prediction exist in the (c) 1.02 – 1.04 GeV energy bin. The RPR and SLA($rK_1K_\gamma = -1.4$) models do a reasonable job of describing the general tendency of the data. The SLA fails however to describe the apparent peak at $\cos^{LAB}_\Lambda = 0.95$, but has a better reproduction of the data than RPR at higher energies and smaller angles. KM does not describe the data at small angles, which is also seen in the comparison of the elementary cross section, and under esti-
mates the angular distribution most significantly in the extreme forward region at angles smaller than \( \cos^2\theta^{LAB} \geq 0.95 \). The amplitudes for the SLA predictions are significantly larger than those of KM for laboratory angles of \( \cos^2\theta^{LAB} \geq 0.95 \). Unlike the results of the KM calculations, the \( d(\gamma, \Lambda)K^0p \) process primarily contributes to the \( \Lambda \) photoproduction in the SLA framework.

**IV.3. Conclusion**

In conclusion, we have measured the angular dependence of \( \Lambda \) photoproduction in the threshold region with the upgraded Neutral Kaon Spectrometer 2 (NKS2+) utilizing tagged photons on a liquid deuterium target. Cross sections were dominant at small scattering angles equal to \( \cos^2\theta^{LAB} = 0.95 \) emphasizing...
that the NKS2 collaboration is capable of roughly measuring the total cross section of Λ. Our findings were supported by predictions of SLA and RPR, however RPR calculations exhibited an over estimation of the $K^+\Lambda$ contribution.

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